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PLEASE CITE THE PUBLISHED VERSION

https://doi.org/10.1016/j.apergo.2021.103501

PUBLISHER

Elsevier BV

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This paper was accepted for publication in the journal Applied Ergonomics and the definitive published version is available at https://doi.org/10.1016/j.apergo.2021.103501.

The ergonomic impact of patient body mass index on surgeon posture during simulated laparoscopy

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Abstract

Laparoscopy is a cornerstone of modern surgical care, with clear advantages for the patients. However, it has also been associated with inducing upper body musculoskeletal disorders amongst surgeons due to their propensity to assume non-neutral postures. Further, there is a perception that patients with high body mass indexes (BMI) exacerbate these factors. Therefore, surgeon upper body postures were objectively quantified using inertial measurement units and the LUBA ergonomic framework was used to assess posture during laparoscopic training on patient models that simulated BMIs of 20, 30, 40 and 50 kg/m². In all surgeons the posture of the upper body significantly worsened during simulated surgery on the BMI 50 kg/m² model as compared to on the baseline BMI model of 20 kg/m². These findings suggest that performing laparoscopic surgery on patients with high BMIs increase the prevalence of non-neutral posture and may further increase the risk of musculoskeletal disorders in surgeons.

Keywords

Laparoscopic Surgery; Posture; Inertial Measurement Units; Ergonomics

1. Introduction

Over the past thirty years Laparoscopic Surgery (LS) has revolutionised patient care and has quickly become the default interventional procedure within a myriad of surgical specialties (Giannotti et al., 2015; Gill et al., 2010; Nguyen et al., 2001; NICE, 2010). The transition from open surgery has been supported by shorter recovery periods, less postoperative pain and lower risk of operative complications for the patient (Agha and Muir, 2003; Buia et al., 2015).

Despite the clear advantages of LS for the patient, the shift away from open surgery seems to have had a negative impact on surgeon health; specifically, an increased prevalence of musculoskeletal disorders (MSDs) (Alleblas et al., 2017; Nguyen et al., 2001). Laparoscopic surgery, as compared to open surgery, has been associated with a significantly greater risk of MSDs in the neck, thorax and shoulders (Stucky et al., 2018), with MSD complaints reported in 88% of 244 surgeons (Franasiak et al., 2012). The most likely cause of increased rates of MSDs has been attributed to the increase in non-neutral postures adopted by surgeons during LS (Epstein et al., 2017).

The emergence and impact of patients with obesity (BMI ≥ 30 kg/m²) has been linked with further deterioration of surgeon posture during LS (Moss et al., 2019). Obesity classification can be subdivided into three categories: Class 1, 30 kg/m² < BMI ≤ 35 kg/m², Class 2, 35 kg/m² < BMI ≤ 40 kg/m² and Class 3, BMI > 40 kg/m² often termed as 'severe' (NICE, 2010). Obesity incidence in the UK has doubled in the past two decades with 29% of the adult population now obese (Class 1 and Class 2) and 4% severely obese (Class 3) (Baker, 2019). A similar trend has been observed worldwide (Blüher, 2019).

Laparoscopic surgery is recognised as the optimal interventional technique for many intra-abdominal pathologies. While literature suggests that Class 1 - 2 obesity has a minimal impact on surgeon posture during LS (Liang et al., 2019; Moss et al., 2019), there is mounting evidence that indicates patients with Class 3 obesity have a negative impact on surgeon posture, exacerbating non-neutral postures in the problem areas previously identified (AlSabah et al., 2019; Hignett et al., 2017; Sers et al., 2021). The rising prevalence of obesity and its associated negative effect on surgeon posture highlight the need for objective analysis to quantify and assess these impacts. The primary aim of this study was to objectively quantify the impact of different levels of patient BMI on surgeon posture. The authors hypothesized that increased patient BMI would degrade the quality of surgeon posture.

2. Materials and Methods

2.1. Participants and Ethics

This study was conducted at the Sports Technology Institute at Loughborough University from November 2018 to June 2019. Ethical clearance for this study was obtained from the Loughborough University Ethics Approvals Sub-Committee and all participants provided voluntary informed consent before testing commenced. Study participants included six laparoscopic surgeons (5 male, 1 female) with a minimum of 4+ years of LS experience (at least > 50 laparoscopic procedures a year). The heights and body masses of the participants ranged from 173 – 188 cm (mean: 181 cm) and 59 – 96 kg (mean: 80 kg), respectively.

2.2. Instrumentation and Equipment

The Perception Neuron V2 inertial motion capture system/suit (NOITOM Ltd, China) was setup in the 18-neuron mode as validated in (Robert-Lachaine et al., 2020; Sers et al., 2020), and previously used within (Kim et al., 2019; Zhang et al., 2019). Only the upper body portion of the motion capture system was used within this study and consisted of 11 'physical' (Figure 1) and 4 'virtual' neurons. Each 'physical' neuron consisted of an inertial measurement unit (IMU) with the following specifications: 3-axis accelerometer (± 16g), 3-axis gyroscope (± 2000 dps), 3-axis magnetometer, dimensions of 12.5 mm x 13.1 mm x 4.3 mm and a mass of 1.2 grams. Each 'virtual neuron' provided orientation data calculated by the systems proprietary algorithm giving data at the neck and approximately the T3, T8 and L1 vertebrae (Figure 1). All physical IMUs were connected in series to a wireless hub attached to the surgeon, with dimensions of 59 mm x 41 mm x 23 mm and powered using a portable 5V USB power supply with dimensions of 141 mm x 72 mm x 145 mm and mass of 213 grams. The raw orientation data for all neurons was wirelessly transferred via TCP/IP (120 Hz) from the hub to an external PC and into the suit's proprietary software. The data was then streamed into MATLAB 2019b (MATLAB, MathWorks, Natick, MA, USA) for analysis. An ad-hoc MATLAB script was written to receive the streamed data over TCP/IP in binary form (Sers, 2021a), then decoded the data to give pre-processed orientation data ready for analysis (Baumann et al., 2019).

Participant segment lengths were obtained from images captured by an Xbox One Kinect 2 (Xbox, Microsoft, Redmond, WA, USA) and quantified using bespoke software written in MATLAB facilitating a completely automated measurement process (Xu and McGorry, 2015). To obtain accurate segment lengths (Otte et al., 2016), the Kinect was setup approximately 2 m in front of the participant with a direct line of sight while the participant assumed a static I pose, i.e. stood with their arms fully adducted and parallel to their latissimi dorsi. The suit was then calibrated following the developers recommended process (NOITOM, 2015). In addition, three static calibrations were taken with the participant in an I pose, to facilitate a neutral posture. This acted as the baseline reference for all measurements.

A laparoscopic trainer (Laparo Aspire, LAPARO Medical Simulators, Wroclaw, Poland) was used (dimensions: 44 cm x 31 cm x 22 cm) to simulate a patient's abdominal cavity (Vitish-Sharma et al., 2011). On the laparoscopic trainer adipose tissue was simulated using foam fixed across the ports, to provide an anthropomorphic representation of obese patients. Models of BMI 20, 30, 40 and 50 kg/m² were developed using foam thickness of 1.7, 6.5, 9.5, and 11 cm, respectively. Baseline BMI data was identified on 32 males and 28 females whose average BMI was ~ 20 kg/m² with an average subcutaneous fat thickness of 1.7 cm (Roopakala et al., 2009). Foam thicknesses of BMI models for 30, 40 and 50 kg/m² were based on (Mohammed et al., 2021). This study utilised a contralateral port placement and remained the same for all BMI models (Hignett et al., 2017).

The base operating surface height was set at 85 cm. The operating height during experiments when BMI thickness were added ranged from ~86.7 cm for BMI 20 kg/m² (85 cm + 1.7 cm) to ~96 cm for BMI 50 kg/m². This range was deemed ergonomically optimal based on participant anthropometrics, as an acceptable surface height range of 84.6 cm – 107.8 cm was calculated to conform with previous ergonomic standards (operating height = 0.7 - 0.8*elbow height) (Berguer et al., 2002; Van Veelen et al., 2002).

During models of BMI 40 and 50 kg/m² a side bar of 7.5 cm in width was connected to the standard operating table to create a wider surface area and replicate the real surgical environment when operating on patients with severe obesity (Burnett et al., 2009; Dybec, 2004). The same laparoscopic training environment and instruments were used by all participants.

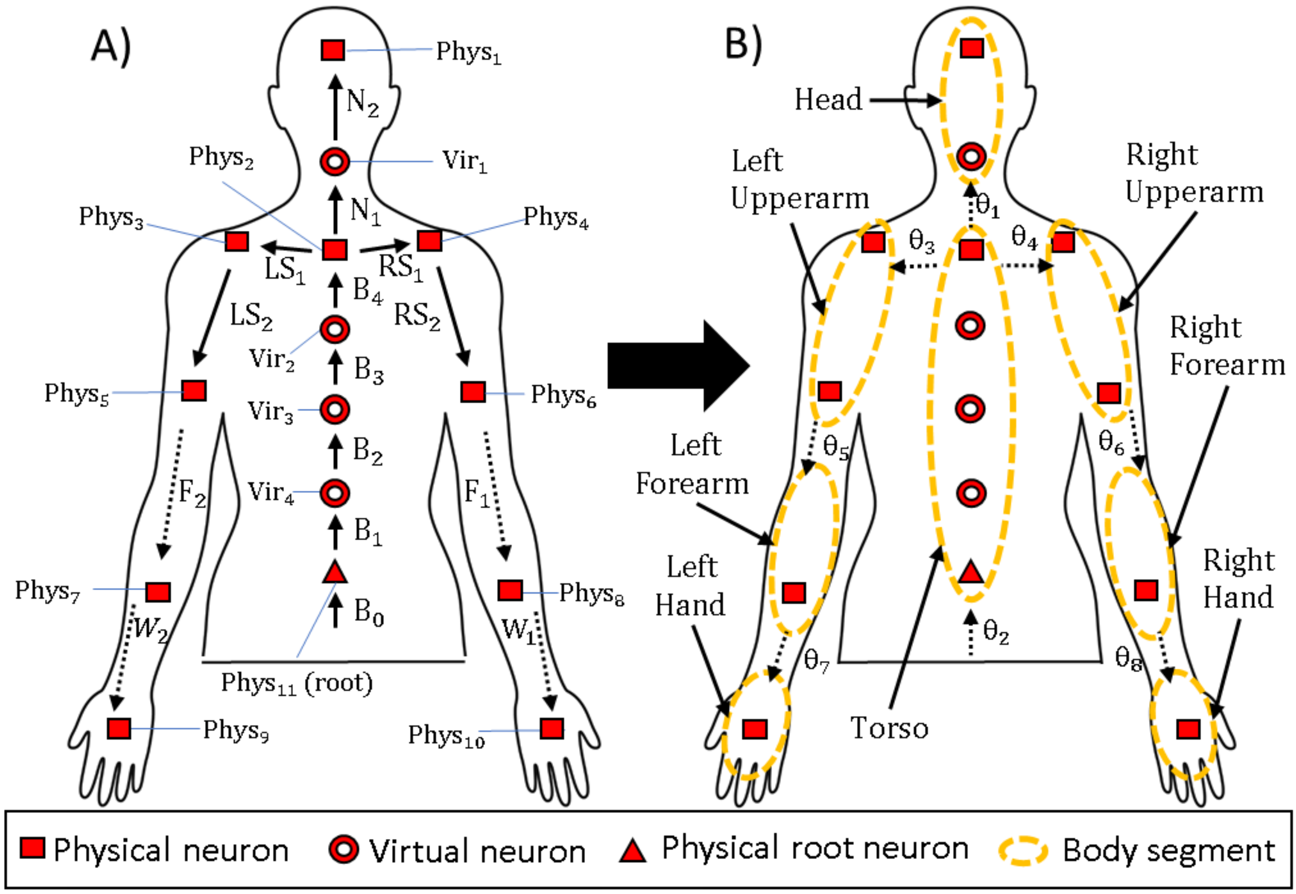

Figure 1. (A) Representation of the kinematic chains for the Perception Neuron model and (B) the adapted model illustrates the joint/segment angles used in the study. In (A) B_{0-4} denote torso quaternion 4D vectors, N_{1-2} denote neck, LS_{1-2}, RS_{1-2} denote shoulder, F_{1-2} denote elbow and W_{1-2} denote wrist quaternion 4D vectors retrospectively. In (B) the dotted circles illustrate the new rigid body segments where the quaternion outputs from the enclosed neurons in each circle were combined through quaternion multiplication (Sers et al., 2020) (Table 1).

Table 1. Upper body segments, the subsequent motion considered, reference segment and the neurons involved in the calculation of resultant angles.

Joint/Segment (Figure 1B)	Axis	Plane of motion	Description	Combination of neurons (Figure 1A)
Neck (θ_1)	Flexion/extension	Sagittal	Angles of the head relative to the torso	Phys_1 and Vir_1
	Lateral flexion	Coronal		
	Medial/Lateral rotation	Transverse		
Torso (θ_2)	Flexion/extension	Sagittal	Angles of the torso in the global coordinate system	Phys_2, Vir_2, Vir_3, Vir_4, Phys_{11}
	Lateral flexion	Coronal		
	Medial/Lateral rotation	Transverse		
Shoulders (θ_3 , θ_4)	Flexion/extension	Sagittal	Angles of the upper arms relative to the torso	Phys_3 and Phys_5 Phys_4 and Phys_6
	Abduction/Adduction	Coronal		
	Internal/External rotation	Transverse		
Elbows (θ_5 , θ_6)	Flexion	Sagittal	Angles of the forearm in reference to the upper arm	Phys_7 and Phys_8
	Pronation/Supination	Transverse		
Wrists (θ_7 , θ_8)	Flexion/extension	Sagittal	Angles of the hand in reference to the forearm	Phys_9 and Phys_{10}
	Radial/Ulnar deviation	Coronal		

2.3. Experimental Protocol

A threading task was selected for the assessment (Figure 2). The task was completed twice for each participant and BMI model of 20, 30, 40 and 50 kg/m². The BMI models were presented in a randomised order with a minimum of three minutes rest taken between trials to minimise the effects of fatigue. The duration of each trial was defined from the moment the participant held the thread with the laparoscopic graspers within the laparoscopic trainer, until the last outer frame of the task had been threaded. No time limit was set during the experiments because fatigue is known to have an effect on posture (Nguyen et al., 2001). Prior to the BMI trials, three formal familiarisation trials were conducted with no foam on the trainer to minimise any learning bias with a total practice time of one hour (Thomas and König, 2018).

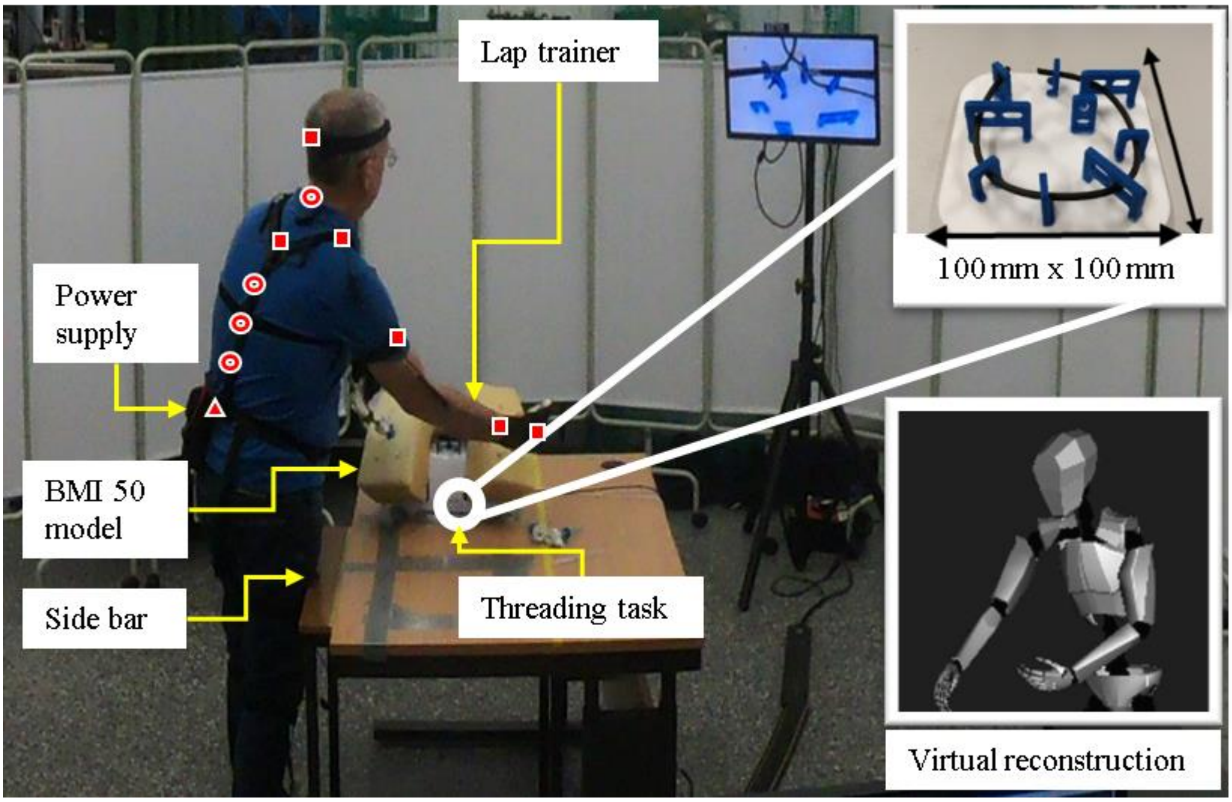

Figure 2. Experimental setup with BMI 50 kg/m² model and Perception Neuron motion capture system described in Figure 1.

2.4. Data preparation

The orientation of the rigid body segments defined in Figure 1B were calculated by following the methodology described in (Sers et al., 2020). To obtain joint angles expressed relative to the appropriate parent segment and in a format suitable for ergonomic assessment, (i.e. head in reference to the torso) the default joint angle outputs from the Perception Neuron model (Figure 1A) required modifying (Table 1). In addition, the Perception Neuron motion capture system produces orientation outputs for each neuron in the format of quaternions. Quaternions express a 3D rotation as a 4D complex vector and provide a more efficient method of representing orientation (Baek et al., 2017). The motion capture system provides quaternion outputs for each neuron in Figure 1A in the local coordinate system. In order to utilise the suits default outputs in a manner that would reference body segments to one another by the appropriate anatomical joint, quaternion outputs were combined using methods presented in (Sers et al., 2020) (Figure 1B, Table 1). Once relevant neuron/quaternion outputs for a joint were combined (Table 1), the resultant quaternions were converted to Euler angles to provide joint rotations for child segments in reference to their parent in a format suitable for ergonomic assessment.

2.5. Postural assessment

The LUBA ergonomic framework was used to assess the motion capture data (Kee and Karwowski, 2001). This framework was selected because it is upper body focused and has been shown to be most effective in medium-risk conditions (Yazdanirad et al., 2018). An emphasis was placed on the use of a framework suited to medium-risk circumstances because LS has been shown to induce prolonged low-risk non-neutral postures as well as episodic high-risk postures (Aitchison et al., 2016; Zhu et al., 2014), therefore a medium risk classification seemed to be the optimal choice given these postural habits.

The LUBA framework was developed based on perceived discomfort scores provided by participants who completed functional movements in each axis of rotation. Discomfort scores were associated with dichotomous movement range categories for each axis of rotation through perceived feedback from study participants (Kee and Karwowski, 2001). In general, the closer to the maximum range of motion for a given rotation, the larger the LUBA score. Hence, non-neutral postures are scored higher and larger LUBA scores represent higher risk postures. A MATLAB script was written to implement the LUBA dichotomous movement range categories for each segment and joint axis of rotation (Sers, 2021a). Specifically, the relative discomfort scores as defined by the LUBA framework in standing postures were used to classify the posture of each joint and segment (Kee and Karwowski, 2001). The Euler angle data for each joint (neck, shoulders, elbows, wrists) and segment (torso) was then classified into the appropriate categories using the LUBA implementation MATLAB script producing sub-scores for each joint/segment. The LUBA sub-scores were then combined using Equation 1 to produce the total LUBA posture score. The total LUBA scores were then grouped based on BMI level.

$$\text{Total LUBA score} = \frac{1}{F}\sum_{f=1}^{F}\sum_{j=1}^{n}\sum_{i=1}^{m_j} S_{fij} \quad (1)$$

where i is the joint/segment angle counter, j is the joint/segment counter; n is the total number of joints/segments included, m_j is the total number of joint/segment angles included for the jth joint/segment, f is the time frame counter, F is the total number of time frames, and S_{fij} is the relative discomfort score of the ith joint/segment angle in the jth joint/segment at an fth instance in time (Kee and Karwowski, 2001). Once an total LUBA score was calculated for the entire upper body it was sorted into one of four posture categories defined in (Kee and Karwowski, 2001). The default total LUBA posture categories defined in the initial framework were modified to accommodate the assessment of both upper extremities, as the predefined categories were developed when only considering one upper extremity. Therefore, category 1 covers postures with a total LUBA score ≤ 10, category 2 covers postures from 10 < total LUBA score ≤ 20, category 3 covers postures from 20 < total LUBA score ≤ 30 and category 4 covers postures with a total LUBA score > 30. The LUBA corrective actions which correspond to each posture category were also considered. While these actions do not correspond to firm timings and detailed conditions, they do provide context for the total LUBA score. Category 1 advises no corrective actions, category 2 suggests further investigation and corrective changes without immediate intervention, category 3 requires gradual corrective action and category 4 requires immediate intervention and corrective action.

2.6. Statistical analysis

Statistical analysis was conducted in SPSS (IBM SPSS Statistics, v. 24, IBM Corp., Armonk, NY). The presented mean responses for total LUBA score and task completion times were taken by grouping the participant data by each BMI level and taking the average (Table 2). Due to the small sample size, non-parametric statistical analyses was performed (Altman et al., 2000). Related-samples Friedman's analysis of variance (ANOVA) tests were conducted with an input category of BMI level for total LUBA score and task completion time. Where significant main effects were found, pairwise comparisons were carried out with Bonferroni correction. An alpha level of $\alpha \leq 0.05$ was set for all statistical testing.

3. Results

3.1. Postural assessment results

There was a significant effect of BMI level on total LUBA score ($p < 0.001$) (Table 2). Pairwise comparisons showed BMI 20 kg/m² – 50 kg/m² ($p = 0.001$) and 30 kg/m² – 50 kg/m² ($p = 0.002$) to be significantly different, with 50 kg/m² inducing significantly larger total LUBA scores in both cases. These results confirmed the hypotheses that significant degradation in posture can be observed when surgeons are subjected to larger BMI models. In all BMI levels, the major contributor to total LUBA scores was the torso. The higher BMI models increased the torso LUBA score more so than any other

(Table 2). Moreover, the most substantial contributor to the torso LUBA scores was sub-optimal torso lateral flexion, with scores ranging from 2.5 – 4.5 across BMIs 20 kg/m² to 50 kg/m². In addition, other key anatomical motions, and scores to highlight included: torso axial rotation LUBA scores ranging from 0.3 - -0.7 and right shoulder abduction/adduction LUBA scores ranging from 0.6 - -1.2. Furthermore, the LUBA scores for both wrists and right upper arm increased when exposed to BMI 40/50 kg/m² models, indicating a degradation in posture for both hands.

3.2. Task completion times

There were no significant effect of BMI level on task completion time ($p = 0.071$). In general, the time to complete the task was larger for BMI 40/50 kg/m² models as compared to 20/30 kg/m² models.

Table 2. Mean (± Standard error) parameter outputs.

Parameters		BMI (kg/m²)			
		20	30	40	50
LUBA Scores	Total	15.6 (±1.3)	16.4 (±1.3)	18.2 (±1.2)	19.5 (±1.5)
	Neck	0 (±0)	0.1 (±0)	0.1 (±0)	0.2 (±0)
	Torso	2.8 (±0.5)	3.4 (±0.6)	5.0 (±0.9)	4.8 (±0.9)
	Left shoulder	0.6 (±0.2)	0.9 (±0.3)	0.8 (±0.2)	0.8 (±0.2)
	Right shoulder	0.8 (±0.3)	1.1 (±0.3)	1.2 (±0.4)	1.7 (±0.3)
	Left elbow	2.9 (±0.1)	2.7 (±0.2)	2.9 (±0.1)	2.7 (±0.1)
	Right elbow	2.6 (±0.6)	2.3 (±0.7)	2.5 (±0.7)	2.2 (±0.7)
	Left wrist	2.8 (±0.3)	2.8 (±0.3)	2.4 (±0.4)	3.2 (±0.2)
	Right wrist	3.1 (±0.6)	3.3 (±0.7)	3.5 (±0.6)	3.8 (±0.6)
Task Completion Time (s)		224 (±29)	207 (±18)	250 (±49)	307 (±41)

4. Discussion

The purpose of this study was to objectively quantify the effect of different levels of simulated patients with obesity (30 kg/m²) and severe obesity (40 – 50 kg/m²) on the posture of experienced laparoscopic surgeons. The upper body posture of surgeons was assessed by classifying motion capture data using the LUBA ergonomic framework. This study contributes to the growing literature concerning the impact of patient BMI on surgeons performing laparoscopy (Franasiak et al., 2012; Hignett et al., 2017; Liang et al., 2019; Moss et al., 2019; Sers et al., 2021). As hypothesised, BMI 50 kg/m² caused significant deterioration in postural neutrality (i.e. increased total LUBA score) as compared to 20 kg/m² (baseline) and 30 kg/m² in the participant cohort (Table 2). Moreover, surgeons suffered substantial degradation in total LUBA scores during severely obese models compared to the baseline and BMI 30 kg/m² models, which emphasises the negative effect that 40/50 kg/m² models had on the postural performance of surgeons regardless of experience. Surgeons recorded significantly larger total LUBA scores at the highest BMI model, which ultimately increased the postural workload and burden on the musculoskeletal system compared to the baseline and BMI 30 kg/m² model.

The LUBA framework identified the torso, the right elbow, and both wrists as the segments/joints with the largest contributions to the total LUBA score (Table 2). An approximate positive linear relationship was found for BMI level in reference to LUBA scores for the aforementioned joints/segments, i.e. increasing the model BMI increased the total LUBA score. The identification of wrists and elbows as large contributors to total LUBA score is insightful, however optimisation in these areas may be more challenging than areas further up the kinematic chain (Nisky et al., 2014). Indeed, every surgical procedure will have individual nuances, therefore no scenario can effectively ensure neutral hand and forearm postures for set tasks as task requirements are intrinsically chaotic. Therefore, as laparoscopic hand and forearm posture is closely related to the required instrument manipulation inherent of a given task, the pursuit for safer postures may compromise task performance. Thus, it is reasonable to suggest that any targeted optimisation of wrist and elbow posture would need to be considered carefully to ensure task performance was not compromised.

The anatomical area that displayed the largest LUBA score across all groups was the torso (Table 2). In theory, the torso is an area where optimisation to minimise LUBA score is feasible as the segment is constrained by passive variables such as port placement, table position and patient BMI. Large torso scores appeared to be systemic across all BMI levels, however scores increased markedly when attempting very high BMI models and this was principally linked to degradation in lateral flexion posture. The increase in BMI level and addition of the side bar induced more severe torso lateral flexion, where torso LUBA scores increased by 70% and 90% respectively when compared to their respective scores for the baseline model. This observation could be a combined effect of both the sidebar and higher BMI model on the surgeon, however further isolated testing of the side bar is required to determine the extent of its impact on surgeon posture.

Excessive torso axial rotation and right shoulder abduction (3.1) in surgeons were also postures that could be improved given the range of scores in these areas during each BMI level. The appropriate manipulation of the joint contributions (shoulder, elbow, wrist) within the upper extremity can allow for an infinite number of redundant motion patterns to achieve the same outcome (Black et al., 2007;

Nisky et al., 2014). As the upper arm segment is further up the kinematic chain and does not directly influence instrument mechanics, reducing sub-optimal shoulder conditions is more feasible allowing the elbow and wrist joints to take the burden of the procedure. This kinematic profile has been previously exhibited by highly experienced surgeons (> 10 years LS experience) as shoulder LUBA scores were close to zero with larger LUBA scores for the elbows and wrists as compared to less experienced surgeons (< 6 years LS experience) (Sers, 2021b). Thus, this kinematic approach could form the basis for future training and optimisation targets of early career surgeons in order to reduce the sub-optimal impact on the shoulder joints.

The contralateral port placement is an ecological factor that may have promoted excessive torso lateral flexion to access the port site on the right side, especially when using the very high BMI models. Port site selection is a highly subjective decision amongst laparoscopists, with many factors such as patient BMI, pathology, surgeon anthropometrics and dominant hand influencing their decision (Hignett et al., 2017). The contralateral port placement setup was chosen over a midline or ipsilateral setup due to its preference amongst surgeons and its recognized risk to the postural wellbeing of surgeons (Hignett et al., 2017). Thus, selecting a contralateral port setup enabled the simulation of high-risk scenarios that young surgeons (< 5 years' experience) may find themselves in early on in their careers.

The key findings of this study were that performing LS on the higher BMI models significantly deteriorated the upper body posture of experienced surgeons. Larger LUBA scores translate to an increased risk of MSDs (Kee and Karwowski, 2001; Yazdanirad et al., 2018), which implies that higher BMI models increases the risk of MSDs in surgeons. Also, the torso and dominant shoulder have been identified as anatomical areas with the most severe LUBA scores that have feasible scope for improvement.

There are limitations that need to be recognised when interpreting the results from this study. The small sample size, completion of a single task and implementation of one port placement may reduce the significance of the relationship between BMI level and total LUBA scores. The consideration of a single heterogenous group of experienced surgeons could misrepresent the clinical interpretation of posture of laparoscopic surgeons with different amounts of previous experience of ≥ 4 years. Further, the use of the LUBA ergonomic framework may overlook lower-risk postures and subsequently underestimate the incidence of non-neutral posture. Therefore, the outcome of the postural assessment is undoubtedly sensitive to the framework applied. Finally, while the ecological validity of using foam to simulate body fat may be seen to be unrepresentative, feedback to support its use has been reported (Sers et al., 2021).

This study quantified the posture of surgeons by applying a segment/joint angle focussed analysis technique. Future work that considers segment/joint angles in conjunction with other biomechanical aspects of performance (e.g. both kinematics and kinetics), cumulative time in non-neutral postures and the total work involved in procedures should be investigated at different BMI levels. Further, the impact of different surgeon experience levels (novice, intermediate, expert) should be considered to understand the impact of patient BMI on early career laparoscopists and experienced surgeons with a greater degree of sensitivity. Finally, the assessment of different port placements and side bar configurations should be investigated during high BMI procedures to understand how this factor impacts surgeon posture.

5. Conclusion

Conducting LS on simulated severe obesity increased the severity of non-neutral postures compared to LS on normal BMI models. The increase in average time spent in severe non-neutral postures when exposed to high BMI models is more physically demanding and aggravates the musculoskeletal workload of the surgeon, which ultimately increases their risk of MSDs. Strict management of workloads, including exposure to patients with high BMIs may be necessary to reduce the risk of MSDs in surgeons.

Acknowledgement

The authors would like to thank the surgeons who participated in this study.

Disclosures

This work has been partially supported by the LU-HEFCE Catalyst grant, the LU-EESE start-up grant, and by the Research Studentship awarded to R. Sers by the Doctoral College of Loughborough University, UK. Ryan Sers, Steph Forrester, Stephen Ward and Massimiliano Zecca have no conflicts of interest or financial ties to disclose. Esther Moss performs da'Vinci robotic gynaecological surgery (Intuitive Surgical) and is a member of the British and Irish Association of Robotic Surgeons (BIARGS), which is supported by robotic/laparoscopic companies to hold education/training events. Esther Moss has served on advisory boards for Inivata and GlaxoSmithKline; received speaker fees from GlaxoSmithKline; has received research grants from Intuitive Surgical and Hope Against Cancer for unrelated work.

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