THE IMPACT OF OBESITY ON SURGEON ERGONOMICS IN ROBOTIC AND STRAIGHT STICK LAPAROSCOPIC SURGERY

[1,2]Esther L Moss (PhD), [3]Panos Sarhanis (FRCOG), [4]Thomas Ind (FRCOG), [5]Michael Smith (FRCOG), [2]Quentin Davies FRCOG), [6,7]Massimiliano Zecca (PhD)

[1]Leicester Cancer Research Centre, University of Leicester

[2]Department of Gynaecological Oncology, University Hospitals of Leicester

[3]Department of Gynaecology, Northwick Park Hospital, Harrow

[4]Department of Gynaecological Oncology, The Royal Marsden Hospital, London

[5]Deparatment of Gynaecological Oncology, The Christie Hospital, Manchester

[6]Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, UK

[7]National Centre for Sport and Exercise Medicine NCSEM-EM, Loughborough, UK

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Author contribution:

EM, PS and MZ designed the study. EM, PS, TI, MS and QD conducted the study. MZ performed the analysis. EM and MZ wrote the paper and all the authors contributed to the final version.

Conflict of interest:

All four surgeons who participated in this study have undergone training in the use of the Da'Vinci robot provided by Intuitive Surgical. TI received a consultancy from Medtronic in 2017.

Address for correspondence:
Dr Esther Moss
Leicester Cancer Research Centre, University of Leicester, University Road,
Leicester, LE1 7RH, UK
Email: em321@le.ac.uk; Tel: +44 300 303 1573; Fax: +44 116 258 8210

ABSTRACT

Objective: Work-related musculoskeletal symptoms (WMS) are reported to be increasing in surgeons performing minimally invasive procedures**.**To investigate the use of Inertial Measurement Units (IMU) and electromyography sensor (EMG) recorders to record real-time information on the muscle movement/activity required to perform training exercises in simulated in normal and high body mass index (BMI) models.

Design: Prospective study

Setting: University Hospital

Sample: Four consultant gynaecological oncology surgeons experienced in complex straight-stick laparoscopic (SS) and robotic surgery (RA).

Interventions: Three exercises (hoops onto pegs and wire chase) using SS and RA on two abdominal models: A) normal BMI; B) high BMI.

Measurements and Main Results: Time to complete exercise and surgeon muscle movement/activity. The time to complete the all the exercises was significantly lower RA as compared to SS ($p<0.001$). The movement of the surgeons' core was significantly greater in model SS-B compared to SS-A for all three exercises ($p<0.001$). Muscle usage, as determined by EMG peak, was significantly higher in SS-A, and even higher in SS-B, but generally flat for all the RA-A and RA-B exercises ($p<0.05$).

Conclusions: Detailed real-time information can be collected through IMU/EMG sensors. Our results indicate that RA requires less surgeon movements and muscle activity to complete tasks compared to SS, particularly in a high BMI model. The implications of these results are that RA in high BMI patients may therefore have less physical impact on the surgeon compare to SS, and may result in lower WMS rates.

KEY WORDS

Straight-stick laparoscopic surgery; robotic-assisted surgery; obesity; ergonomics; work-related musculoskeletal symptoms

PRECIS

Objective measurement of surgeon's muscle activity/movements when performing straight-stick (SS) and robotic-assisted (RA) exercises in normal/high BMI model showed that RA required less surgeon movements and muscle activity compared to SS, particularly in the high BMI model.

INTRODUCTION

Gynaecology has always been at the forefront of minimally invasive surgery (MIS) development and as a result MIS is a cornerstone of everyday surgical practice due to the significant benefits for patient outcome [1]. As experience with MIS has increased over the years, the complexity and duration of surgery has also risen and whilst this has a positive effect on intra- and post-operative morbidity it can have a physical impact on the surgeon [2]. Work-related musculoskeletal symptoms (WMS) have anecdotally increased with this change in practice with surgeons from a wide range of specialties reporting more neck, and shoulder pain, as well as fatigue and numbness, after performing MIS than open surgery [3]. Several factors have been identified as increasing the risk of WMS with straight stick (SS) laparoscopy the most consistently reported being high volume work load and patient obesity [2]. WMS have also been reported to be significantly higher in female surgeons with significantly higher rates of shoulder/neck/upper back discomfort in women with smaller glove sizes compared to men (p=0.004) [4].

Specifically designed theatre suites have been shown to improve the ergonomics of MIS and consequentially impact on surgeons' neck posture [5], however such facilities are not available to every surgeon performing MIS. Other techniques have been explored with the aim of reducing WMS, include video assessment with feedback [6], teaching coping techniques and awareness[7], a physical ergonomic body support [8] and subliminal visual stimulation[9], with varying success.

Robotically-assisted (RA) MIS has been shown to have an advantage when operating on patients with a high BMI and is reported to be associated with a lower rate of WMS compared to SS and open surgery [2, 10]. The higher financial cost and limited availability of robots for use across gynaecology have led to the restricted use of RA, however the additional advantage in high BMI patients with respect to the impact of the surgeon has not been considered.

A pilot experiment [11] measured the performance of one consultant gynaecologist on two exercises (beads into pots and hoops onto pegs) in three different scenarios: a) laparoscopic trainer; b) robotic simulator; and c) laparoscopic trainer raised by 8cm to simulate the effect of obesity. The surgeon's muscle activity and positioning were measured through two Electromyography (EMG) sensors and six Inertial Measurement Units (IMU) respectively. The acquired data showed that was possible to objectively quantify and assess the benefits of robotic surgery for the surgeon, in particular when working on the simulated high-BMI patient. Significant differences were observed in the use of shoulders both from the kinematics and the dynamics points of view, in particular between the laparoscopy (high BMI) and robotic simulation for both exercises. Robotic surgery, in particular, was associated with reduced muscle activity compared to laparoscopy in simulated high BMI patients. These initial findings showed the feasibility for using this technology in investigating surgeon ergonomics in preparation for conducting similar testing in a real world surgical setting.

The aim of this study was to investigate the use of Inertial Measurement Units (IMU) and muscular electrical activity (EMG) recorders to record surgeon's muscle activity and movements when performing laparoscopic and robotic exercises in simulated normal BMI and high BMI patients using SS and RA MIS. Our hypotheses were that

SS MIS is physically more demanding on an obese patient than one with a BMI within the normal range, whereas RA MIS is equally demanding irrespective of BMI.

MATERIALS AND METHODS

Four consultant gynaecological oncologists, who routinely perform complex SS and RA surgery, participated in the study. Ethical approval was not required for this study. Two abdominal models were used: A) the basic model, representing a patient with a BMI within normal range; B) a modified model, wrapped in foam to a depth of 6cm, to simulate an obesity (equating to BMI 30). The ports were placed on contra-laterally in the same position for all the exercises, 8 cm from the camera port (Figure 1A).

The exercises were standard training tests: beads into a pot; hoops onto pegs and wire chase (one hand only) (Figure 1B). The surgeons were asked to use both their left and right hands equally when completing the exercises in order to correct for handedness. There were five repetitions of each exercise and each exercise was performed on models A and B both with SS and RA. The order of the exercises and models was fixed: SS-A, SS-B, RA-A, RA-B; exercises always in the order 1, 2, 3.

The upper limbs posture of the surgeons was recorded by using 6 WB-4R Inertial Measurement Units (IMU) [12], a compact and light-weighted (17 x 20 x 8mm, 3.9g) Inertial Measurement Unit (IMU) containing a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer. The IMUs on the waist and chest and upper left/right arms were attached with elastic bands, enabling the sensor to sit tightly against the body. The IMUs on the left/right upper shoulders were attached with medical tape directly to the skin to secure maximum fidelity of the data with the shoulder's movements. All IMUs were individually calibrated in advance to ensure optimal performance [13].

The standard deviation of the raw muscular electrical activity (EMG) signal is monotonically related to the number of the activated motor units and the rate of their activation, and can be used to approximate the magnitude of the EMG (EMG amplitude) [14]. Two WB-EMG electromyography sensors [15] were placed on the left and right trapezius muscles, attached with medical tape, to measure muscular activity. The optimal placement of the sensors was verified through a quick calibration exercise. Before the exercises, 3 sets of calibration movements were performed:

1) standing 20 seconds in relaxed position (static test designed for extracting the vertical axis in all sensors)
2) bowing 5 times while standing, while keeping the head, chest and waist as a rigid body (dynamic test designed for estimating the sagittal plane and extracting the medial-lateral axis)
3) pressing against a fixed obstacle with maximum intensity for about 5 seconds, one arm at the time (designed for calculating the Maximum Voluntary Contraction (MVC) for each of the trapezii)

All data were acquired wirelessly through ad-hoc software and stored in a pc for backup and further off-line processing. All acquired data were filtered and processed in Matlab [16] for time synchronisation and alignment [13, 17]. All IMU data were processed and classified following the methodology already outlined in previous papers [12]. All EMG data were pre-filtered through an ad-hoc Wavelet denoising technique [18].

The three main parameters analysed were time, movements (core, right/left arms) and muscle usage. Results for the surgeons were averaged for each exercise, therefore each bar on the graphs represents the mean and standard deviation of 20 repetitions. The different exercises are shown separately SS (white background); RA (light blue background); lean model (blue box); obese model (yellow box). On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol.

RESULTS

Time

The time to complete the all the exercises was significantly lower for RA as compared to SS and this was seen with all the surgeons ($p<0.001$) (Figure 2) (Table 1). Specifically, exercise 1 was significantly quicker in model SS-A compared to SS-B, and both were significantly slower ($p<0.05$) compared to RA-A and RA-B. The time was significantly lower ($p<005$) in all 3 exercises for SS-B compared to RR-A and RR-B. In all three exercises, no significant difference in completion time was observed between RA-A and RA-B models in any of the surgeons.

Movements

Overall, the amount of the movement of the surgeons' core was usually higher in SS-B compared to SS-A ($p<0.001$ in exercises 2 and 3; higher but not significant in exercise 3), and it was usually lower in RA (Figure 3), with some variations between the individual surgeons. Specifically, the amount of core movement for RA-A and RA-B was lower than SS-A and SS-B in both exercises 2 and 3, and in between the two values for exercise 1. The range of movement of the arms also showed differences, in particular for SS-A vs SS-B in exercise 1 ($p<0.01$), and SS-B vs. both RA-A and RA-

B in exercise 3 ($p<0.001$). In all three exercises, no significant difference in movements (both core and arms) was observed between RA-A and RA-B models in any of the surgeons.

Muscle usage

Muscle usage showed significant differences in several parameters. Specifically, the normalised peak EMG was significantly higher in both SS-A ($p<0.01$), and SS-B ($p<0.01$), compared to a generally flat and lower value of all the RA-A and RA-B exercises ($p<0.01$) (Figure 4). This was observed in particular for exercises 2 and 3. The Integrated EMG (iEMG), defined as the area under the curve of the rectified EMG signal, i.e. the mathematical integral of the absolute value of the raw EMG signal, clearly showed that the shoulder's muscles were used significantly less for RA-A and RA-B, in particular for exercises 2 and 3 ($p<0.001$) (Figure 5). No significant difference was observed between SS-A and SS-B.

The same trends could be seen in all other parameters extracted from the EMG signals, with a higher muscle usage in SS-A and SS-B, and lower muscle usage in RA-A and RA-B. The standard deviation of the EMG signal showed a significant difference of SS-A with respect to SS-B, in particular for exercises one and two, and a clear difference of both SS models with respect to both RA models. As with all other parameters, in all three exercises no significant difference in muscle usage was observed between RA-A and RA-B models in any of the surgeons.

DISCUSSION

This study has shown that it is possible to obtain detailed information on surgeons' muscle activity and positioning using IMU and EMG sensors. Through this we have shown that SS is physically more demanding for the surgeon, with regard to muscle movement and activity, in the case of simulated obesity.

Although the use of wearable IMUs have been reported previously [19], we have shown that the addition of EMG data gives a better insight on how the movement is created. This technology is able to generate vast quantities of data thereby enabling very detailed analysis of movement and positioning but also muscle activity, which cannot be generated by other techniques such as video analysis of movements [20].

Since its introduction robotic technology has been reported to have greater benefits for surgeons' musculoskeletal health as compared to SS [21, 22], although it is not without ergonomics issues typically from fixed position at the console [19, 23], compared to SS [24], which instead has a greater impact on shoulder and arm movement [25]. Newer robotic platforms are currently under development that have worked on this aspect with open consoles that will hopefully help address this issue. We have shown that although there is a difference in surgeon movements between SS and RA, the difference is significantly greater in the presence of obesity. These findings objectively confirm that obesity is a factor in WMS by demonstrating the greater movements and muscle activity required to complete tasks compared to a normal BMI model. The obesity epidemic that is being seen in many countries is not only fuelling a rise in obesity-related endometrial malignancies; as MIS is default route for the surgical management of such cases [26], this is also adding to the complexity of routine gynaecological surgery [27]. Providing the correct equipment and appropriately training theatre staff for managing high BMI cases will not only improve patient care but should also reduce the risk of adverse events, including staff injury. In the case of super morbid obesity (BMI >50), although SS can be performed, the potential physical impact on the surgeon would be greater and raises the question as to whether such cases should be managed in specialized centres with have access to RA.

Another finding of our study was that obesity did not have an effect on the time to complete the task in the RA group but this was significantly longer with SS. These results confirm the finding from studies that showed no significant difference in robotic operative time between normal BMI and morbidly obese patients [28]. The increased duration of SS surgery in obese patients may contribute to a higher WMS injury rate since longer procedures are known to be associated with greater levels of surgeon discomfort [21].

WMS risk and surgeon longevity are vital for service provision, especially with the increasing feminisation of the medical work force, and consideration is needed when designing surgical instruments so that the characteristics of the surgeons who will be using them in the future are taken into account. The information gained from IMU/EMG analysis could be used to develop training tools in order to encourage surgeons to adopt better working practices, such as subliminal visual stimulation, which has been successfully used to improve the upper limb posture in SS training [9].

Study Limitations

The main limitations of this study were the small number of surgeons who participated and that the tasks they performed were short duration exercises in a fixed order rather than live operating. Also the high-BMI model may not be replicate the real-world challenges of intra-abdominal adiposity and the weight of the anterior abdominal wall. The next step is for the IMU/EMG equipment to be tested in a real-world setting analysing surgeons' movements during live surgery, in particular increasing the number of surgeons participating to explore whether differences in results are explained by different surgeon characteristics. Since the recorders are small and light it is anticipated that it should have not hinder the surgeons' ability.

The port positions chosen for this study may not be universally used when performing SS surgery in high BMI cases, since the patients' abdominal wall measurements will need to be taken into consideration, however were chosen because they are still the favoured sites for many gynaecologists when performing a Type I laparoscopic hysterectomy [29]. It is acknowledged that some surgeons may choose different positions, for example two ipsilateral ports, especially when performing long procedures or operating on high BMI patients however it was not possible to repeat this study using different port sites positions.

CONCLUSION

We have shown that it is possible to gain extensive real-time information on surgeon movements and muscle activity through IMU and EMG sensors. Our results indicate that RA requires less surgeon movements and muscle activity to complete tasks compared to SS, particularly in high-BMI models. The implications of these results are that RA in high BMI patients may therefore have less physical impact on the surgeon compare to SS, and may result in lower WMS rates. A randomized-controlled trial investigating both patient and surgeon outcomes with RA and SS surgery in high-BMI patients is needed in order to examine this issue in greater depth.

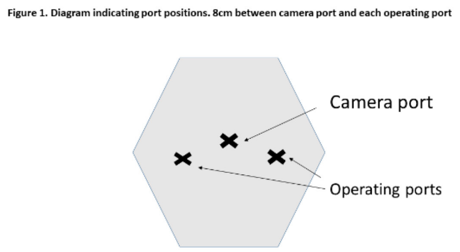
REFERENCES

1. Galaal K, Bryant A, Fisher AD, Al-Khaduri M, Kew F, Lopes AD: **Laparoscopy versus laparotomy for the management of early stage endometrial cancer**. *Cochrane Database Syst Rev* 2012(9):CD006655.
2. Franasiak J, Ko EM, Kidd J, Secord AA, Bell M, Boggess JF, Gehrig PA: **Physical strain and urgent need for ergonomic training among gynecologic oncologists who perform minimally invasive surgery**. *Gynecol Oncol* 2012, **126**(3):437-442.
3. 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, **27**:1-8.
4. Sutton E, Irvin M, Zeigler C, Lee G, Park A: **The ergonomics of women in surgery**. *Surg Endosc* 2014, **28**(4):1051-1055.
5. van Det MJ, Meijerink WJ, Hoff C, van Veelen MA, Pierie JP: **Ergonomic assessment of neck posture in the minimally invasive surgery suite during laparoscopic cholecystectomy**. *Surg Endosc* 2008, **22**(11):2421-2427.
6. Rosenblatt PL, McKinney J, Adams SR: **Ergonomics in the operating room: protecting the surgeon**. *J Minim Invasive Gynecol* 2013, **20**(6):744.
7. Xiao DJ, Jakimowicz JJ, Albayrak A, Goossens RH: **Ergonomic factors on task performance in laparoscopic surgery training**. *Appl Ergon* 2012, **43**(3):548-553.
8. Albayrak A, van Veelen MA, Prins JF, Snijders CJ, de Ridder H, Kazemier G: **A newly designed ergonomic body support for surgeons**. *Surg Endosc* 2007, **21**(10):1835-1840.
9. Zhang D, Sessa S, Kong W, Cosentino S, Magistro D, Ishii H, Zecca M, Takanishi A: **Development of subliminal persuasion system to improve the upper limb posture in laparoscopic training: a preliminary study**. *Int J Comput Assist Radiol Surg* 2015, **10**(11):1863-1871.
10. Bagrodia A, Raman JD: **Ergonomics considerations of radical prostatectomy: physician perspective of open, laparoscopic, and robot-assisted techniques**. *J Endourol* 2009, **23**(4):627-633.
11. Moss E, Sarhanis P, Wong W, Zecca M: **Robotic surgery and surgeon ergonomics: reduced muscle activity compared to laparoscopic surgery**. In: *British and Irish Association of Robotic Gynaecological Surgeons: 2015; Wirral*; 2015.
12. Lin Z, Uemura M, Zecca M, Sessa S, Ishii H, Tomikawa M, Hashizume M, Takanishi A: **Objective skill evaluation for laparoscopic training based on motion analysis**. *IEEE Trans Biomed Eng* 2013, **60**(4):977-985.

13. Sassa S, Zecca M, Lin Z, Bartolomeo L, Ishii H, Takanishi A: **A Methodology for the Performance Evaluation of Inertial Measurement Units**. *J Intell Robot Syst* 2013, **71**(2):143-157.
14. Clancy EA, Hogan N: **Relating agonist-antagonist electromyograms to joint torque during isometric, quasi-isotonic, nonfatiguing contractions**. *IEEE Trans Biomed Eng* 1997, **44**(10):1024-1028.
15. Imtiaz U, Bartolomeo L, Lin Z, Sessa S, Ishii H, Saito K, Zecca M, Takanishi A: **Design of a wireless miniature low cost EMG sensor using gold plated dry electrodes for biomechanics research**. In: *IEEE International Conference on Mechatronics and Automation: 2013; Takamastu, Japan*; 2013.
16. MATLAB: **MathWorks - MathWorks United Kingdom.** In.
17. Kong W, Sessa S, Zecca M, Takanishi A: **Anatomical Calibration through Post-processing of Standard Motion Tests Data**. *Sensors* 2016, **16**(12).
18. Bartolomeo L: **Baseline adaptive wavelet thresholding technique for sEMG denoising**. In: *AIP Conf Proc.* vol. 1371; 2011: 205-214.
19. 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, **31**(2):877-886.
20. Craven R, Franasiak J, Mosaly P, Gehrig PA: **Ergonomic deficits in robotic gynecologic oncology surgery: a need for intervention**. *J Minim Invasive Gynecol* 2013, **20**(5):648-655.
21. 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, **22**(2):234-238.
22. Dalager T, Sogaard K, Bech KT, Mogensen O, Jensen PT: **Musculoskeletal pain among surgeons performing minimally invasive surgery: a systematic review**. *Surg Endosc* 2017, **31**(2):516-526.
23. 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, **6**(1):65-72.
24. McDonald ME, Ramirez PT, Munsell MF, Greer M, Burke WM, Naumann WT, Frumovitz M: **Physician pain and discomfort during minimally invasive gynecologic cancer surgery**. *Gynecol Oncol* 2014, **134**(2):243-247.
25. 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):61-67.
26. NICE: **Laparoscopic hysterectomy (including laparoscopic total hysterectomy and laparoscopically assited vaginal hysterectomy) for endometrial cancer**. In.; 2010.
27. Kondalsamy-Chennakesavan S, Bouman C, De Jong S, Sanday K, Nicklin J, Land R, Obermair A: **Clinical audit in gynecological cancer surgery: development of a risk scoring system to predict adverse events.** *Gynecol Oncol* 2009, **115**(3):329-333.
28. Cunningham MJ, Dorzin E, Nguyen L, Anderson E, Bunn WD, Jr.: **Body mass index, conversion rate and complications among patients undergoing robotic surgery for endometrial carcinoma**. *J Robot Surg* 2015, **9**(4):339-345.

29. Hignett S, Gyi D, Calkins L, Jones L, Moss E: **Human Factors Evaluation of Surgeons' Working Positions for Gynaecological Minimal Access Surgery**. *J Minim Invasive Gynecol* 2017.

Figure 1. A) Diagram indicating port positions. 8cm between camera port and each operating port.



B) Selected exercises. From left to right: 1) Beads into a pot; 2) Hoops onto pegs; 3) Wire chase (one hand only)

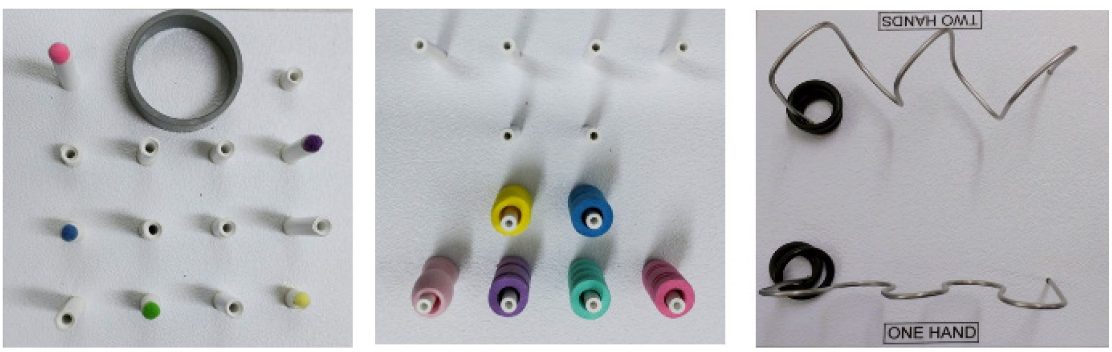


Figure 2. Time to complete exercise (n=20 for each exercise).

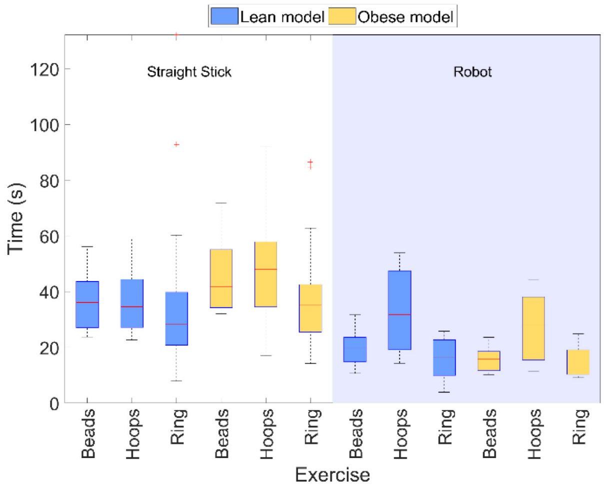


Figure 3. Movements of the surgeon's core (n=20 per exercise)

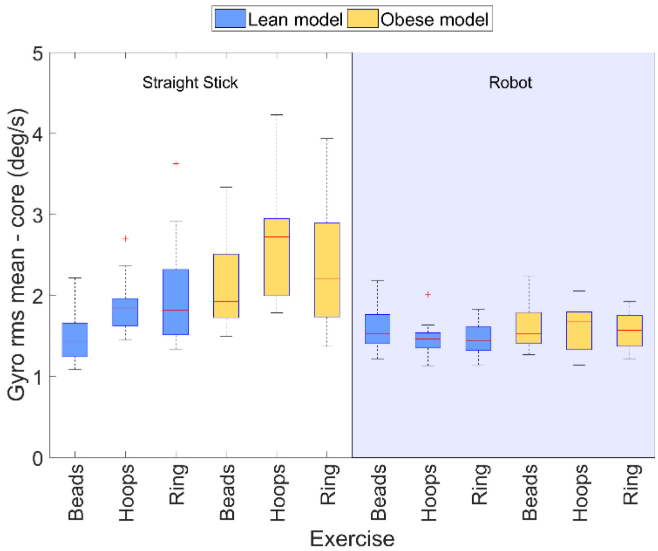


Figure 4. EMG amplitude, magnitude of muscular electrical activity (n=20 per exercise)

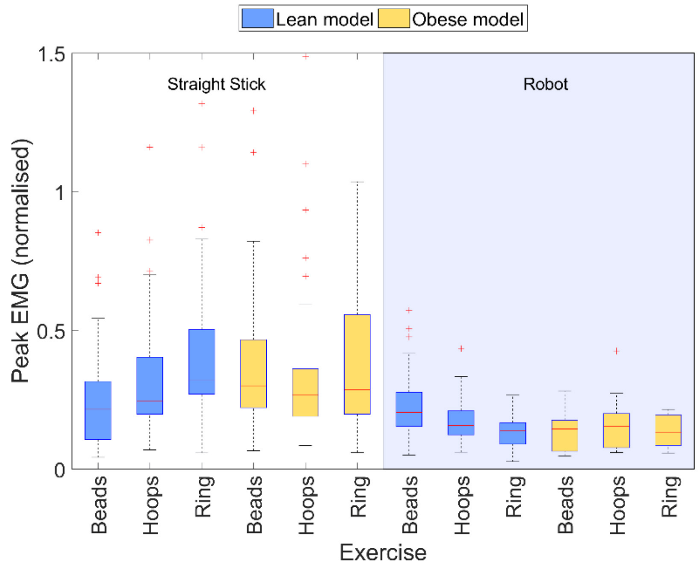


Figure 5. Integrated EMG signal (n=20 per exercise)

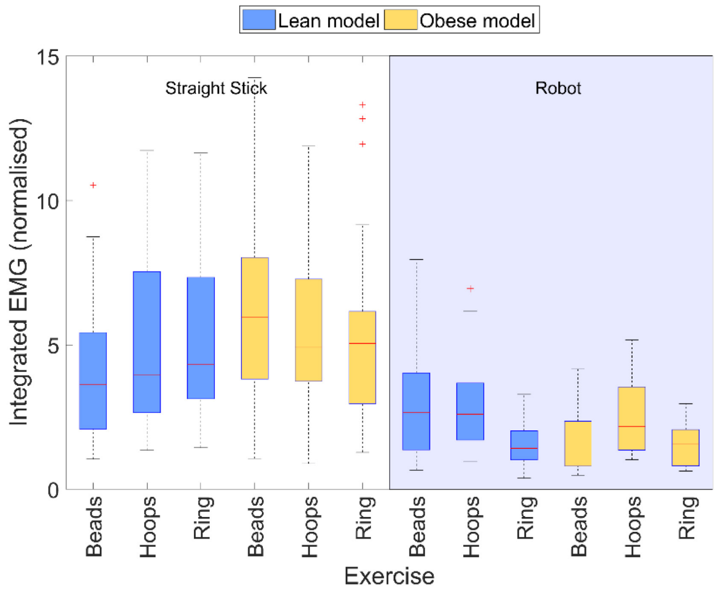


Table 1. Values for the exercises. SS = straight stick, RA = robotic assisted, A= normal BMI model, B= high BMI model

a) Exercise 1 (beads)

	Straight stick (SS)		Robot (RA)		Main effect	Post hoc Bonferroni					
	(A) Lean	(B) Obese	(A) Lean	(B) Obese		SS-A - SS-B	SS-A - RA-A	SS-A - RA-B	SS-B - RA-A	SS-B - RA-B	RA-A - RA-B
Time (seconds)	36.50±10.22	44.98±12.35	19.35±5.50	15.49±4.14	F = 51.432, p < 0.001	<0.05	<0.001	<0.001	<0.001	<0.001	n.s.
Range of arm movement (deg)	24.71±16.96	34.76±24.97	27.98±14.38	29.13±17.90	F = 3.897, p = 0.009	<0.01	n.s.	n.s.	n.s.	n.s.	n.s.
Angular speed core (deg/s)	1.47±0.29	2.10±0.51	1.60±0.28	1.62±0.29	F = 8.559, p < 0.001	<0.001	n.s.	n.s.	n.s.	n.s.	n.s.
Normalised Peak EMG	0.25±0.19	0.38±0.26	0.22±0.12	0.14±0.07	F = 7.760, p < 0.001	<0.01	n.s.	<0.05	<0.01	<0.001	n.s.
Normalised Mean EMG	0.10±0.07	0.11±0.05	0.10±0.07	0.08±0.04	F = 2.673, p = 0.049	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Normalised Integrated EMG	4.03±2.44	6.07±3.19	2.84±1.97	1.73±1.02	F = 2.595, p = 0.055	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Normalised EMG sig power	5,097.38±5,334.49	6,058.09±5,231.67	4,650.44±6,502.61	2,742.14±3,294.01	F = 0.625, p = 0.600	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Normalised EMG SD	0.06±0.05	0.09±0.07	0.05±0.03	0.03±0.02	F = 9.704, p < 0.001	<0.05	n.s.	n.s.	<0.01	<0.001	n.s.

b) Exercise 2 (hoops)

	Straight stick (SS)		Robot (RA)		Main effect	Post hoc Bonferroni					
	(A) Lean	(B) Obese	(A) Lean	(B) Obese		SS-A - SS-B	SS-A - RA-A	SS-A - RA-B	SS-B - RA-A	SS-B - RA-B	RA-A - RA-B
Time (seconds)	37.29± 10.73	48.21± 19.92	33.31± 14.88	27.37± 11.35	F = 7.154, p < 0.001	n.s.	n.s.	n.s.	<0.05	<0.001	n.s.
Range of arm movement (deg)	31.90± 25.80	36.56± 21.32	29.45± 17.18	31.95± 17.63	F = 1.636, p = 0.181	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Angular speed core (deg/s)	1.85±0.31	2.65±0.72	1.45±0.20	1.60±0.28	F = 27.061, p < 0.001	<0.001	<0.05	n.s.	<0.001	<0.001	n.s.
Normalised Peak EMG	0.32±0.23	0.35±0.30	0.17±0.08	0.15±0.08	F = 10.132, p < 0.001	n.s.	<0.01	<0.05	<0.001	<0.001	n.s.
Normalised Mean EMG	0.12±0.08	0.10±0.06	0.07±0.04	0.08±0.04	F = 16.647, p < 0.001	n.s.	<0.001	<0.001	<0.001	<0.001	n.s.
Normalised Integrated EMG	5.16±2.86	5.66±3.22	2.85±1.34	2.45±1.21	F = 12.183, p < 0.001	n.s.	<0.001	<0.001	<0.001	<0.001	n.s.
Normalised EMG sig power	8,242.81±15,920.55	5,608.92±4,076.16	2,640.03±2,768.33	2,589.90±2,942.81	F = 5.198, p = 0.002	n.s.	<0.05	<0.01	n.s.	n.s.	n.s.
Normalised EMG SD	0.07±0.06	0.08±0.07	0.04±0.02	0.03±0.02	F = 10.051, p < 0.001	<0.05	n.s.	n.s.	<0.01	<0.001	n.s.

c) Exercise 3 (ring)

	Straight stick (SS)		Robot (RA)		Main effect	Post hoc Bonferroni					
	(A) Lean	(B) Obese	(A) Lean	(B) Obese		SS-A - SS-B	SS-A - RA-A	SS-A - RA-B	SS-B - RA-A	SS-B - RA-B	RA-A - RA-B
Time (seconds)	38.17±29.17	39.11±20.36	16.18±7.20	14.98±5.11	F = 10.303, p < 0.001	n.s.	<0.01	<0.01	<0.01	<0.001	n.s.
Range of arm movement (deg)	33.44±30.80	45.12±42.96	23.04±16.06	22.98±16.51	F = 10.483, p < 0.001	n.s.	n.s.	n.s.	<0.001	<0.001	n.s.
Angular speed core (deg/s)	1.98±0.61	2.55±1.34	1.46±0.19	1.57±0.23	F = 5.143, p = 0.003	n.s.	n.s.	n.s.	<0.01	<0.05	n.s.
Normalised Peak EMG	0.41±0.28	0.38±0.23	0.13±0.06	0.14±0.06	F = 22.435, p < 0.001	n.s.	<0.001	<0.001	<0.001	<0.001	n.s.
Normalised Mean EMG	0.14±0.09	0.12±0.07	0.07±0.04	0.08±0.04	F = 16.512, p < 0.001	n.s.	<0.001	<0.001	<0.001	<0.001	n.s.
Normalised Integrated EMG	5.40±3.34	5.77±3.56	1.54±0.77	1.61±0.76	F = 11.620, p < 0.001	n.s.	<0.001	<0.001	<0.001	<0.001	n.s.
Normalised EMG sig power	6,802.36±6,001.73	8,071.53±6,391.77	2,876.70±3,470.26	3,293.45±3,341.06	F = 5.624, p = 0.001	n.s.	<0.05	n.s.	<0.05	<0.01	n.s.
Normalised EMG SD	0.11±0.09	0.09±0.06	0.03±0.01	0.03±0.01	F = 19.053, p < 0.001	n.s.	<0.01	<0.01	<0.001	<0.001	n.s.