Review Article

Manipulation ergonomics and robotic surgery—a narrative review

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Contributions: (I) Conception and design: Both authors; (II) Administrative support: None; (III) Provision of study materials or patients: None; (IV) Collection and assembly of data: SW Wong; (V) Data analysis and interpretation: Both authors; (VI) Manuscript writing: Both authors; (VII) Final approval of manuscript: Both authors.

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Background and Objective: The robotic system offers manipulation ergonomic advantages through articulated instruments with seven degrees of freedom (DOF), fulcrum elimination, filtration of tremor, and scaling of movement. The objective of this narrative review is to address the manipulation ergonomic considerations of robotic surgery.

Methods: A literature review was performed to find evidence for the postulated manipulation advantages and disadvantages.

Key Content and Findings: An increase in DOF from four to six has been shown to reduce task completion time by 40%. The detrimental effect of the fulcrum effect (including the associated scaling of movement) on performance of a laparoscopic task has been demonstrated for novice surgeons. Tremor filtration alone may not improve accuracy during robotic tasks. Scaling of movement can increase accuracy by 20–30%. Conferring of ambidexterity improves the accuracy of the non-dominant hand. Control of camera and three instruments, and use of intuitive hand controllers and foot pedals can improve efficiency. Surgeons should be conscious of the fact that different robotic instruments have different grip forces. Lack of haptic feedback and robot arm clashes are manipulation disadvantages that need to be overcome.

Conclusions: Advanced technology has been used to support manipulation in robotic-assisted surgery. The integrated technologies of flexible instrument tips with seven DOF, scaling effect, removal of the fulcrum effect, and control of more instruments offer ergonomic benefits to the surgeon. On the other hand, limitations related to lack of haptic feedback and arm clashing need to be overcome to improve the surgeon experience.

Keywords: Manipulation; ergonomics; robotic surgery (RS)

Received: 24 November 2023; Accepted: 02 March 2024; Published online: 28 March 2024.
doi: 10.21037/ales-23-64
View this article at: https://dx.doi.org/10.21037/ales-23-64

Introduction

Robotic surgery (RS) offers improved ergonomics for the surgeon with its seated positioning and ability to support the forearms on the console bar. Ergonomics has been classified as having physical, organisational, and cognitive components. Previous review articles have addressed postural, visualisation, cognitive and workflow ergonomics associated with RS. Studies have reported conflicting results with activation of different muscle groups when comparing RS with laparoscopic surgery (LS), but a meta-analysis demonstrated significantly lower activation only for the biceps with RS (1). Other postural ergonomic benefits of RS include distribution of upper limb muscle fatigue to the non-dominant side and ability to take micro-breaks (2,3). Visualisation ergonomic advantages of RS include clearer exposure with better lighting, three-dimensional vision, steady camera control by the surgeon, and location

Table 1 The search strategy summary

Items	Specification
Date of search	1st September 2023
Databases and other sources searched	MEDLINE (PubMed)
Search terms used	manipulation, ergonomics, robotic surgery, degrees of freedom, fulcrum, tremor, scaling of movements, ambidexterity, camera control, fourth arm, hand controllers, instruments, haptic feedback, robot arm clashes
Timeframe	No restrictions on timeframe
Inclusion criteria	Original articles in peer-reviewed journals, all study designs, restricted to English language only
Selection process	Selection was performed by the first author
Any additional considerations, if applicable	Additional hand search of references cited in the studies. This was a narrative and not systematic review

of the screen closer to the hands (4). Other visualisation ergonomic considerations include stereo-acuity, sensory mistatch, visuospatial ability, and visual fatigue. Physical separation of the surgeon is the main contributor for flow disruptions (FDs) during RS, which may result in increased error rates (5). Intervention which may counter FDs include team training, better operating room spatial configuration, standardised communication taxonomy with read-back, technology implementation, support for resilience, and use of checklists. The impact of robotic assistance on cognitive workload is complex (6). The better associated postural, visualisation and manipulation ergonomics may facilitate less need to delegate cognitive resources to the physical tasks, but this may be offset by reduced situational awareness related to physical separation, communication difficulties, need to control more instruments, limited visual field and lack of haptic feedback.

The robotic system offers potentially better manipulation ergonomics through articulated instruments with seven degrees of freedom (DOF), fulcrum elimination, filtration of tremor, and scaling of movement (7). The presence of these robotic manipulation benefits has been shown to enhance the dexterity of the right hand by 55% and the left hand by 45% as compared with LS (8). The median skill-based errors dropped from 23 during laparoscopic suturing task to 8.5 during robotic suturing task with 2-dimensional vision in a simulation setting. Studies on manipulation benefits of the robotic system have been performed mainly in a simulation setting and assessed performance using kinematic data and operating time of surgeons of different experience levels. These factors may affect the validity of the studies in the real-life operation setting. The aim of the study is to examine the beneficial and detrimental manipulation ergonomic factors of the robotic system individually. We present this article in accordance with the Narrative Review reporting checklist (available at https://ales.amegroups.com/article/view/10.21037/ales-23-64/rc).

Methods

A literature search was conducted on 1st September 2023, using MEDLINE (PubMed) for this narrative review (*Table 1*). All original studies published in peer reviewed journals from inception to 1st September 2023 were considered and no restrictions was imposed regarding study design. Only English language papers were reviewed. To find relevant publications, keywords 'manipulation', 'ergonomics', and 'robotic surgery' were used. Other keywords used were extracted from previous review articles on ergonomics and RS or LS. These keywords are used as subheadings in the discussion. The other search terms used were degrees of freedom, fulcrum, tremor, scaling of movements, ambidexterity, camera control, fourth arm, hand controllers, instruments, haptic feedback, and robot arm clashes. References cited in the studies and reviews were hand searched to ensure literature saturation.

Discussion

Manipulation ergonomics and LS

Breedveld *et al.* summarised the important factors which impede and facilitate indirect manipulation during LS compared with direct hand manipulation during open surgery (9). They categorised the differences to transformation of spatial or grasping movements. The impeding spatial transformation factors were reduced DOF, fulcrum effect, scaling of hand movements and tip forces, and instrument shaft friction. Technical developments to overcome some of these impeding factors are incorporated in robotic systems. They include introduction of master-slave system, additional DOF, neutralisation of the mirroring and scaling effects, and compensation for friction. The impeding grasping transformation factors were difference in size, difference in grip and reduced tactile feedback. Grasping can be improved by increasing the number of jaws, using flexible jaws, and improving tactile feedback. The impeding effects may be more significant for inexperienced surgeons as some effects are relatively small and easy to adapt to with increasing experience.

Most handgrips of laparoscopic grasping instruments are ergonomically poorly designed. Van Veelen *et al.* found that laparoscopic manipulating instrument handles satisfied only three of the eight ergonomic requirements (10). Laparoscopic instruments have been associated with carpal tunnel syndrome and thenar neuropathy as well as reduced efficiency from handle to tip with a transmitted force of one third (11). An increase ratio of extracorporeal to intracorporeal length of laparoscopic instrument reduced manoeuvrability inside the abdominal cavity and increased shoulder movement and fatigue (12).

DOF

DOF is the ability for independent movement in a particular orientation or rotation. Open surgery allows the use of all six DOF (along the translational x-y-z axis and orientation around the rotational roll-pitch-yaw axis) (13). Laparoscopic instruments offer four potential DOF movements: rotation along the long axis, in and out, side to side (yaw) and up and down (pitch) (12). Instrument actuation (with the gripping action of grasping instruments) is sometimes considered the seventh DOF. With LS, two of the possible three translational DOF are lost due to restrictions imposed by the trocar entry point which only allows one path to reach a point inside the abdominal cavity (along the trocar direction only). The articulated robotic instruments offer an additional two DOF due to an extension/flexion and a tilt function at the distal wrist (14).

Studies have shown better manipulation performance with more DOF. Wilhelm *et al.* found that suturing and knot tying were significantly faster with availability of six DOF compared with four DOF ($P<0.001$) (13). An increase in DOF from four to six has been shown to reduce task completion time by 40% (15). A review article concluded that suturing using robotic assistance compared with conventional laparoscopy was superior in terms of time, safety and vessel patency (14). In a simulation study involving medical students, mastery of laparoscopic and robotic instruments was easier to learn and required four hours of training, whereas mastery of a steerable laparoscopic instrument (with two additional DOF) required six hours of training (16). However, the time to perform a complex suturing task was more than twice as long using standard laparoscopic instruments compared with using robotic or the steerable laparoscopic instruments.

Fulcrum

With LS, the abdominal wall trocar creates a fulcrum point which results in scaled counterintuitive movements of the surgeon hand and instrument tip (17). The fulcrum effect has been compared with picture orientation in a pinhole camera (14). The fulcrum effect has been shown to have a detrimental effect on novice surgeon laparoscopic task performance (18). Experienced laparoscopic surgeons are acclimatised to the “fulcrum effect” of the abdominal wall on instrument manipulation and movements can be performed without additional mental workload (19). Crothers *et al.* showed that novice surgeons benefited from Y-axis image inversion during simulated laparoscopic tasks (but it had a detrimental effect on the initial performance of experienced surgeons with subsequent improvement after training (19). In a similar study but instead of image inversion, Spiers *et al.* designed a laparoscopic tool which negated the natural inversion and found statistically higher rates of motor skill improvement in novice surgeons as demonstrated by faster task completion time and reduced error rate (20). The effects of scaling of movement associated with the fulcrum effect has also been studied. Nisky *et al.* found that perception of stiffness, by testing with springs of different stiffness, was affected by internal and external length/ratio of the laparoscopic tool when used by a novice (21). Motion inversion can cause movement constraints and perceptual distortions (21). The identification of trocar location is of vital importance for navigation and elimination of the fulcrum effect by the robotic system. The da Vinci robot (Intuitive Surgical) has four arms which all have a remote centre of motion that aligns with the motion constraint imposed by the trocars (22).

Tremor filtration

Surgeons have normal physiological fine tremor which oscillates at a frequency of 8- to 12-Hertz (23). Transmission of hand movement along the shaft of laparoscopic instruments to the tip can magnify tremor. The robotic system can filter hand tremor by using software to provide smooth and stable movements. The computer system can isolate and remove high frequency oscillating motions by digitizing the surgeon's movements (24). In one simulation study, tremor filtration alone did not significantly improve accuracy during target-piercing tasks (24). In addition, there are no studies which have shown that surgical outcomes are affected by exaggerated physiological tremor (23).

Scaling of movements

Scaling can change the movement ratio between the macro hand input and the micro instrument tip output, resulting in improved precision and dexterity (25). Scaling on the da Vinci robot can be changed from 2:1 to 1.5:1 or 3:1 by use of the touch display. Accuracy has been shown to be improved by 20% to 30% when motion scaling was activated (24). The trade-off for improved precision is increased operative time. In a study of participants who were not surgeons, target-piercing simulator tasks were completed with greater accuracy using robotic instruments with motion scaling compared with using standard laparoscopic instruments (24). Activation of tremor filtration function in this subject group did not contribute additional benefit derived from motion scaling. Motion scaling has been shown to reduce the impact of signal latency on performance which is important with remote telesurgery. One study reported improved accuracy and efficiency of peg transfer task, even in the presence of a simulated signal latency of 750 ms, but not at the equivalent level of performance without signal latency (26). Accuracy is potentially increased ten-fold when using robotic systems to perform microvascular anastomoses (27,28).

Ambidexterity

Robotic assistance improves the fine motor skills of the nondominant hand and confers virtual ambidexterity (29,30). The accuracy of the nondominant hand with help of motion scaling during RS even superseded that of the dominant hand during LS (24). Studies have found significant differences in execution time and manual dexterity between the dominant and nondominant hands when performing laparoscopic and open surgical tasks, which were nullified when the same tasks were performed with robotic assistance (30,31).

Camera control and fourth arm

A meta-analysis concluded that the robotic camera holder significantly outperformed human assistants on the frequency of lens cleaning and inappropriate movements (32). With the Da Vinci system, the surgeon can control the camera with one of the robotic arms and adjust the camera zoom on the touch display or via a "clapping" motion when activating both finger clutches. The camera can be controlled more intuitively with other systems. Dardona *et al.* designed an immersive system that allow simultaneous control of instruments and the camera via a head-mounted display (33). The TransEnterux Surgical Senhance offers camera control by eye movements through an infrared eye-tracking system (34). The Da Vinci and Medtronic Hugo surgical systems have an inbuilt safety mechanism which suspends robotic arm movement when the surgeon looks away from the screen (35).

The da Vinci robotic system has four robotic arms to control the camera and three instruments. The ability of the surgeon to control an extra instrument can improve efficiency and bypass potential communication problems with the human assistant. The availability of the extra arm has been shown to improve tissue manipulation/ retraction and reduce console time (36,37). The benefits of fourth arm use during lung lobectomy included less need to change instruments, reduced clashing of thoracoscopic and robotic instruments, better exposure, and application of more appropriate tension (38). Similarly, the use of the extra arm can potentially increase the number of surgical options available during robotic right hemicolectomy surgery, such as lifting of the right colon upwards to expose the ileocolic vessels on the medial side (39).

Hand controllers and foot pedals

The apposition of the thumb and index fingers in a pinching motion which are placed in the hand controller loops intuitively mimics the movement of the end-effectors (40). Some surgeons prefer not to place their fingers inside the loops to allow a wider range of pronation/supination movement but with the possibility of a higher risk of slippage (unpublished data, Shing Wong). Prolonged pinching of the thumb and index finger can lead to temporary neuropraxia/numbness (41,42). The maximum activation of the thenar muscles as measured by electromyography has been shown to be lower for RS compared with LS (43). Senhance use hand controls that resemble traditional laparoscopic instrument controls which has been shown to reduce the training time for surgeons transitioning from LS (40). Ergonomic problems would be like those experienced with use of laparoscopic instrument handles. Other robotic systems use a hand grip system.

Use of the foot pedal on the da Vinci robot can change the control of the finger manipulators to the endoscope or any of the other three instrument arms (40). The robot arms not controlled by the finger manipulators are locked into position. Medical errors can result from interruptions to the flow of surgery when using foot pedals to switch between arms (33). In addition, camera-hopping between the two central ports or the inconsistent use of two left hands and one right hand or two right hands and one left hand can lead to increase mental workload and confuse the brain about which instruments has been activated for movement (unpublished data, Shing Wong). The other foot pedals are used for monopolar or bipolar diathermy activation, stapler closing and firing, fluid irrigation and suction, and vessel sealer activation and cutting.

Activation of the clutch can temporarily disconnect the robotic arms guidance from the console so that the console controls can be repositioned to allow for additional robotic arm movement (44). Console controls movement is limited by the physical console space and the reach of the surgeon's arms. Studies have shown that use of the clutch control is more frequent with initial coaching and increasing robotic experience (45,46).

Robotic instruments

With the da Vinci surgical platform, the different robotic instruments have a wide range of grip forces (47). Surgeons should be aware of these differences during surgery and in some situations, pushing on tissues may be less traumatic than pulling on them. Deflections at the proximal wrist joint of robotic instruments have been shown to result in slightly lower grip forces (~5%) (47). Johnson et al found that the force input at the finger control was not proportional to the grasper instrument output (48). There is a "gulf of execution", and surgeons should not expect gentle pressure applied to the finger pads would translate to gentle pressure applied to the tissue. The authors also found that the finger grip angle and grasper jaw angle were nonproportional. This mismatch however can be overcome by visualisation of the jaw displacement.

A meta-analysis reporting on rectal anastomotic leak reported a non-statistically significant benefit of robotic stapler over laparoscopic stapler, as a result of better manoeuvrability in the confined space of the pelvis and requirement for fewer firings (49). Studies have revealed a higher anastomotic leak rate with more than one firing of the linear stapler (50). The Smartfire technology associated with the Da Vinci Sureform stapler measures tissue compression during firing, pausing to increase compression if inadequate before resumption of firing, to ensure a more consistent delivery of staples (51). The maximum angulation of the laparoscopic powered stapler is 45 degrees. One prospective study reported that over two-thirds of rectal transection with the robotic stapler required at least one firing at greater than this angle (52).

Lack of haptic feedback

Lack of haptic feedback is a disadvantage of RS with the da Vinci system. Haptic feedback can be kinesthetic (which senses forces and torques) or tactile (which senses pressure and deformation) (53). To acquire and convey haptic feedback information to the surgeon during RS, a combination of sensors and displays are required. The sensing element can be located in the robotic arms (indirect) or at the instrument tip (direct) (40). Intra-abdominal direct sensing can offer more precise feedback but is disadvantaged by the need to be small, durable, and sterilisable (54). The creation of a surgical corridor with virtual boundaries within which surgeons can operate safely in and avoid essential anatomical structures is another potential application of haptic feedback (53).

Lack of haptic feedback can result in application of excessive force causing tissue trauma or inadequate gripping force (55). The surgeon can overcome some of the force problems by knowing which da Vinci robotic instrument to use for grasping different tissues because the grip force is different with each instrument. The addition of haptic feedback during simulation RS has been shown to improve performance, reduce grasping forces on porcine bowel, and increase consistency and precision during knot tying (56,57). Experienced robotic surgeons can operate efficiently and safely without haptic feedback by unconsciously using visual cues such as tissue deformation as force surrogates (58). Restoration of three-dimensional vision is an important compensatory factor (59). Haptic force feedback is offered by some of the newer robotic systems but there have been no non-simulated studies comparing surgeon performance with and without haptic feedback (60).

Robot arm clashes

Robot arm collisions can lead to impaired control of instruments, restriction of movement, and injury to the patient or assistant. This was more common with the older da Vinci Si surgical systems because of their thicker robotic arms (36). Robot arm clashes can be reduced by placing the trocars at the appropriate positions for RS. The patient clearance buttons, which can drop the posterior elbows of the robot arms without changing the position of the instrument tips, can be used to minimise external robot arm collisions (61).

Wider spacing of ports and tailoring the placement of ports according to the planned surgery has been shown to improve manipulation angles (62). Bedside assistant injury can be prevented by judicious positioning of robotic and assistant ports and being aware of the scaling component of the fulcrum effect (63). With a single integrated patient cart, such as with the da Vinci system, the arms have instant registration with each other but arm clashing is more of a problem (40). Arm clashes can be avoided more easily with robotic systems which use individual patient carts for each arm (such as with the Senhance, Hugo, and CMR Versius systems).

Conclusions

Advanced technology has been used to support manipulation in robotic-assisted surgery. The integrated technologies of flexible instrument tips with seven DOF, scaling effect, removal of the fulcrum effect, and control of more instruments offer ergonomic benefits to the surgeon. On the other hand, limitations related to lack of haptic feedback and arm clashing need to be overcome to improve the surgeon experience.

Acknowledgments

Funding: None.

Footnote

Reporting Checklist: The authors have completed the Narrative Review reporting checklist. Available at https://ales.amegroups.com/article/view/10.21037/ales-23-64/rc

Peer Review File: Available at https://ales.amegroups.com/article/view/10.21037/ales-23-64/prf

Conflicts of Interest: Both authors have completed the ICMJE uniform disclosure form (available at https://ales.amegroups.com/article/view/10.21037/ales-23-64/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

References

1. Hislop J, Tirosh O, McCormick J, et al. Muscle activation during traditional laparoscopic surgery compared with robot-assisted laparoscopic surgery: a meta-analysis. Surg Endosc 2020;34:31-8.
2. Dalager T, Jensen PT, Eriksen JR, et al. Surgeons' posture and muscle strain during laparoscopic and robotic surgery. Br J Surg 2020;107:756-66.
3. Park AE, Zahiri HR, Hallbeck MS, et al. Intraoperative "Micro Breaks" With Targeted Stretching Enhance Surgeon Physical Function and Mental Focus: A Multicenter Cohort Study. Ann Surg 2017;265:340-6.
4. Wong SW, Crowe P. Visualisation ergonomics and robotic surgery. J Robot Surg 2023;17:1873-8.
5. Wong SW, Crowe P. Workflow disruptions in robot-assisted surgery. J Robot Surg 2023;17:2663-9.
6. Wong SW, Crowe P. Cognitive ergonomics and robotic surgery. J Robot Surg 2024;18:110.
7. Wong SW, Ang ZH, Yang PF, et al. Robotic colorectal surgery and ergonomics. J Robot Surg 2022;16:241-6.
8. Moorthy K, Munz Y, Dosis A, et al. Dexterity enhancement with robotic surgery. Surg Endosc

2004;18:790-5.
9. Breedveld P, Stassen HG, Meijer DW, et al. Manipulation in laparoscopic surgery: overview of impeding effects and supporting aids. J Laparoendosc Adv Surg Tech A 1999;9:469-80.
10. Van Veelen MA, Meijer DW. Ergonomics and design of laparoscopic instruments: results of a survey among laparoscopic surgeons. J Laparoendosc Adv Surg Tech A 1999;9:481-9.
11. Supe AN, Kulkarni GV, Supe PA. Ergonomics in laparoscopic surgery. J Minim Access Surg 2010;6:31-6.
12. Schlussel AT, Maykel JA. Ergonomics and Musculoskeletal Health of the Surgeon. Clin Colon Rectal Surg 2019;32:424-34.
13. Wilhelm P, Lambidis L, Williams J, et al. Reducing Degrees of Freedom in Surgical Suturing: Implications for Minimally Invasive Device Development-A Prospective Experimental Study. Surg Laparosc Endosc Percutan Tech 2021;31:421-7.
14. Kenngott HG, Muller-Stich BP, Reiter MA, et al. Robotic suturing: technique and benefit in advanced laparoscopic surgery. Minim Invasive Ther Allied Technol 2008;17:160-7.
15. Falk V, McLoughlin J, Guthart G, et al. Dexterity enhancement in endoscopic surgery by a computer-controlled mechanical wrist. Minim Invasive Ther Allied Technol 1999;8:235-42.
16. Dewaele F, De Pauw T, Kalmar A, et al. Is the Human Brain Capable of Controlling Seven Degrees of Freedom? J Surg Res 2019;238:1-9.
17. Pearle AD, Kendoff D, Musahl V. Perspectives on computer-assisted orthopaedic surgery: movement toward quantitative orthopaedic surgery. J Bone Joint Surg Am 2009;91 Suppl 1:7-12.
18. Gallagher AG, McClure N, McGuigan J, et al. An ergonomic analysis of the fulcrum effect in the acquisition of endoscopic skills. Endoscopy 1998;30:617-20.
19. Crothers IR, Gallagher AG, McClure N, et al. Experienced laparoscopic surgeons are automated to the "fulcrum effect": an ergonomic demonstration. Endoscopy 1999;31:365-9.
20. Spiers AJ, Baillie S, Pipe TG, et al. Negating the fulcrum effect in manual laparoscopic surgery: Investigating skill acquisition with a haptic simulator. Int J Med Robot 2017;13:e1837.
21. Nisky I, Huang F, Milstein A, et al. Perception of stiffness in laparoscopy - the fulcrum effect. Stud Health Technol Inform 2012;173:313-9.
22. Dong L, Morel G. Robust trocar identification and its application in robotic minimally invasive surgery. Int J Med Robot 2022;18:e2392.
23. Fargen KM, Turner RD, Spiotta AM. Factors That Affect Physiologic Tremor and Dexterity During Surgery: A Primer for Neurosurgeons. World Neurosurg 2016;86:384-9.
24. Prasad SM, Prasad SM, Maniar HS, et al. Surgical robotics: impact of motion scaling on task performance. J Am Coll Surg 2004;199:863-8.
25. Kim VB, Chapman WH, Albrecht RJ, et al. Early experience with telemanipulative robot-assisted laparoscopic cholecystectomy using da Vinci. Surg Laparosc Endosc Percutan Tech 2002;12:33-40.
26. Orosco RK, Lurie B, Matsuzaki T, et al. Compensatory motion scaling for time-delayed robotic surgery. Surg Endosc 2021;35:2613-8. Erratum in: Surg Endosc 2021;35:2619.
27. Ibrahim AE, Sarhane KA, Selber JC. New Frontiers in Robotic-Assisted Microsurgical Reconstruction. Clin Plast Surg 2017;44:415-23.
28. Taylor R, Jensen M, Whitcomb L, et al. A steady-hand robotic system for microsurgical augmentation. Int J Rob Res 1999;18:1201-10.
29. Badalato GM, Shapiro E, Rothberg MB, et al. The da vinci robot system eliminates multispecialty surgical trainees' hand dominance in open and robotic surgical settings. JSLS 2014;18:e2014.00399.
30. Choussein S, Srouji SS, Farland LV, et al. Robotic Assistance Confers Ambidexterity to Laparoscopic Surgeons. J Minim Invasive Gynecol 2018;25:76-83.
31. Mucksavage P, Kerbl DC, Lee JY. The da Vinci(®) Surgical System overcomes innate hand dominance. J Endourol 2011;25:1385-8.
32. Wan GY, Zhou XY, Duan HX, et al. Comparison of robotic camera holders with human assistants in endoscopic surgery: a systematic review and meta-analysis. Minim Invasive Ther Allied Technol 2023;32:153-62.
33. Dardona T, Eslamian S, Reisner LA, et al. Remote Presence: Development and Usability Evaluation of a Head-Mounted Display for Camera Control on the da Vinci Surgical System. Robotics 2019;8:31.
34. Koukourikis P, Rha KH. Robotic surgical systems in urology: What is currently available? Investig Clin Urol 2021;62:14-22.
35. Gueli Alletti S, Chiantera V, Arcuri G, et al. Introducing the New Surgical Robot HUGO™ RAS: System Description and Docking Settings for Gynecological Surgery. Front Oncol 2022;12:898060.
36. Kira S, Mitsui T, Sawada N, et al. Feasibility and necessity of the fourth arm of the da Vinci Si surgical system for robot-assisted partial nephrectomy. Int J Med Robot 2020;16:e2092.

37. Rogers CG, Laungani R, Bhandari A, et al. Maximizing console surgeon independence during robot-assisted renal surgery by using the Fourth Arm and TilePro. J Endourol 2009;23:115-21.
38. Veronesi G, Galetta D, Maisonneuve P, et al. Four-arm robotic lobectomy for the treatment of early-stage lung cancer. J Thorac Cardiovasc Surg 2010;140:19-25.
39. Mangano A, Gheza F, Bustos R, et al. Robotic right colonic resection. Is the robotic third arm a game-changer? Minerva Chir 2020;75:1-10.
40. Longmore SK, Naik G, Gargiulo GD. Laparoscopic Robotic Surgery: Current Perspective and Future Directions. Robotics 2020;9:42.
41. Monfared S, Athanasiadis DI, Umana L, et al. A comparison of laparoscopic and robotic ergonomic risk. Surg Endosc 2022;36:8397-8402.
42. 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;6:65-72.
43. Berguer R, Smith W. An ergonomic comparison of robotic and laparoscopic technique: the influence of surgeon experience and task complexity. J Surg Res 2006;134:87-92.
44. Abiri A, Tao A, LaRocca M, et al. Visual-perceptual mismatch in robotic surgery. Surg Endosc 2017;31:3271-8.
45. Raza SJ, Froghi S, Chowriappa A, et al. Construct validation of the key components of Fundamental Skills of Robotic Surgery (FSRS) curriculum--a multi-institution prospective study. J Surg Educ 2014;71:316-24.
46. Van't Hullenaar CDP, Mertens AC, Ruurda JP, et al. Validation of ergonomic instructions in robot-assisted surgery simulator training. Surg Endosc 2018;32:2533-40.
47. Mucksavage P, Kerbl DC, Pick DL, et al. Differences in grip forces among various robotic instruments and da Vinci surgical platforms. J Endourol 2011;25:523-8.
48. Johnson PJ, Schmidt DE, Duvvuri U. Output control of da Vinci surgical system's surgical graspers. J Surg Res 2014;186:56-62.
49. Tejedor P, Sagias F, Flashman K, et al. The use of robotic or laparoscopic stapler in rectal cancer surgery: a systematic review and meta-analysis. J Robot Surg 2020;14:829-33.
50. Balciscueta Z, Uribe N, Caubet L, et al. Impact of the number of stapler firings on anastomotic leakage in laparoscopic rectal surgery: a systematic review and meta-analysis. Tech Coloproctol 2020;24:919-25.
51. Intuitive Sureform staplers, accessed 15 August 2023. Available online: https://www.intuitive.com/en-us/products-and-services/da-vinci/stapling/sureform
52. Somashekhar SP, Saldanha E, Kumar R, et al. Prospective analysis of 164 fires of da Vinci SureForm SmartFire stapler in oncological cases: Indian cohort of 76 consecutive cases. J Minim Access Surg 2023;19:384-9.
53. Okamura AM. Haptic feedback in robot-assisted minimally invasive surgery. Curr Opin Urol 2009;19:102-7.
54. Heney P. Challenges of building haptic feedback for surgical robots. The Robot Report. 2019 Jul 18 [cited 2020 Oct 18]. Available online: https://www.therobotreport.com/haptic-feedback-design-challenges-surgical-robots
55. Amirabdollahian F, Livatino S, Vahedi B, et al. Prevalence of haptic feedback in robot-mediated surgery: a systematic review of literature. J Robot Surg 2018;12:11-25.
56. Wottawa CR, Genovese B, Nowroozi BN, et al. Evaluating tactile feedback in robotic surgery for potential clinical application using an animal model. Surg Endosc 2016;30:3198-209.
57. Bethea BT, Okamura AM, Kitagawa M, et al. Application of haptic feedback to robotic surgery. J Laparoendosc Adv Surg Tech A 2004;14:191-5.
58. Meccariello G, Faedi F, AlGhamdi S, et al. An experimental study about haptic feedback in robotic surgery: may visual feedback substitute tactile feedback? J Robot Surg 2016;10:57-61.
59. van der Meijden OA, Schijven MP. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. Surg Endosc 2009;23:1180-90.
60. Darwich I, Stephan D, Klöckner-Lang M, et al. A roadmap for robotic-assisted sigmoid resection in diverticular disease using a Senhance™ Surgical Robotic System: results and technical aspects. J Robot Surg 2020;14:297-304.
61. van der Horst S, Voli C, Polanco IA, et al. Robot-assisted minimally invasive esophagectomy (RAMIE): tips and tricks from the bedside assistant view-expert experiences. Dis Esophagus 2020;33:doaa071.
62. Wong SW, Ang ZH, Chua JL, et al. Ergonomic port placement in robotic colorectal surgery. Colorectal Dis 2021;23:2593-603.
63. Wong SW, Ang ZH, Crowe P. Improving ergonomics for the bedside assistant in robotic colorectal surgery. J Surg Case Rep 2023;2023:rjad007.

doi: 10.21037/ales-23-64

Cite this article as: Wong SW, Crowe P. Manipulation ergonomics and robotic surgery—a narrative review. Ann Laparosc Endosc Surg 2024;9:15.