Appendix 1. Automated performance metrics

Metrics in surgical video films can be assessed at different levels of granularity. Granularity reflects the level of detail in the analysis, ranging from the overall procedure to steps, tasks, and down to individual instrument movements. Appendix 1 shows some of the APMs that have been explored in previous studies, and Appendix 2 provides the mathematical calculations supporting some of these APMs.

The analyzed motion metrics will be organized into two categories: time-related metrics and space-related metrics. These metrics will be extracted from two-dimensional surgical videos. Examples of the APMs used in other studies and implemented in this study include:

1. Operative time (s): Total time to complete a task
2. Path length (m): Total length of the tip trajectory of an instrument
3. Velocity (cm/s): Average velocity of the tip of an instrument
4. Acceleration (cm/s): Average acceleration of the tip of an instrument
5. Jerk (cm/s): Average jerk of the tip of an instrument (jerk is the changing rate of acceleration, and it represents motion smoothness)
6. Frequency of opening and closing (times): Total number of iterations of opening and closing the jaws of forceps (a series of opening and closing the forceps once counts as one iteration; series defined as opening and closing for more than 3 times)
7. Distribution of velocity: The number of frames in which instrument velocity falls within a specific velocity band, expressed as a ratio of the total number of frames
8. Distribution of working area (WA): Path length within a certain area relative to the target object (areas and target objects will be procedure-specific)
9. Average inserting time (s): Duration between the insertion of an instrument into the abdomen through a trocar and its removal
10. Idle time, total operative time, and path length: Idle time is characterized by a lack of movement of both hands and may represent periods of motor planning or decision making, which can differentiate performance
11. Time spent in specific zones: Zones are procedure-specific and will be defined for each procedure
12. Instrument collision: Number of times surgical tools clash or collide during the task (lower scores indicate better performance)
13. Number of unnecessary needle piercings (e.g., during suturing): Identified by experts, and the system will be trained accordingly
14. Economy of motion: Total distance travelled by all instruments (lower scores indicate better performance)
15. Economy of the area: Ratio between the maximum surface area occupied by the instrument in the task plane and the total path length
16. Economy of volume: Ratio between the maximum volume occupied by the instrument in the setting and the total path length (both metrics measure space usage efficiency in the box trainer)
17. BD: Ability to control two instruments simultaneously, calculated by correlating the velocity of the left and right-hand instrument tips (reflects balanced use of both hands)
18. Average speed (mm/s): Calculated as total path length divided by time
19. Motion smoothness (mm/s): Calculated as O (time × total path length × average speed)
20. Working area (mm): Average distance between instrument tips
21. Time off screen (%): Proportion of time the instrument tip is not in the operative field
22. Handedness (m): Average difference in path length
23. Accuracy: Number of correct actions performed
24. Energy expenditure: Energy expenditure assessment in surgical video typically uses accelerometers and other sensors to measure physical activity (physical movement) and objective measurements of activity
25. Tools/instrument orientation: Metrics related to the instrument's orientation may be explored
26. Camera manipulation metrics: Strongly correlate with surgeon expertise and good outcomes
27. Additional metrics: Ebina[2] suggested 10 metrics, newly calculated based on hypotheses generated during the authors' video review process and their previous papers: BD, ratio of frequency of opening/closing both forceps, ratio of path length for both hands, average distance between both forceps when opening/closing, average distance between both forceps, depth path length, depth velocity, average gripper rotation angle, average attitude angle (Roll, Pitch, Yaw), angular length (Roll or Pitch/Yaw), and WA

Appendix 2. Mathematical formulas for the measurement of automated performance metrics

Indices	Unit	Definitions	Formulae
General			
Operative time (time)	(s)	The time to complete a task	
Bimanual dexterity		This index evaluates the coordinated movement between both hands and is calculated from the relationship between the tip velocity of surgical instruments handled by both hands simultaneously.[10]	$\frac{\sum_{i=1}^{n}\left(v_L(i)-\overline{v_L}\right)\left(v_R(i)-\overline{v_R}\right)}{\sqrt{\sum_{i=1}^{n}\left(v_L(i)-\overline{v_L}\right)^2\sum_{i=1}^{n}\left(v_R(i)-\overline{v_R}\right)^2}}$, Where n is the total number of MoCap frames, and $v_L(i)$ and $v_R(i)$ are three-dimensional tip velocities of instruments handled by left and right hands in frame i, respectively. $v_L(i)$ and $v_R(i)$ are calculated as follows: $v_L(i) = \|\boldsymbol{v}_L(i)\|$, $v_R(i) = \|\boldsymbol{v}_R(i)\|$. Here, $\overline{v_L}$ and $\overline{v_R}$ are averages of $v_L(i)$ and $v_R(i)$ in the measured task.
Ratio of frequency of opening/closing both forceps		The ratio of the opening/closing frequency of forceps handled by the left and right hands during a dissection task (left hand: grasping forceps, right hand: scissors forceps)	$\frac{N_{OC_grasper}}{N_{OC_scissor}}$, where $N_{OC_grasper}$ and $N_{OC_scissor}$ are the opening/closing frequencies of grasping and scissor forceps, respectively.
Ratio of path length for both hands		The ratio of the path lengths of the forceps tip position of both hands in the dissection task (left hand: grasping forceps, right hand: scissors forceps)	$\frac{PL_{grasper}}{PL_{scissor}}$, where $PL_{grasper}$ and $PL_{scissor}$ are path lengths of grasping and scissor forceps, respectively.
Average distance between both forceps when opening/closing	(m)	The average distance between the tip positions of instruments handled by both hands when opening and closing the grasping forceps in the dissection task	$\frac{\sum_{i=1}^{N_{OC_grasper}}\left\|\boldsymbol{p}_{tip(grasper_oc)}(i)-\boldsymbol{p}_{tip(scissor_oc)}(i)\right\|}{NOC_{grasper}}$, where $\boldsymbol{p}_{tip(grasper_OC)}(i)$ and $\boldsymbol{p}_{tip(scissor_oc)}(i)$ are the tip positions of grasping and scissors forceps in the i th opening/closing operation, respectively.
Average distance between both forceps	(m)	Average distance between tip positions of both forceps in the suturing/knotting task	$\frac{\sum_{i=1}^{n}\left\|\boldsymbol{p}_{tip(right)}(i)-\boldsymbol{p}_{tip(left)}(i)\right\|}{n}$, where $\boldsymbol{p}_{tip(left)}(i)$ and $\boldsymbol{p}_{tip(right)}(i)$ are the tip position of the left and right needle holder in frame i, respectively.
Forceps motion			
Path length	(m)	Total movement of the tip of an instrument during the measured task; the tip trajectory that moved outside the box trainer is excluded from calculation	$\sum_{i=1}^{n-1}\|\boldsymbol{p}_{tip}(i+1)-\boldsymbol{p}_{tip}(i)\|$, where, $\boldsymbol{p}_{tip}(i)$ is the tip position of an instrument in frame i. The positional vector $\boldsymbol{p}_{tip}$ is smoothed by the Savitzky–Golay filter.
Average velocity ($\overline{v}$)	cm/s	Average tip velocity of an instrument	$\frac{1}{n}\sum_{i=1}^{n}\left\|\frac{d}{dt}\boldsymbol{p}_{tip}(i)\right\|$, where $\frac{d}{dt}\boldsymbol{p}_{tip}(i)$ is calculated by the Savitzky–Golay filter.
Average acceleration ($\overline{a}$)	(cm/s^2)	Average tip acceleration of an instrument; acceleration is defined as the changing rate of velocity	$\frac{1}{n}\sum_{i=1}^{n}\left\|\frac{d^2}{dt^2}\boldsymbol{p}_{tip}(i)\right\|$, where $\frac{d^2}{dt^2}\boldsymbol{p}_{tip}(i)$ is calculated by the Savitzky–Golay filter.
Average jerk ($\overline{j}$)	cm/s^3	Average tip jerk of an instrument; Jerk is defined as the changing rate of acceleration, and it represents motion smoothness	$\frac{1}{n}\sum_{i=1}^{n}\left\|\frac{d^3}{dt^3}\boldsymbol{p}_{tip}(i)\right\|$, where $\frac{d^3}{dt^3}\boldsymbol{p}_{tip}(i)$ is calculated by the Savitzky–Golay filter.
Distribution of working area (Close/Near/Far zone)	Close	(%)	This index is calculated as the ratio of the path length moving around the target objects in a certain area (Close, Near, and Far) to the total path length; In the dissection task, the dissection area of the aorta was set as the target, and in the suturing/knotting task, the incised line of the kidney parenchyma was set as the target; the target objects were designated by putting the tip of forceps of both hands on the start/end point of the target for 5 s before conducting the experiment.	$\frac{\sum_{i=1}^{n-1}\|\boldsymbol{p}_{tip}(i+1)-\boldsymbol{p}_{tip}(i)\|}{PL} = \left\{ i \in (0,\ldots n-1) \middle\| \left(\boldsymbol{p}_{start} + l\frac{\boldsymbol{p}_{end}-\boldsymbol{p}_{start}}{\|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\|}\right) - \boldsymbol{p}_{tip}(i+1)\right\| < 0.02 \right\}$ (cm), where $\boldsymbol{p}_{start}$ and $\boldsymbol{p}_{end}$ are positions of start and end points of the target object, and l is defined as follows: $l = \begin{cases} 0 & (d \le 0) \\ d & (0 < d < \|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\|) \\ \|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\| & (\|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\| \le d) \end{cases}$. Here, d is calculated as follows: $d = \frac{\frac{\boldsymbol{p}_{end}-\boldsymbol{p}_{start}}{\|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\|}\cdot(\boldsymbol{p}_{tip}(i+1)-\boldsymbol{p}_{start})}{\|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\|^2}$.
	Near		$\frac{\sum_{i=1}^{n-1}\|\boldsymbol{p}_{tip}(i+1)-\boldsymbol{p}_{tip}(i)\|}{PL} = \left\{ i \in (0,\ldots n-1) \middle| 0.02 \le \left\|\left(\boldsymbol{p}_{start} + l\frac{\boldsymbol{p}_{end}-\boldsymbol{p}_{start}}{\|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\|}\right) - \boldsymbol{p}_{tip}(i+1)\right\| < 0.04 \right\}$ (cm).
	Far		$\frac{\sum_{i=1}^{n-1}\|\boldsymbol{p}_{tip}(i+1)-\boldsymbol{p}_{tip}(i)\|}{PL} = \left\{ i \in (0,\ldots n-1) \middle| 0.04 \le \left\|\left(\boldsymbol{p}_{start} + l\frac{\boldsymbol{p}_{end}-\boldsymbol{p}_{start}}{\|\boldsymbol{p}_{end}-\boldsymbol{p}_{start}\|}\right) - \boldsymbol{p}_{tip}(i+1)\right\| \right\}$ (cm).
Distribution of velocity (Idle/Low/Middle/High/Very high)	Idle	(%)	This index was calculated as the ratio of the number of frames whose instrument moves in a certain velocity band (Idle, Low, Middle, High, and Very high) to the total number of frames of the measured task	$\frac{\lvert n_{Idle}\rvert}{n} : n_{Idle} = \{ i \in (0,\ldots n) \mid 0 \le v(i) < 0.5 \}$ (cm/s), where v(i) is the tip velocity of an instrument in frame i.
	Low			$\frac{\lvert n_{Low}\rvert}{n} : n_{Low} = \{ i \in (0,\ldots n) \mid 0.5 \le v(i) < 2.0 \}$ (cm/s).
	Middle			$\frac{\lvert n_{Middle}\rvert}{n} : n_{Middle} = \{ i \in (0,\ldots n) \mid 2.0 \le v(i) < 5.0 \}$ (cm/s).
	High			$\frac{\lvert n_{High}\rvert}{n} : n_{High} = \{ i \in (0,\ldots n) \mid 5.0 \le v(i) < 12.0 \}$ (cm/s).
	Very high			$\frac{\lvert n_{Veryhigh}\rvert}{n} : n_{Veryhigh} = \{ i \in (0,\ldots n) \mid 5.0 \le v(i) < 12.0 \}$ (cm/s).
Depth path length	(m)		Total movement of the tip of an instrument along its sheath axis in the measured task	$\sum_{i=1}^{n}\lvert x_{L(i-1)tip}(i) - x_{L(i-1)tip}(i-1)\rvert$, where $x_{L(i-1)tip}(i)$ is tip position of an instrument on the X-axis in frame i, which is represented in the local coordinate system of the instrument in frame $(i-1)$. The tip position of an instrument in frame i $\boldsymbol{v}_{L(i-1)tip}(i) = \left[x_{L(i-1)tip}(i) \quad y_{L(i-1)tip}(i) \quad z_{L(i-1)tip}(i)\right]$ is represented as follows: $\boldsymbol{v}_{L(i-1)tip}(i) = \boldsymbol{M}\{\boldsymbol{v}_{Gtip}(i) - \boldsymbol{v}_{Go}(i-1)\}$, where $\boldsymbol{M}$ is the rotation matrix, calculated as follows: $\boldsymbol{M} = R_x(-\alpha_{i-1})R_y(-\beta_{i-1})R_z(-\gamma_{i-1})$. Here, R_x, R_y, and R_z are rotation matrices around X, Y, and Z-axes, respectively, and α_{i-1}, β_{i-1}, and γ_{i-1} are attitude angles around X, Y, and Z-axes (Roll, Pitch, and Yaw) in frame $(i-1)$, respectively. These angles are represented as Z-Y-X euler angles.
Depth velocity	cm/s		Average velocity of the tip of an instrument on its sheath axis	$\frac{1}{n}\sum_{i=1}^{n}\frac{\lvert x_{L(i-1)tip}(i) - x_{L(i-1)tip}(i-1)\rvert}{DT}$, where DT (s) is the sampling period of the MoCap system. In this study, the sampling frequency was set to 30 Hz, and DT was calculated as $DT = \frac{1}{30} = 0.0333 \cdots$ (s).
Number of opening/closing operations (N_{OC})	(times)		The sum of repetitions of opening and closing the forceps jaw; one repetition is defined as a series of opening and closing performed once	
Average gripper rotation angle	(°)		Average rotation angle of the gripper of grasping forceps during the measured task	$\frac{1}{n}\sum_{i=1}^{n}\theta_{gripper}(i)$, where $\theta_{gripper}(i)$ is the gripper rotation angle of an instrument in frame i.
Average attitude angle (Roll/Pitch/Yaw)	Roll	(°)	Average attitude angle (Roll/Pitch/Yaw) of an instrument during the measured task; these angles are represented as Z-Y-X Euler angles	$\frac{1}{n}\sum_{i=1}^{n}\alpha(i)$.
	Pitch			$\frac{1}{n}\sum_{i=1}^{n}\beta(i)$.
	Yaw			$\frac{1}{n}\sum_{i=1}^{n}\gamma(i)$.
Angular length (AL-Roll/AL-Pitch/ Yaw)	AL-Roll	(°)	The sum of changes in the attitude angle of an instrument; this index was defined for two items: the attitude angle around its sheath axis (Roll) and around the point of instrument insertion (Pitch/Yaw)	$\sum_{i=1}^{n}\sqrt{(\alpha_i - \alpha_{i-1})^2}$.
	AL-Pitch/Yaw			$\sum_{i=1}^{n}\sqrt{(\beta_i - \beta_{i-1})^2 + (\gamma_i - \gamma_{i-1})^2}$.
Working area	(cm^2)		The moving area of the tip of forceps in a plane orthogonal to the target object (Y-Z plane in Figure 1)	$(y_{tip(q=0.975)} - y_{tip(q=0.275)})(z_{tip(q=0.975)} - z_{tip(q=0.275)})$, where $y_{tip(q=0.975)}$ and $y_{tip(q=0.275)}$ are the 97.5-percentile and 2.5-percentile of the tip position of an instrument in the Y-axis, respectively. $z_{tip(q=0.975)}$ and $z_{tip(q=0.275)}$ are calculated in the same way in the Z-axis.
Average inserting time	(s)		Average operating time to apply the clip using Hem-o-lok; this index is calculated as the time between inserting Hem-o-lok into and removing it from the box trainer	$\frac{1}{n_{inserting}}\sum_{i=1}^{n_{inserting}}T_{inserting}(i)$, where $n_{inseting}$ is the total number of insertions of Hem-o-lok in the measured task, and $T_{inserting}(i)$ is the operating time of the i th insertion.
Reference: Ebina 2022[2]				

Appendix 3. Clinical registration form		
Local patient identifier	**Not uploaded to REDCap**	**Unique REDCap identifier**
Pre-operative data		
Patients' age (on day of operation)		Years (category of 10 years)
Gender (assigned at birth)		Male/Female
Body mass index		
Co-morbidity		
Disease severity		
American Society of Anesthesiologists grade		1/2/3/4/5
Previous abdominal surgery		No/Yes (minimally invasive, open, or conversion to open)/Not known
Intraoperative data		
Date of the procedure		00/00/0000
Is this the index procedure (i.e., prior to receiving the automated performance metrics report)?		No/Yes
How many procedures were performed after the index procedure within 6 months?		
Primary operating surgeon for abdominal wall closure		Consultant colorectal surgeon/Trainee colorectal surgeon/Consultant general surgeon/Trainee general surgeon
Most senior surgeon in theatre		Consultant colorectal surgeon/Trainee colorectal surgeon/Consultant general surgeon/Trainee general surgeon
Indication		Malignancy/Ulcerative colitis/Crohn's disease/Diverticular disease
Duration of surgery (minutes) knife-to-skin to completion of skin closure		1-60/61-119/120-179/180-239/≥240
Postoperative data (up to 30 postoperative days)		
Total length of hospital stay		Days
Postoperative complications		No/Yes
Clavien-Dindo score of the most severe complication		1-5
Re-operation within 30 days		No/Yes
REDCap: Research Electronic Data Capture		