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Objective Motion Analysis of Simulated Thoracoscopic Repair of Esophageal Atresia with Tracheoesophageal Fistula

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Abstract

Background: Objective assessment of technical performance remains challenging in neonatal minimally invasive surgery. Instrument motion analysis may complement conventional assessment during simulation-based training.

Objective: To explore relationships among instrument motion parameters during simulated thoracoscopic repair of esophageal atresia with tracheoesophageal fistula and characterize patterns according to surgical experience and simulation model.

Methods: In this prospective observational study, 30 participants were stratified by surgical experience into experienced (n = 18) and inexperienced (n = 12) groups and randomly assigned to one of two synthetic esophageal atresia models. Following standardized video instruction, participants performed fistula closure and division, proximal pouch opening, and esophageal anastomosis within a 30-minute limit. The Laparo Analytic system continuously recorded instrument movements to quantify motion efficiency, smoothness, spatial utilization, and bimanual coordination. Spearman correlation analysis examined relationships among motion metrics within surgical experience and simulation model subgroups.

Results: Thirty participants were enrolled: 18 experienced and 12 inexperienced surgeons. Correlations were numerically stronger among experienced surgeons for economy of area versus path length ($\rho = -0.98$ versus -0.79), depth perception versus economy of volume ($\rho = -0.97$ versus -0.86), and clamp distance versus path length ($\rho = 0.86$ versus 0.71). Excessive acceleration correlated closely with hectic time in both groups ($\rho = 0.98$ and 0.96), whereas bimanual dexterity showed little association with path length ($\rho = 0.13$ and -0.07). Strong inverse correlations between economy of volume and path length were observed with both models ($\rho = -0.98$ and -0.94).

Conclusion: Motion analysis revealed interrelated spatial and kinematic parameters, with exploratory differences in correlation patterns according to surgical experience. These findings

support further investigation of motion metrics as complementary assessment tools; their ability to discriminate proficiency requires validation in larger cohorts.

Keywords: Esophageal atresia; Thoracoscopy; Surgical simulation; Motion analysis; Surgical training; Pediatric surgery.

Introduction

Minimally invasive techniques are increasingly adopted worldwide for various indications in pediatric surgery and are becoming the gold standard for certain procedures. The successful application of minimally invasive surgery (MIS) in children has also led to its increased use in neonates and infants. Performing MIS is technically more challenging than conventional open surgery, with higher complication risks during initial proficiency stages, increasing the demand for well-trained and certified MIS surgeons. The application of MIS in neonates and infants therefore poses considerable technical challenges and remains an unfamiliar procedure for numerous pediatric surgeons. Furthermore, the majority of infants undergoing MIS repair are exceptionally small at the time of surgery, resulting in a confined and narrow surgical field.

To support the safe implementation of MIS approaches, early and intensive training is required [4]. The reproducibility of simulation-based training provides both practicing surgeons and surgical trainees with a structured environment for the acquisition and refinement of operative techniques and discrete procedural steps. It enables deliberate practice, including error recognition and correction, within standardized and supervised settings. Although simulation in surgical education cannot fully substitute for direct clinical exposure, it represents an effective modality for developing a broad range of essential technical and procedural competencies. Simulation-based surgical training conducted in a standardized environment outside the operating room facilitates the acquisition of fundamental laparoscopic psychomotor competencies while enabling objective, quantitative performance assessment. Traditionally,

MIS skills have been assessed subjectively using forms such as Objective Structured Assessment of Technical Skills (OSATS), Global Operative Assessment of Laparoscopic Skills (GOALS), and Operative Performance Rating System (OPRS) [5], [6], [7]. Error-based assessment systems (EBAS), including the Generic Error Rating Tool (GERT) and Objective Clinical Human Reliability Analysis (OCHRA), identify technical errors as proxies for performance quality. While these tools are widely used, they remain dependent on expert raters, are influenced by evaluator perception and experience, and are limited by the lack of granular quantitative data [8]. The integration of motion-tracking technologies into laparoscopic simulators has introduced objective performance metrics based on instrument kinematics. Traditional Motion Analysis Parameters (MAPs) typically include time, path length, motion smoothness, depth (perception), speed, acceleration, idle time, economy of area, economy of volume, bimanual dexterity. Although these metrics provide valuable information, their ability to fully characterize complex psychomotor performance is limited. Moreover, studies correlating motion analysis outputs with surgical experience and quality of laparoscopic task execution remain scarce. Recent approaches have explored classification of surgeons based on instrument motion patterns recorded during box-trainer tasks, yet the expansion and validation of more advanced kinematic descriptors are still needed [9]. Motion analysis may enhance patient safety by enforcing predefined safety thresholds. Exceeding these limits results in task failure, encouraging deliberate practice and the development of safe motor habits. However, it must be acknowledged that MAP-based evaluation reflects movement quality rather than the full clinical outcome of a procedure. By expanding the spectrum of motion-derived metrics and investigating their relationship to surgical expertise, this study seeks to contribute to the development of more precise, standardized, and data-driven approaches to surgical training and competency assessment. Determinants of technical proficiency in instrument handling have been operationalized using composite MAPs [10]. In addition, force-derived parameters have

been integrated into performance evaluation frameworks, as they serve as surrogate indicators of tissue handling quality and the potential for iatrogenic tissue trauma [10].

The primary aim of this study was to comprehensively analyze surgeons' performance and workflow within a laparoscopic simulator using both established and newly proposed MAPs. By expanding the spectrum of kinematic descriptors beyond conventional measures, this study seeks to advance data-driven, standardized approaches to surgical training and competency assessment. The present work builds upon our previously reported validation of two synthetic esophageal atresia with tracheoesophageal fistula (EA/TEF) simulation models and the assessment of MIS training perceptions, further extending the objective evaluation framework within this clinically relevant training context .

Materials and Methods

This prospective observational study was conducted during the MIS course offered at the 68th Czech and Slovak Pediatric Surgery Congress in Slovakia in 2024. Written informed consent was obtained from all participants prior to enrollment. Furthermore, each study participant completed a questionnaire regarding their surgical experience. The questionnaire included information such as: the number of performed MIS procedures, experience with pediatric MIS, and experience in simulator training. The study builds on our previously reported validation (face and content validation) of two synthetic esophageal EA/TEF simulation models and the assessment of perceptions regarding MIS training [4]. The objective of the present study was to analyze motion-derived performance metrics during simulated thoracoscopic EA/TEF repair using two 3D-printed EA/TEF models among participants attending a laparoscopic workshop. All data were anonymized prior to analysis. Participants were stratified according to clinical experience. The inexperienced group (IN group) consisted of surgical trainees in their 1st to 10th year of postgraduate training. The experienced group (EX group) included board-certified

pediatric surgeons with ≥11 years of independent clinical practice. Participants reported years of surgical experience, number of MIS procedures performed, and prior exposure to MIS procedures. Before performing the study task, all participants viewed standardized instructional videos outlining the procedural steps and technical objectives. No individualized technical coaching was provided during the assessment phase.

Simulation platform and instrumentation. Training and performance assessment were performed using the Laparo Analytic simulators (LAPARO® Medical Simulators, Poland, European Union). Laparo Analytic integrates motion-tracking hardware with dedicated analysis software for quantitative evaluation of MIS instrument handling. The MIS setup consisted of a 5 mm 30° rigid telescope and 5-mm instruments including a grasper, needle holder, and scissors. Two previously validated synthetic silicone EA/TEF models were available (Figure 1, Figure 2).

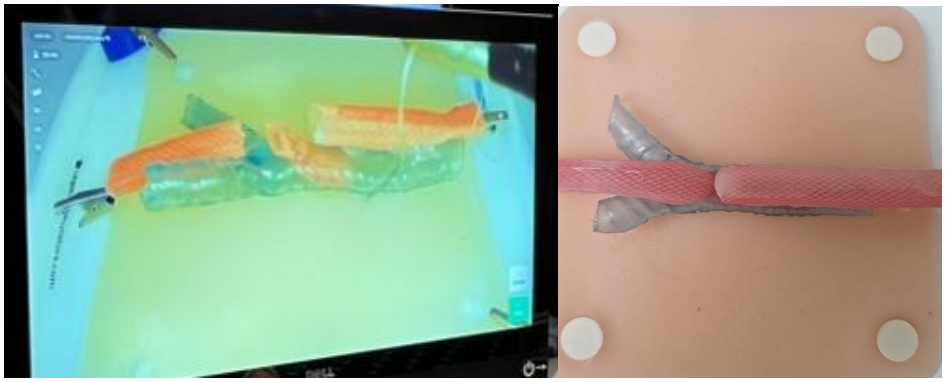


Figure 1. In-house 3D-printed EA/TEF model (SK model).



Figure 2. Commercially available silicone model of EA/TEF by LAPARO® Medical Simulators (PL model).

Simulated surgical procedures. Participants were randomly assigned to one of the two models. Each participant was allocated a maximum of 30 min to complete the task. Participants performed a standardized sequence simulating thoracoscopic repair of EA/TEF. The task included:

(1) closure of the tracheoesophageal fistula using a clip applier

(2) division of the fistula

(3) opening of the proximal esophageal pouch

(4) end-to-end esophageal anastomosis using sliding-knot suturing.

***Motion tracking and data acquisition*.** Instrument motion was recorded using a proprietary electronic trocar system integrated into the simulator. Motion capture was based on measurement of insertion depth and instrument orientation. Sensors located within the trocar measured inclination angles and insertion depth. Additional sensors integrated into the instrument handle measured jaw opening (clamp position). Based on these inputs, three-dimensional coordinates (x, y, z) of the instrument tip were calculated in real time. Instrument visibility within the operative field was determined using camera-based image processing algorithms. Collision events were recorded by hardware sensors. The following time-dependent variables were recorded continuously during task performance: time (t), instrument tip position (x, y, z), rotation angle (α), clamp position, hand oscillation, instrument visibility, instrument side, and collision events.

Signal processing and computation of motion parameters. Raw sensor data were resampled to ensure uniform temporal resolution and smoothed using Gaussian kernel filtering to reduce measurement noise. Time-derivative variables were calculated using midpoint numerical approximation methods, and integral quantities were computed using the trapezoidal rule. These preprocessing steps were applied prior to extraction of motion analysis parameters. A

comprehensive set of (MAPs was calculated to quantify precision and motion smoothness, efficiency, coordination, operative space utilization, and safety-related aspects of the laparoscopic procedure performance. These included total task time, path length, economy of area, economy of volume, motion smoothness, idle time, clamp distance, visible path length, visible clamp distance, visible time, maximum speed, average hand oscillation, excessive acceleration, excessive hand oscillation.

Feedback modalities. During task execution, the simulator provided real-time alerts when instrument motion exceeded predefined speed thresholds or when instruments were manipulated outside the visual field. After task completion, participants received a structured performance report summarizing all MAPs, including comparison with predefined reference ranges. Raw data could be exported for further analysis using dedicated motion-analysis software. The primary outcome was the association between motion-derived parameters and surgical experience (inexperienced vs experienced). Secondary analyses examined correlations between MAPs and years of practice and self-reported MIS case volume.

Statistical analysis

Correlation analysis was used to evaluate the relationships between individual motion analysis parameters (such as clamp distance, path length, depth perception, economy of area and volume, motion smoothness, excessive acceleration, and hectic time). To account for the sample size and data distribution, the strength and direction of monotonic relationships between the variables were assessed using Spearman's rank correlation coefficient (rho). To investigate potential differences arising from surgical experience and the specific working environment, analyses were conducted with stratification into subgroups: experienced surgeons (EX group) and inexperienced surgeons (IN group), as well as by the evaluated models (SK model, PL model). The strength of the correlation was interpreted according to the absolute value of the

coefficient (|r|) as follows: 0.00–0.19 as very weak, 0.20–0.39 as weak, 0.40–0.59 as moderate, 0.60–0.79 as strong, and 0.80–1.00 as very strong. Positive values indicated a direct monotonic relationship, whereas negative values indicated an inverse relationship. The relationships were illustrated using heatmaps and scatter plots with a fitted linear regression line. For each line, 95% confidence intervals were determined (presented as shaded bands) to visually assess the trend estimation.

Results

A total of 30 participants were enrolled in the study. The median age of the cohort was 45 years, with an interquartile range of 29.1–48.0 years, and women accounted for 26.6%.. Based on previous surgical experience, 18 experienced (60%) and 12 inexperienced (40%). Most respondents (30%) worked in centers performing more than 151 pediatric MIS procedures annually, while 6% reported fewer than 50 procedures per year. Observed or assisted operative exposure was comparable between experienced and inexperienced surgeons (66.7% vs. 66.7% reporting fewer than 50 procedures; $p = 0.989$). However, 86.7% of inexperienced surgeons performed fewer than 50 MIS procedures as lead operators during the same period.

Each participant was allocated 60 min to perform predefined thoracoscopic tasks on the silicone model, including TEF closure using a clip applier, TEF division, opening of the upper esophageal pouch, and esophageal anastomosis using sliding knots. The silicone models were randomly assigned to the participants. Task performance was assessed according to completion of the predefined procedural steps and the number of sufficient anastomotic stitches placed within the 30-min time limit. The analysis of the obtained results was conducted across several key areas essential for the performance of the surgical procedure: (1) time management, (2) trajectory precision and motion smoothness, (3) utilization of the operative space, (4) instrument handling and bimanual coordination, (5) motion kinematics and dynamics, (6) field

of view control, and (7) stability and safety. A comprehensive summary of the evaluated motion analysis parameters (MAPs), including their corresponding measurement units and mathematical formulas, is presented in Table 1. These parameters serve as objective, quantitative indices that map directly onto the seven functional domains described above, translating raw kinematic and sensor data into standardized metrics to assess each participant's technical proficiency, movement economy, and procedural safety.

Table 1. A comprehensive summary of the evaluated MAPs.

MAP	Units	Formula
Time	s	$T = \int \quad dt$
Path length	m	$PL = \int_0^T \quad dt \, \lvert \dot{r}(t) \rvert$
Economy of area	-	$EOA = \sqrt{[max_t\, x(t) - min_t\, x(t)] \cdot [max_t\, z(t) - min_t\, z(t)]} \,/\, PL$
Economy of volume	-	$EOV = \sqrt[3]{[max_t\, x(t) - min_t\, x(t)] \cdot [max_t\, y(t) - min_t\, y(t)] \cdot [max_t\, z(t) - min_t\, z(t)]} \,/\, PL$
Motion smoothness	m / s^3	$MS = \sqrt{\frac{T^5}{2PL^2}\int_0^T \quad dt \left[\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^2\right]^2}$
Idle time	%	$IT = \frac{1}{T}\int_0^T \quad dt \, \theta[v_0 - v(t)]$
Bimanual dexterity	-	$BD = (\langle v_L \, v_R \rangle - \langle v_L \rangle \langle v_R \rangle) / \sqrt{\langle v^2{}_L \rangle - \langle v_L \rangle^2} / \sqrt{\langle v^2{}_R \rangle - \langle v_R \rangle^2}$
Clamp distance	a.u.	$CD = \frac{1}{T}\int_0^T \quad dt \, \lvert \dot{c}\,(t) \rvert$
Visible path length	%	VPL = visible path length / total path length · 100%
Visible clamp distance	%	VCD = visible clamp distance / total clamp distance · 100%
Visible time	%	VT = visible time / total time · 100%
Maximum speed	m / s	$v_{max} = max_t\, v(t)$
Average hand oscillation	a.u.	$HO = \frac{1}{T}\int_0^T \quad dt \;\; ho(t)$
Excessive acceleration	%	$EA = \frac{1}{T}\int_0^T \quad dt \, \theta\,[a(t) - a_0)]$
Excessive hand oscillation	%	$EHO = \frac{1}{T}\int_0^T \quad dt \, \theta\,[ho(t) - ho_0)]$

Kinematic Relationships According to Surgical Experience

To identify motion patterns characteristic of specific proficiency levels, a Spearman's rank correlation analysis was performed between key motion analysis parameters (MAPs). The assessment revealed noticeable differences in the strength of the relationships between

individual parameters between the expert (EX) and novice (IN) groups. In the experienced surgeons group (EX), very strong correlation coefficients (rho close to 1 or -1) were obtained for the majority of the analyzed parameter pairs (Figure 5). A very strong negative correlation was demonstrated between economy of area and motion smoothness (r = -0.83) as well as total path length (r = -0.98) (Figure 3), meaning that the smaller the workspace utilized by the expert, the smoother and shorter their movements were. A similar, almost perfect negative relationship was noted for economy of volume and path length (r = -0.98) (Figure 5). Conversely, in the novice group (IN), the strength of these same correlations was weaker. The relationship between clamp distance and path length was r = 0.71 (compared to r = 0.86 in experts) (Figure 5). Similarly, the negative correlation between economy of area and total path length was weaker (r = -0.79 vs. -0.98 in experts) (Figure 3), and the correlation between depth perception and economy of volume was r = -0.86 (compared to r = -0.97 in the EX group) (Figure 5). Regardless of the level of experience, close relationships were observed within the error and spatial metrics. A strong positive correlation was found between excessive acceleration and the hectic time (r = 0.98 for EX; r = 0.96 for IN) (Fig. 4), as well as a strong correlation between economy of area and economy of volume (r = 1.00 for EX; r = 0.96 for IN). The analysis of the results also identified a subgroup of metrics that demonstrated weak or non-significant correlations. Bimanual dexterity exhibited virtually no relationship with total task completion time (r = -0.004 for EX; r = 0.21 for IN), path length (r = 0.13 for EX; r = -0.07 for IN), or economy of area (r = -0.08 for EX; r = -0.14 for IN) (Figure 5). Similarly, the percentage of idle time correlated with total time at merely r = -0.04 in the expert group (EX) and r = 0.36 among novices (IN). Furthermore, kinetic parameters directly related to safe force application, such as excessive acceleration, did not correlate significantly with overall path length (r = 0.13 for EX; r = 0.21 for IN) or task completion time (r = -0.21 in both groups), despite their strong internal association with hectic time (Figure 4, 5) .

Kinematic Relationships According to the Applied Training Model

The impact of the specific characteristics of the applied training model (model SK vs. model PL) was also reflected in the correlation analysis results. In the case of the commercial model (model PL), the strength of the relationships between key MAPs was systematically higher compared to the SK model. This was particularly evident in the relationships reflecting the precision of instrument handling. The correlation between clamp distance and total path length was r = 0.87 for the PL model, whereas for the SK model it was r = 0.74 (Figure 5). Furthermore, a stronger negative correlation was observed between economy of area and total path length (model PL: r = -0.98 vs. model SK: r = -0.92) (Figure 3), as well as a very strong relationship between depth perception and economy of area (model PL: r = -0.98 vs. model SK: r = -0.93) (Figure 5). Furthermore, the analysis of the results revealed a negative relationship between economy of volume and total path length for both models (model PL: r = -0.98; Model SK: r = -0.94), as well as a strong positive correlation between the hectic time and excessive acceleration parameters (r = 0.95 for model PL and r = 0.93 for model SK) (Figure 4,5).

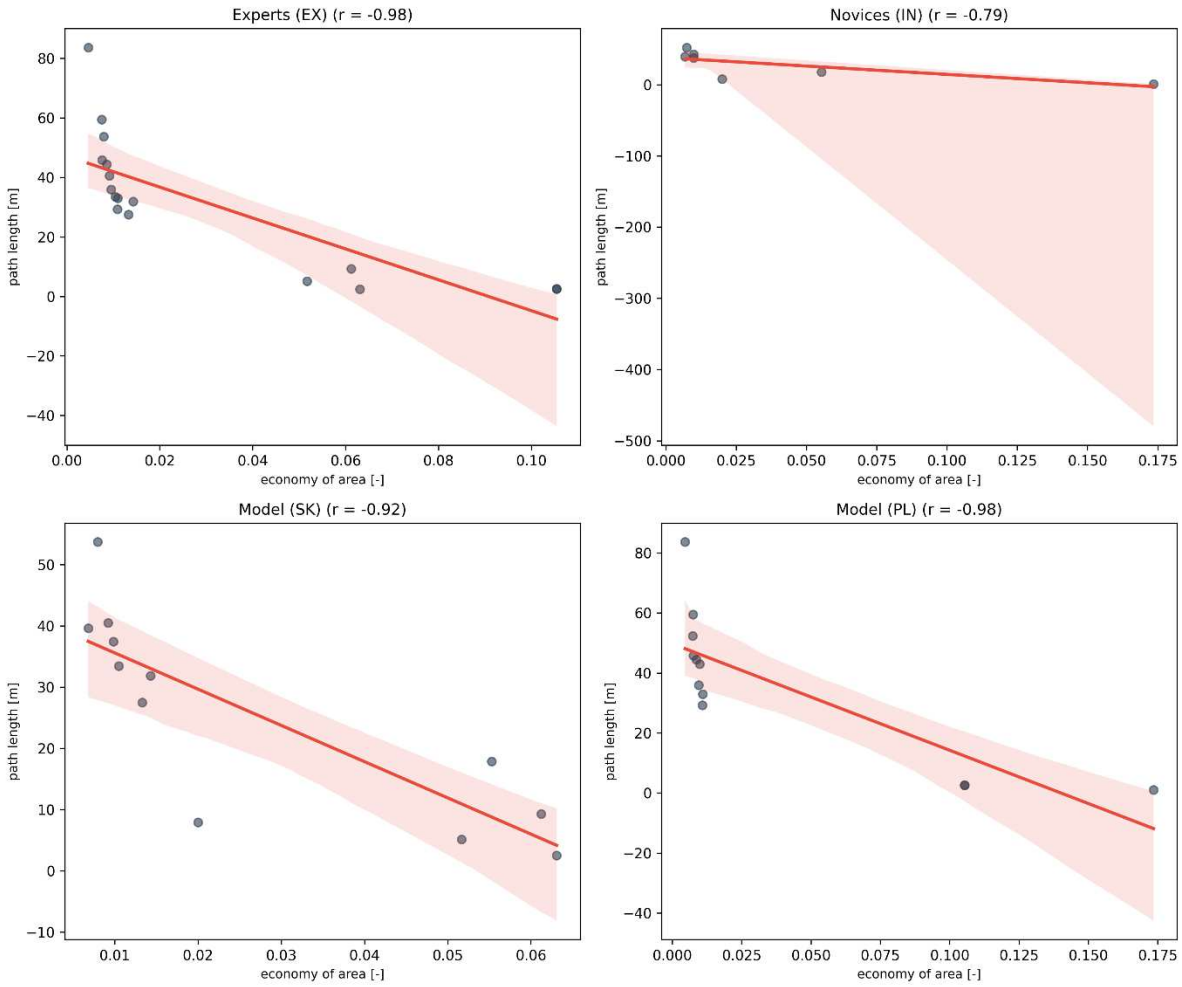


Figure 3. Scatter plots illustrating the correlation between economy of area and total path length. The data are stratified by surgical experience (experts vs. novices; upper panels) and simulation model (model SK vs. model PL; lower panels). The solid red line represents the linear regression fit, while the shaded region indicates the 95% confidence interval. Spearman's rank correlation coefficient (rho) is provided for each subgroup, demonstrating a strong negative relationship that is particularly pronounced in the expert cohort.

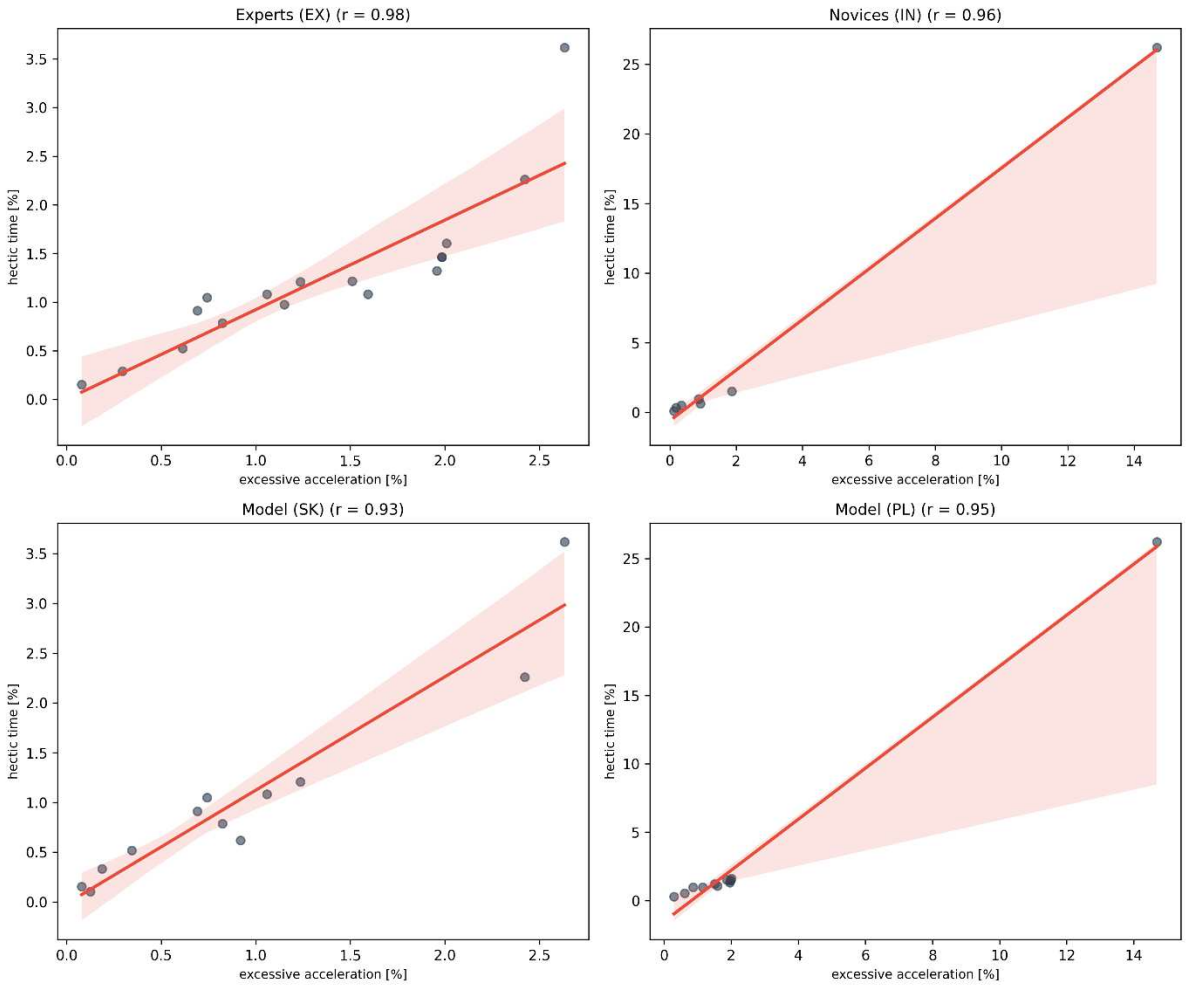
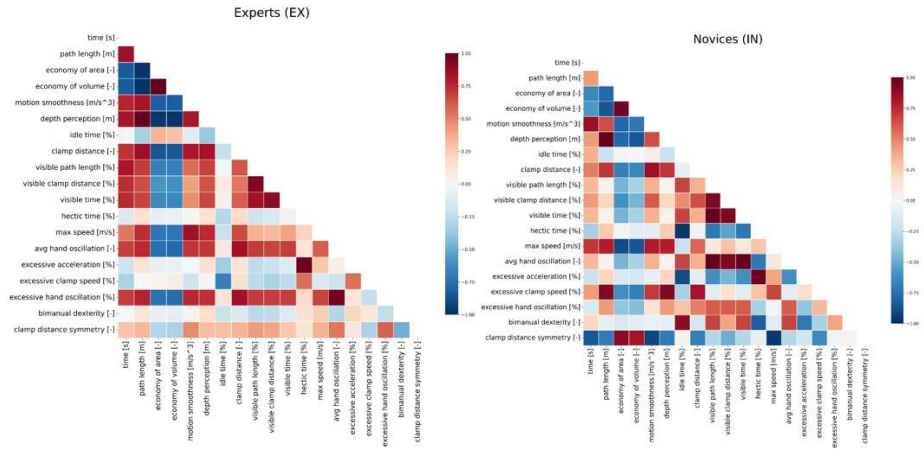


Figure. 4. Scatter plots illustrating the correlation between excessive acceleration and hectic time. The panels display data stratified by surgical experience (experts vs. novices; upper panels) and simulation platform (model SK vs. model PL; lower panels). Solid red lines denote the linear regression fit, with 95% confidence intervals depicted by the shaded areas. A strong positive correlation is consistently observed across all subgroups, as indicated by the corresponding Spearman's rank correlation coefficients (rho).



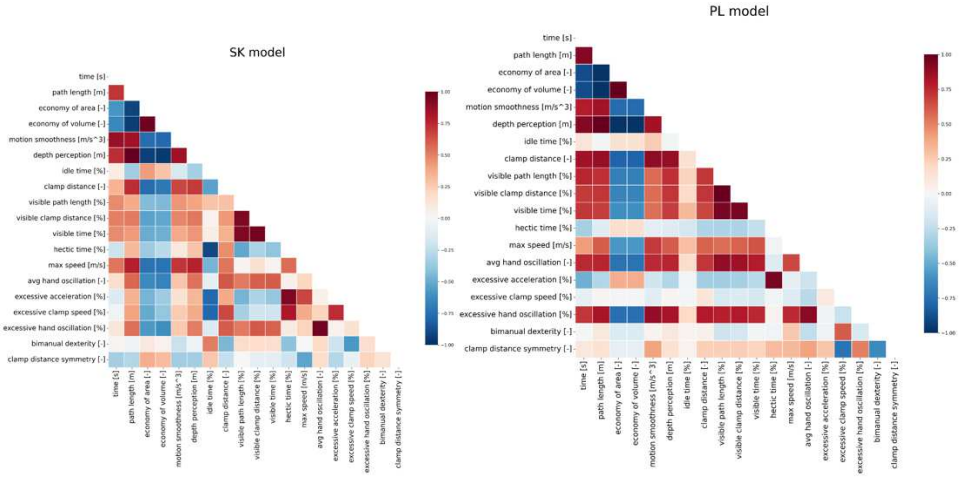


Figure 5. Correlation heatmaps of motion analysis parameters stratified by A, B. surgical experience (experts vs. novices) and C. D, simulation model (model SK vs. model PL). The color gradient reflects Spearman's rank correlation coefficient (rho), ranging from -1.0 (strong negative correlation, dark blue) to 1.0 (strong positive correlation, dark red).

Discussion

Simulation-based training has become an essential component of MIS education, as several previous studies have demonstrated its value for structured skill acquisition, objective performance assessment, and reduction of the learning curve outside the operating room [11], [12], [13], [14], [15], [16], [17] This is particularly relevant in neonatal MIS, where limited case volume, restricted anatomical dimensions, and the need for highly precise tissue handling make conventional intraoperative training insufficient and ethically challenging. In our previous study, we demonstrated that synthetic neonatal models for EA/TEF repair reproduced key procedural steps and provided a realistic platform for structured surgical training, supporting their educational feasibility and procedural relevance. Building on these findings, the present study showed that all measured assessment parameters differed significantly between expert and novice participants, confirming the construct validity of the model and its ability to objectively discriminate between different levels of surgical expertise [4]. Our findings are in agreement with the landmark study by Gallagher et al., which established the discriminative validity of the MIST-VR simulator by demonstrating significant performance differences between novice and expert laparoscopic surgeons across objective psychomotor

metrics. Similarly, our results confirmed that simulation-based assessment reliably differentiates levels of surgical expertise while simultaneously facilitating progressive acquisition of advanced technical skills through repetitive deliberate practice [1]. However, whereas MIST-VR assessed generic laparoscopic psychomotor skills in a virtual environment, our study extends this principle to a high-fidelity, procedure-specific neonatal simulation model that reflects the confined operative workspace, delicate tissue manipulation, complex spatial orientation, and advanced bimanual coordination required for neonatal thoracoscopic surgery. In accordance with prior results, this study showed that all MAPs differed significantly between experts and novices [11], [18]. Our findings are partly consistent with previous motion-analysis studies in laparoscopic simulation, which have shown that experienced surgeons demonstrate superior speed-related parameters, including velocity, acceleration, and jerk, together with more economical instrument use reflected by shorter path length and reduced unnecessary opening and closing of grasping forceps [19], [20], [21]. Similarly, in our study, expert performance was characterized by smoother instrument trajectories and fewer abrupt changes in acceleration, indicating more refined psychomotor control and greater movement fluidity compared with novices. However, in contrast to the study using animal-organ-based simulation, where experts demonstrated shorter path lengths, the distribution of path length in our cohort was comparable between experts and novices [22]. This discrepancy may be explained by the specific technical demands of neonatal thoracoscopic simulation. In our model, expert participants may have performed a greater number of deliberate micro-movements, particularly during precise needle positioning, tissue alignment, and controlled manipulation within a confined neonatal workspace. Therefore, although path length is commonly interpreted as a marker of movement economy, our findings suggest that in highly complex neonatal minimally invasive procedures, path length alone may not fully reflect technical proficiency. Instead, parameters reflecting movement quality, such as jerk,

smoothness, and controlled acceleration, may be more sensitive indicators of expert performance than total instrument travel distance alone. Motion analysis provides a quantitative framework for interpreting technical performance in neonatal minimally invasive surgery, where instrument control must be achieved within an exceptionally confined and anatomically vulnerable operative space. This interpretation is supported by previous motion-analysis studies demonstrating that expert laparoscopic performance is characterized by more efficient instrument trajectories, shorter path length, improved motion smoothness, and better spatial control compared with novice performance. Hofstad et al. reported that expert laparoscopic surgeons outperformed novices in most instrument-motion metrics during animal-organ-based simulation, including parameters reflecting limited movement, bimanual coordination, and motion smoothness [23]. Similarly, Ebina et al. showed that experts demonstrated shorter path length and superior velocity-, acceleration-, and jerk-related parameters during complex wet-lab laparoscopic tasks, supporting the relevance of motion metrics for objective assessment of surgical competency [22]. In our study, parameters related to economy of area and economy of volume appear particularly relevant because the neonatal thoracic cavity provides only a minimal working space around the esophagus. Lower values for these parameters may therefore reflect controlled manipulation within the intended operative corridor, whereas higher values may indicate unnecessary spatial dispersion of movements and a potential risk of inadvertent contact with adjacent structures. This is conceptually consistent with Oropesa et al., who emphasized that motion metrics are complementary and task-dependent, with path length, depth, smoothness, and related parameters reflecting different components of laparoscopic psychomotor skill [20].

In the present analysis, data were evaluated separately for two EA/TEF models and subsequently pooled according to surgical experience.

This study has several limitations. First, the sample size was relatively small and the distribution between experienced and inexperienced participants was unequal, which limited the possibility of robust statistical testing and subgroup analysis. For this reason, the results should be interpreted primarily as exploratory and hypothesis-generating. Second, the study was conducted during a structured laparoscopic workshop, which may have introduced selection bias, as participants were likely to have a specific interest in minimally invasive surgical training. In addition, surgical experience was categorized according to years of practice and self-reported clinical exposure, which may not fully reflect individual technical proficiency in neonatal thoracoscopic surgery. Another limitation is that the simulated task was performed in a controlled training environment using synthetic EA/TEF models. Although these models were previously validated and designed to reproduce key procedural steps of thoracoscopic EA/TEF repair, simulation cannot fully replicate the complexity of live neonatal surgery, including tissue variability, bleeding, respiratory motion, intraoperative decision-making, and the consequences of tissue injury. Therefore, motion-derived performance metrics should be interpreted as indicators of technical instrument handling rather than direct measures of clinical outcome. Furthermore, the 30-min time limit may have influenced task completion and performance patterns, particularly among inexperienced participants. Some participants were unable to complete all procedural steps, which restricted the comparability of motion metrics across the full procedure. Cases with very short procedural duration were excluded after video review because the task had only been initiated and subsequently abandoned, but this may have further reduced the analyzable dataset. The motion-analysis system provided objective quantitative data on instrument movement, including path length, smoothness, speed, acceleration, visibility, and safety-related parameters. However, such metrics capture only selected aspects of surgical performance and do not fully assess procedural judgment, anatomical understanding, quality of tissue handling, or final anastomotic integrity. In addition,

some parameters may be influenced by the physical properties of the simulator, instruments, and trocar resistance rather than by surgical expertise alone. Finally, although the study aimed to explore an expanded set of motion-analysis parameters, the available dataset did not permit calculation of all newly proposed proprietary indicators. Future studies with larger cohorts, standardized procedural completion, independent expert video assessment, and correlation with validated scoring systems such as OSATS, GOALS, or OPRS are needed to further confirm the construct validity and educational value of motion-derived metrics in neonatal minimally invasive surgery training. These limitations are consistent with the exploratory design described in the study, including the small group sizes, unequal distribution, and emphasis on individual performance ranges rather than aggregate statistical comparisons.

Conclusion

One of the key findings of this study is that MAPs can be utilized to significantly enhance MIS training and its effectiveness, especially when evaluated directly by the simulator. The implementation of MAPs allows for the detailed assessment of individual skills and the identification of specific parameters that distinguish experienced from inexperienced practitioners. Furthermore, this data-driven approach enables surgical educators to focus on particular dexterities considered clinically important and to objectively track skill development and learning curves over time.

Despite the relatively small sample size, comparison between experienced and inexperienced participants remained meaningful and demonstrated clinically interpretable differences in motion parameters. However, because the available dataset did not allow calculation of the newly proposed proprietary motion-analysis indicators, this component should be removed from the stated study objectives and presented instead as a potential direction for future research.

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Authors' contributions: PZ, SH and MB contributed to the conception and design of the study, development of the simulation model, data acquisition, interpretation of results, and drafting of the manuscript. ML contributed to data acquisition, analysis, interpretation of results, and manuscript revision. JB contributed to the study design, clinical supervision, interpretation of surgical training outcomes, and critical revision of the manuscript. MM contributed to participant recruitment, data acquisition, and critical revision of the manuscript. SH contributed to the educational and simulation methodology, study coordination, data interpretation, and manuscript revision. FV contributed to simulation methodology, technical implementation, and interpretation of training-related outcomes. AW contributed to motion-analysis methodology, processing of kinematic data, interpretation of motion-derived parameters, and manuscript revision. MK contributed to biomechanical and engineering aspects of the motion-analysis framework, data processing, and manuscript revision. ŠD contributed to study supervision, interpretation of results, and critical revision of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials: The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication: Not applicable. Please confirm before submission.

Ethics approval and consent to participate: Ethical approval was obtained from the Ethics Committee of National Institute of Children's Diseases Bratislava, Slovakia. Written informed consent was obtained from all participants prior to enrolment

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