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Evaluating suturing skill improvement for pediatric minimally invasive esophageal anastomosis model: an observational cohort study based on simulator training

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The study aimed to evaluate the enhancement of minimally invasive surgery (MIS) suturing skills through intensive simulator training, to compare various experimentally measured movement parameters with the established scoring system and to identify movement parameters that may be crucial for achieving proficiency. 55 participants of the intensive practical course of endoscopic surgery in children were included. Training commenced with daily single surgical knot practice, progressed to executing on the final day an anastomosis resembling those performed in esophageal atresia repair. The training effectiveness was gauged by the successful completion of anastomosis. Skills were evaluated by simulator equipped with specialized sensors, which converted data into a set of instrument movement parameters. Additionally, two researchers assessed skills using recorded videos and the objective structured assessment of technical skills (OSATS) questionnaire. Significant improvements in single surgical knot proficiency were noted each day, specifically in metrics: time, movement economy, smoothness, acceleration, instrument activity, and overall score. Strong correlation was observed between automated and human assessments. 48/55 participants attempted anastomosis on the final day, among whom 70% (34/48) attained success (median score 5.1/10, only 16.7% scored above 7/10). Movement economy and instrument distance covered emerged as the most relevant predictors of the anastomosis success. Intensive simulation training significantly enhances endoscopic suturing skills.

Keywords Simulator training, Minimally invasive surgery simulation, Esophageal atresia, Endoscopic suturing, Simulation techniques, Learning curve

Minimally invasive surgical (MIS) techniques offer significant advantages, particularly in pediatric patients, including reduced pain, quicker recovery, decreased hospitalization length, smaller postoperative scars, and fewer thoracic musculoskeletal deformities[1,2].

However, mastering MIS techniques, especially suturing skills for complex procedures, entails a prolonged learning curve and consistent training. Proficiency in MIS suturing enables surgeons to perform a wide array of procedures, including reconstructive surgeries, and manage intraoperative complications without conversion. Notably, thoracoscopic end-to-end esophageal anastomosis in esophageal atresia (EA) exemplifies the highest level of difficulty in MIS suturing[3,4]. In long-gap EA (LGEA) cases and very low birth weight (VLBW) neonates the complexity is compounded by several factors. These include both a significant distance between esophageal pouches and tension, necessitating multi-staged repair in LGEA, as well as constrained surgical space, delicate tissue structure and preterm, VLBW patients' instability, restricting the operative time. The scarcity of EA cases

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limits opportunities for practice, elongating the learning curve. Simulation training emerges as a crucial way for skill development. The most effective simulators for manual skill acquisition should closely mimic natural tissues in both structure and size, thereby representing real surgical conditions[5].

In this study, we assessed the effectiveness of planned intensive simulator training in improving suturing skills, with a focus on exercises involving single surgical knots and anastomosis performance resembling those used in EA repair. The primary objective is to evaluate the improvement of participants' skills and their ability to perform an anastomosis suturing maneuver within a condensed 3–day intensive training period. Furthermore, the study aims to elucidate specific instrument movement parameters that may be crucial for advanced suturing skills. The utilized devices are capable of tracking these parameters, aiding in the assessment of technical skill progress and serving as an objective proficiency measurement system, facilitating skill transfer to the operating theater.

Methods

The study was conducted across three editions of the Intensive Practical Course of Endoscopic Suturing in Children, in the Medical Simulation Center of Wroclaw Medical University in 2021. This series of courses was intended for surgeons from various operative specialties. Both specialists and residents from all around Poland were included. Each course spanned three days of theoretical session and practical exercises on simulators. Two participants were assigned to each endoscopic simulation workstation. Prior to commencing the exercises, researchers provided detailed procedural explanations, supplemented by videos demonstrating optimal task execution. Throughout the course, researchers continuously supervised the correctness of the study exercises.

While the majority of participants had some experience with MIS, not all had prior exposure to endoscopic suturing, and none had experience with thoracoscopic esophageal anastomosis. Participants were categorized according to their level of experience (resident, specialist), reference level of healthcare facility and type of specialization (pediatric surgery, general surgery, urology). In order to establish a baseline proficiency level, all attendees initially demonstrated their existing skills by performing a single surgical knot. This initial assessment served as a benchmark for subsequent skill evaluation. The effectiveness of the course was determined by participants' capacity to successfully complete an end-to-end anastomosis on the third day. The anastomosis performance was appraised as a number of participants who had performed a technically appropriate connection between two pouches.

The course was performed on the Laparo Analytics (LAPARO Sp. z o.o. Poland).

The course commenced with a theoretical session each day, that lasted one and a half to two hours. This part comprised of lectures covering the principles of ergonomics in MIS, instrumentation, suturing techniques, and simulation methodologies, followed by an overview of various laparoscopic and thoracoscopic procedures in the field of pediatric surgery. Subsequent to the theoretical component, trainees participated in a five–hour practical sessions each day.

The course program involved a variety of training tasks, however, to monitor progress throughout the course, we selected a single surgical knot exercise, and the final anastomosis performance (Fig. 1c,d,k,l). All these exercises were meticulously recorded for subsequent evaluation. Additionally, participants performed other tasks according to the course program involving thread manipulation (Fig. 1e,f), rubber band handling (Fig. 1g,h), cone placement (Fig. 1i,j), needle manipulation and rotation, knot tying: square–knot, sliding–knot in vertical and horizontal alignment, tissue preparation, round–shape cutting, suturing: single sutures, continuous sutures, suturing under tension, suturing in limited space. All these exercises were conceptualized and supervised by the first and the last author, who are pediatric surgeons experienced in MIS. The last author (DP) has performed over 400 thoracoscopic EA repairs across various healthcare institutions in Poland and internationally, highlighting the department's proficiency in executing MIS interventions.

The course program included tasks performed on minimally invasive laparoscopic simulators equipped with automatic analysis capabilities. These simulators possess a defined working area with a volume of 2.09 L, determined by the limits of the camera's field of view and the boundaries of the exercise plate. Instrument deviations beyond this designated working area were measured and logged as errors. 5 mm instruments were used throughout the course. The simulators utilize integrated instrument sensors and camera view analysis to track and record instrument movements (Fig. 1a,b). The trocars in these devices are capable of measuring instrument movements at a rate of 10 Hz. The data is recorded for every task and is then processed to derive the following parameters:

1. Overall score.
2. Total exercise time (in seconds) and time score.
3. Economy of movements—a parameter determined by the distance covered by instrument tips and the total number of instrument jaw openings and closures, expressed as a linear correlation.
4. Total distance (in millimeters) covered by instruments and distance score.
5. Smoothness—a parameter based on acceleration, jolt, hand oscillation, and clamp speed.
6. Acceleration—the sudden increase in speed and the derivative of velocity from sensors integrated into the controller of instrument tips.
7. Instrument activity—data derived from sensors integrated into the controller of instrument tips, categorized on the type of activity (inactive, normally active, overactive) and one-hand/ both-hand activities depending on the exercise.
8. Instrument jolt—a rapid tug and the derivative of acceleration based on accelerometer integrated into the trocar.
9. Instrument visibility—a measure of the distance or opening/closure of instruments beyond the camera's recording range, expressed as a score along with the percentage of training time.

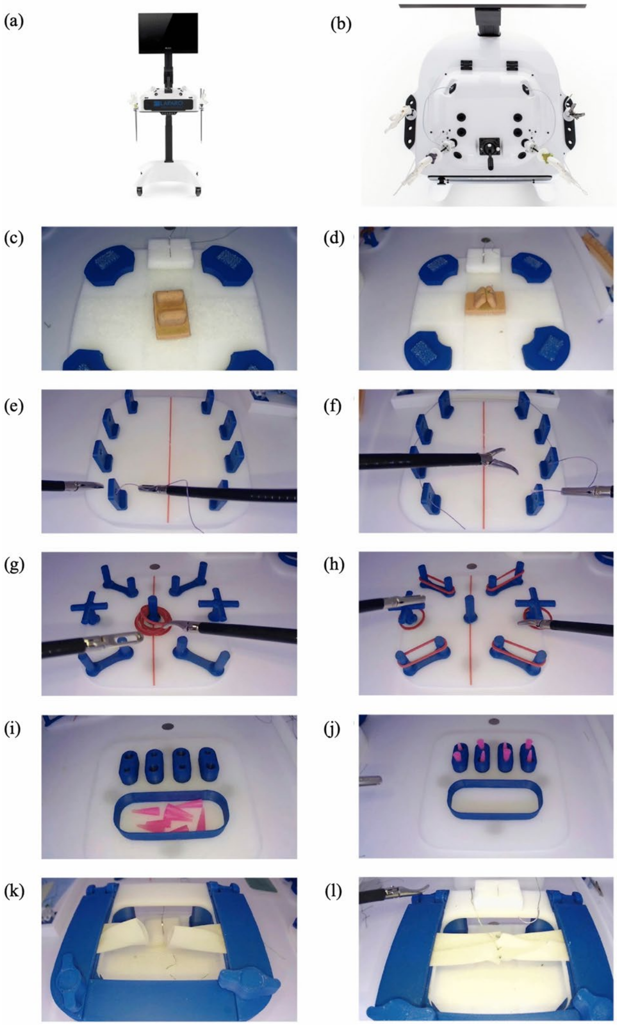


Fig. 1. The picture illustrated training workstations (**a**,**b**) and exercises involved during the course, that are depicted as initial setup and exercise completed: Single Surgical Knot exercise (**c**,**d**), Thread manipulation (**e**,**f**), rubber band training (**g**,**h**), cone placement exercise (**i**,**j**) and anastomosis exercise (**k**,**l**). In this study we focused on the detailed analysis of the single surgical knot and the anastomosis performance.

The scoring models are based on expert recordings and presented as weighted averages of components. Additionally, the Single Surgical Knot and the Anastomosis exercises underwent independent evaluation by two researchers using the recorded videos and the objective structured assessment of technical skills (OSATS) survey principles, as detailed in the literature[6,7]. The OSATS survey encompasses assessments for the following components: Respect for tissue, time and motion, instrument handling, flow of operation, and forward planning[6,7]. Each parameter was assigned a score ranging from 1 to 5. Recordings from both the Single Surgical Knot and the Anastomosis exercises were randomly assessed by the two researchers, who were blinded to the identity of the participants. Subsequently, an arithmetic average of the scores was computed. One of the two researchers who conducted the OSATS survey is a pediatric surgery specialist with experience in MIS, neonatal surgery and simulation. The researcher has served as an instructor during various practical MIS courses in Poland and internationally. The second researcher was experienced in simulation techniques and contributed to the technical and conceptual development of the exercises and the associated educational program.

The initial proficiency level of the trainees was assessed through a preliminary single surgical knot, which every participant performed on the first day following the theoretical session. Subsequently, participants performed the Single Surgical Knot task on each day (Fig. 1c,d), prior to proceed to other exercises delineated in a structured course program. These modules were meticulously designed to ensure consistency and mitigate variance across attempts. Each module featured identical starting needle positions, predefined thread lengths, and standardized target locations for suturing.

On the third day of training, participants attempted to perform an end-to-end anastomosis (Fig. 1i,j) between two segments of a 2–centimeters diameter soft Penrose drain, separated by a distance of 2 cm. The segments of Penrose drain were secured to a specific exercise plate that limited instrument movement to that area. The anastomosis comprised four single sliding–knots applied in a defined sequence and order. The sliding–knot, a spatial form of a square–knot, enables precise tissue approximation and tension adjustment to close tissues with accuracy and in a limited space, that is particularly beneficial in EA repair[8]. The suturing material was 3-0 braided suture, round needle, ½ circle, 22 mm.

The course effectiveness was defined by the enhancement of technical competencies necessary to perform the anastomosis. The success of the anastomosis was evaluated based on the number of participants who achieved technically appropriate connection between the two pouches, adhering to predefined principles.

A statistical analysis was performed in STATISTICA v. 13.3 (TIBCO Software Inc., Palo Alto, Ca, USA). Verification of the normality of quantitative variables was performed using the Shapiro–Wilk test. Quantitative variables were reported as medians (*Me*) and quartiles (*Q1* and *Q3*) due to non-normal distributions, while qualitative variables (success of anastomosis performance) were collected in contingent tables as numbers (*n*) and percentages (%). Quantitative variables were compared using the Kruskal–Wallis test, while categorical variables were compared using the chi-square test or the Fisher exact test. Continuous and ordinal variables were converted to dichotomous variables according to ROC curves analysis. A chance for successful anastomosis performance depending on specific movement parameters was obtained using odds ratio (OR). The Spearman's rank correlation coefficient and the Pearson's linear correlation coefficient were used to assess the dependence strength. $P < 0.05$ were considered statistically significant.

This study was approved by the Ethics Committee of Medical University in Wroclaw with the Approval Code of 169/2022 and Approval Date 24.02.2021. All methods were performed in accordance with the relevant guidelines and regulations. Informed consent was obtained from all subjects of the study.

Conference presentation

It is based on a previous communication to a society during IPEG & ESPES Congress 2023, which took place in Sorrento, Italy in July 2023. All authors have complete access to the study data that support the publication.

Results

The study involved 55 participants—36 representatives of pediatric surgery, 13 general surgeons, and 6 urologists. In terms of qualifications there were 40 trainees and 15 specialists/consultants. Not all participants attended the course on all training days. The final test was attempted by 48 (87%) participants. In addition, some trainings, due to technical errors, were not recorded and it was not possible to evaluate them. Therefore, the number of participants for whom the evaluation was conducted on each training day was 54, 43, and 51 for days 1, 2, and 3, respectively, as presented in the (Fig. 2).

The OSATS—analytic correlation

A moderate, but statistically significant positive correlation was observed between the automatic Analytic scores for the Single Surgical Knot performance (the Overall Score) and the average OSATS assessments conducted by two researchers. A one-unit increase in the Analytic Overall Score corresponded to a 0.5—point increase in the Researchers' score (Fig. 3).

A statistically significant positive correlation was also identified between the OSATS scores assigned by two researchers for the evaluation of the Single Surgical Knot exercise (Fig. 4).

The single surgical knot task

The results for the Single Surgical Knot task were measured using automatic simulator analysis. The Table 1 provided a comparison of performance metrics for the Single Surgical Knot exercise during three consecutive days with associated statistical significance levels. These results indicate significant improvements in various performance metrics for the Single Surgical Knot task, highlighting the effectiveness of the training course (Table 1, Fig. 5).

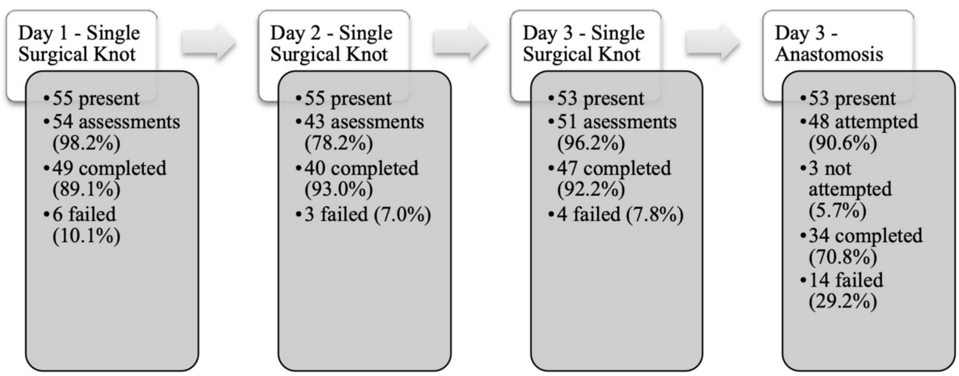
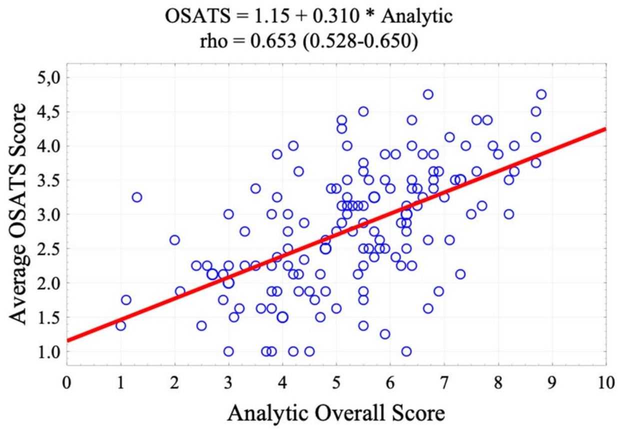


Fig. 2. The flow chart presented data on course participation, showing the total number of attendees present during each day of the course, the number of assessments collected, and the outcomes of the trainees—highlighting those who completed the task successfully (%) and those who did not (%).



Training day	rho	95% CI	*r*	95% CI
1st	0.497	(0.267 - 0.674)	0.485	(0.252 - 0.665)
3rd	0.574	(0.355 - 0.734)	0.577	(0.359 – 0.736)
1st and 3rd	0.653	(0.528 - 0.750)	0.650	(0.525 - 0.748)

Fig. 3. The figure depicted correlation diagram of the Single Surgical Knot performance assessments made by simulator analysis and by two researchers. The correlation coefficient ρ was 0.653 (0.528–0.650). ρ–Spearman's rank correlation coefficient, r–Pearson's correlation coefficient, 95% CI 95% confidence interval for the correlation coefficient.

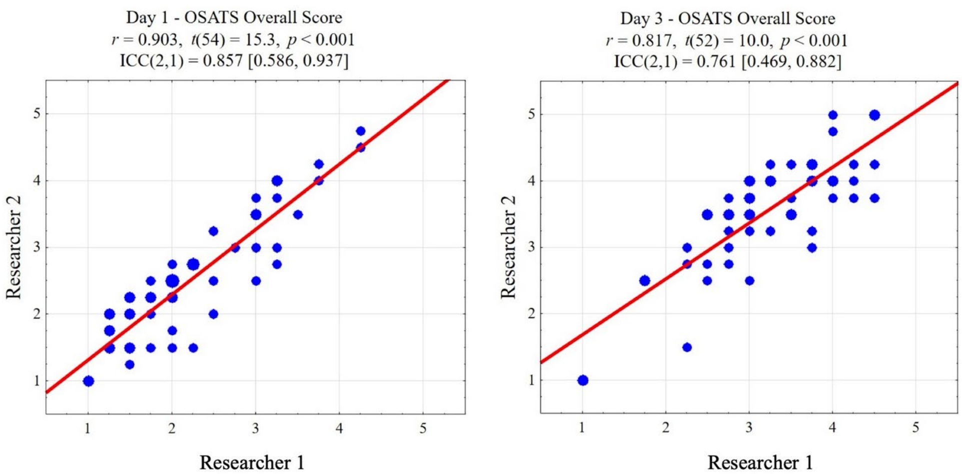


Fig. 4. The figure illustrated scatter plot of average scores given by two researchers for performing the single surgical knot task on day 1 and day 3 of the course, as well as the value of the Pearson correlation coefficient r and the ICC coefficient.

The final end-to-end anastomosis

The final assessment selected to evaluate the course effectiveness was the anastomosis exercise performed on the 3rd day. 48 participants (87.3%) attempted the exercise. Among them, 34 participants (70.8%) successfully completed the anastomosis. The median of the overall analytic score was 5.1/10. Notably, 29.2% attained the overall analytic score of more than 6/10, while 16.7% achieved scores exceeding 7/10 (Table 2).

Parameters indicating the probability of the anastomosis performance success

The successful Anastomosis performance was not correlated with level of participants' experience, reference level of healthcare facility, as well as type of specialization, as pointed out in the (Table 3).

An odds ratio was computed to assess the likelihood of the successful Anastomosis, based on the results obtained from the single surgical knot exercises performed on the 1st and the 3rd days. Interestingly, none of the movement parameters recorded on the 1st day Single Surgical Knot exercise demonstrated a significant impact on the success of the Anastomosis, as presented in the (Table 4). In contrast, during the 3rd day Single Surgical Knot exercise, both OSATS and Analytic parameters exhibited significant predictive value for determining the success of the Anastomosis performance. Notably, several parameters, including economy of movement,

Single surgical knot	Day 1 N = 54	Day 2 N = 43	Day 3 N = 51	Day 1 vs Day 2 *p*-value	Day 2 vs Day 3 *p*-value	Day 1 vs Day 3 *p*-value
Overall (score)	4.4 (1.4)	5.6 (1.8)	6.0 (1.4)	**0.002**[a]	0.192[b]	**< 0.001**[b]
Time (score)	0.9 (1.9)	1.7 (2.5)	3.5 (2.8)	**0.035**[b]	**0.001**[b]	**< 0.001**[b]
Time (seconds)	859 (455)	665 (337)	435 (138)	**< 0.001**[b]	**< 0.001**[b]	**< 0.001**[b]
Economy of movement (score)	5.2 (2.5)	6.7 (2.9)	8.3 (1.7)	**0.003**[a]	**0.004**[b]	**< 0.001**[a]
Distance (score)	3.1 (3.3)	5.3 (3.9)	7.3 (2.5)	**0.001**[a]	**0.016**[b]	**< 0.001**[a]
Distance (mm)	33.1 (18.9)	24.1 (17.1)	15.9 (6.4)	**0.001**[b]	**0.008**[b]	**< 0.001**[b]
Smoothness (score)	5.6 (2.0)	6.5 (2.0)	6.4 (1.8)	0.132[a]	0.742[a]	**0.001**[b]
Acceleration (score)	5.2 (2.8)	6.5 (2.5)	6.3 (2.5)	**0.037**[b]	0.793[a]	**0.007**[a]
Jolt (score)	7.1 (1.7)	7.6 (2.3)	7.6 (1.8)	0.221[b]	0.872[a]	**0.034**[a]
Activity (score)	4.4 (2.3)	5.4 (2.3)	5.1 (1.9)	0.075[a]	0.610[a]	**0.004**[b]
Visibility (score)	5.8 (3.3)	7.0 (3.1)	6.5 (3.5)	0.068[a]	0.742[b]	0.198[a]
Visible (%)	95.1 (5.1)	96.2 (5.5)	95.9 (4.9)	0.058[b]	0.988[b]	0.188[b]

Table 1. The table presented the results for the single surgical knot exercise using automatic simulator analysis with analyzed instrument movement parameters. The comparison between the results on day 1 and day 3 with statistical significance levels (*p*-values). *N* corresponds the number of participants who attempted the exercise. Mean (SD), [a]t-test for paired sample, [b]Wilcoxon test.

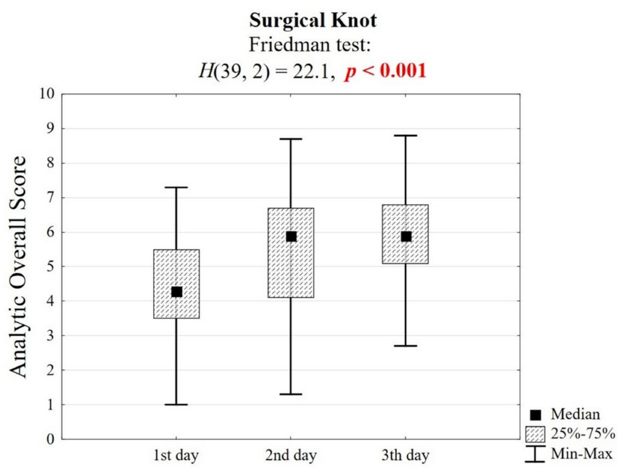


Fig. 5. The image illustrated the analytic overall score results for the single surgical knot task across the first, second, and third days of the course, highlighting the median, quartiles (*Q1–Q3*), minimum and maximum values, as well as the results of the significance test.

distance, Jolt and OSATS time and motion emerged as the most influential factors determining the probability of success, as detailed in the Table 5 and illustrated in the (Fig. 6).

Discussion

The aim of this study was to evaluate the enhancement of MIS suturing skills through intensive, practical simulator training, to compare various experimentally measured movement parameters with the established scoring system and to identify movement parameters that may be crucial for achieving proficiency. A task indicative for advanced proficiency level was the End–to–End Anastomosis exercise imitating the esophageal pouch connection in EA repair.

The most substantial progress among all exercises performed over the three-day period was achieved in the Single Surgical Knot task. While considering the movement parameters, measured by simulator analysis, significant enhancements were evident in the majority of them. Certain components of motion smoothness, such as accelerations, oscillations, and high instrument clamp speed seem to be particularly characteristic among less advanced in MIS techniques surgeons[9,10]. The literature also reported a higher frequency of excessive force events among intermediate and novice practitioners, thus force application may serve as an indicator of competence[11,12]. Arguably, these ones may be attributed to a reduced sense of depth perception and indirect haptic feedback in MIS compared to open surgery, that requires practice to acquire experience[13,14]. Over the course of training, such cumbersome movements have becoming increasingly rare, emphasizing the importance of differentiated exercises utilizing materials closely imitating natural tissues in both structure and size[15].

The assessment of simulator analysis	
The anastomosis exercise (Score range 0–10 for parameters expressed as scores)	**Day 3**
	***N* = 48, *Me (Q1–Q3)* value**
Overall (score)	5.1 (4.3–6.3)
Time (score)	4.7 (2.8–8.1)
Time (seconds)	2287 (1632–2768)
Economy of movement (score)	7.1 (5.4–9.3)
Distance (score)	6.1 (3.8–9.4)
Distance (millimeters)	63.2 (47.8–92.4)
Smoothness (score)	6.2 (5.5–7.8)
Acceleration (score)	6.3 (5.5–8.3)
Jolt (score)	7.6 (6.5–8.7)
Activity (score)	5.5 (4.5–7.0)
Visibility (score)	2.5 (0.0–4.9)
Visible (%)	89.5 (68.8–94.9)
The assessment of two researchers according to OSATS survey	
The anastomosis exercise (Score range 1–5 for parameters expressed as scores)	**Day 3**
	***N* = 48, *Me (Q1–Q3)* value**
Overall OSATS score	2.2 (1.5–3.6)
Task success	
No	14 (29.2%)
Yes (one rater)	1 (2.1%)
Yes (both raters)	33 (68.8%)
Respect for tissue (score)	2.5 (2.0–3.0)
Time and motion, (score)	2.0 (1.3–3.8)
Instrument handling (score)	2.5 (1.5–3.5)
Flow of operation and forward planning (score)	2.5 (1.0–4.0)
Number of knots completed	4 (1–4)
0	4 (8.3%)
1	3 (6.3%)
2	5 (10.4)
3	2 (4.2%)
4	34 (70.8%)

Table 2. The Anastomosis quality in the assessment of simulator analysis and in the assessment of two researchers with OSATS survey. Medians (*Me*) and quartiles (*Q1–Q3)*.

Variable	Performing the anastomosis				*p*-value	OR [95% CI]
	Yes N = 34		No N = 21			
Level of experience:						
Specialist, n (%)	11	(32.4)	4	(19.0)	0.359	2.03 [0.55; 7.49]
Resident, n (%)	23	(67.6)	17	(81.0)		1.00 (ref.)
Reference level of healthcare facility:						
Large, n (%)	24	(70.6)	12	(57.1)	0.386	1.80 [0.58; 5.61]
Small, n (%)	10	(29.4)	9	(42.9)		1.00 (ref.)
Type of specialization:						
Pediatric surgery, n (%)	20	(58.8)	16	(76.2)	0.116	0.78 [0.21; 2.86]
Urology, n (%)	6	(17.7)	0	(0.0)		8.41 [0.39; 181]
General surgery, n (%)	8	(23.5)	5	(23.8)		1.00 (ref.)

Table 3. The table illustrated the number (proportion) of course participants in the groups differing in the success of the Anastomosis according to the level of experience, the reference level of healthcare facility and the type of specialization. The analysis involved the entire population of participants.

1st day—single surgical knot results	Anastomosis performance success		*p*-value	OR (95% CI)
	Yes (N = 34)	No (N = 14)		
Analytic overall ≥ 3.1 scores	31 (91.2%)	10 (71.4%)	0.171	4.13 (0.78–21.7)
Analytic time ≥ 7.1 scores	1 (2.9%)	0 (0.0%)	1.000	–
Time < 714 s	20 (58.8%)	5 (35.7%)	0.255	2.57 (0.71–9.33)
Analytic economy ≥ 3.6 scores	25 (73.5%)	9 (64.3%)	0.522	1.54 (0.41–5.85)
Analytic distance ≥ 2.7 scores	19 (55.9%)	6 (42.9%)	0.615	1.69 (0.48–5.93)
Distance < 16.1 mm	6 (17.6%)	1 (7.1%)	0.656	2.79 (0.30–25.6)
Analytic smoothness ≥ 5.6 scores	17 (50.0%)	4 (28.6%)	0.174	2.50 (0.65–9.55)
Analytic acceleration ≥ 7.5 scores	11 (32.4%)	1 (7.1%)	0.081	6.21 (0.72–53.7)
Analytic jolt ≥ 8 scores	15 (44.1%)	2 (14.2%)	0.095	4.74 (0.92–24.5)
Analytic activity ≥ 6.0 scores	12 (35.3%)	2 (14.2%)	0.181	3.27 (0.63–17.1)
Analytic visibility ≥ 0.2 scores	32 (94.1%)	11 (78.6%)	0.140	3.44 (0.57–20.7)
Tools visible ≥ 87.4%	33 (97.1%)	11 (78.6%)	0.069	9.00 (0.85–95.7)
Average OSATS ≥ 2.25 scores	20 (58.8%)	5 (35.7%)	0.255	2.57 (0.71–9.33)
OSATS task success ≥ 1	33 (97.1%)	12 (85.7%)	0.200	5.50 (0.46–66.3)
OSATS task understanding = 2	13 (38.2%)	3 (21.4%)	0.328	2.27 (0.53–9.70)
OSATS respect for tissue ≥ 2	30 (88.2%)	10 (71.4%)	0.208	3.00 (0.63–14.3)
Time and motion ≥ 3.0	10 (29.4%)	2 (14.3%)	0.465	2.50 (0.47–13.3)
Instrument handling ≥ 2.5	15 (44.1%)	5 (35.7%)	0.830	1.42 (0.39–5.14)
Flow of operation and forward planning ≥ 3.0	13 (38.2%)	4 (28.6%)	0.741	1.55 (0.40–5.97)

Table 4. The number (proportion) of course participants in the groups differing in the success of the Anastomosis and the results of exercises on the first day of the course, the results of independence tests and odds ratios (OR). The movement parameters were quantified using receiver operating characteristic (ROC) curve analysis. Continuous and ordinal variables were transformed into dichotomous variables, allowing for the generation of ROC curves to evaluate the probability of successful anastomosis.

Our study revealed that the course effectively improved technical skills in MIS for surgeons irrespectively of their prior experience. Interestingly, the achievement of threshold scores for specific movement parameters during the 3rd day Single Surgical Knot significantly influenced the final success of the Anastomosis and the majority of participants performed the acceptable anastomosis after just a few days of intensive training according to predefined principles. We evaluated the trainees rigorously and every deviation in performance or task understanding lowered the final score. Although the course was effective in suturing skills improvement, only a subset of trainees attained the anastomosis at an advanced level, emphasizing the relevance of regular practice and continuously repeated suturing maneuver.

The investigation prompts inquiry into the specific, quantifiable distinctions in instrument movements among novice, intermediate, and expert practitioners[5,16]. Our findings highlight the significance of the movement economy scores and the absolute distance covered by instruments in influencing the final success with anastomosis performance. This may underscore the key role of movement economy in distinguishing between surgeons of varying skill levels and may be attributed to purposeful, deliberate movements, minimal errors, and uninterrupted transition between procedural steps, ultimately leading to reduced task completion time[16]. While McDonald et al. pointed out operative time as a primary metric for learning curve evaluation, our study identified OSATS Time and Motion parameter as a relevant factor in predicting the anastomosis success[17]. Notably, the reduction in operative time does not actually hinge on swifter movements. In the realm of MIS techniques and advanced newborn procedures, precision and slow motion are paramount due to reduced operative space, magnified visualization, and the risk of tissue injury. Therefore, the most sophisticated skills seem to underly in minimizing unnecessary maneuvers to achieve a balance between procedure time and precision. The evolution of simulation techniques appears promising in identifying specific movement components, that can be directly enhanced through targeted training programs and exercises[18]. It is worth highlighting those complex exercises encompassing multiple steps and offering various completion pathways, can foster forward planning abilities, non-technical skills and movement economy among trainees[19].

Our study focused on the improvement in the suturing skill over the intensive training course. The suturing maneuver includes some essential sub-components, contributing to the overall proficiency in suturing:

- Needle manipulation in 3D space with 2D view perception;
- Thread manipulation and understanding of its properties such as stiffness and memory;
- Familiarity with knot tying technique and their mechanical properties to ensure reliable closure;
- Haptic perception and tissue respect to apply minimal force to overcome tissue resistance while maintaining tissue integrity[11,12].

3rd day—single surgical knot results	Anastomosis performance success		*p*-value	OR (95% CI)
	Yes (*N* = 33*)	No (*N* = 14)		
Analytic overall ≥ 7.0 scores	12 (36.4%)	0 (0.0%)	**0.009**	–
Analytic time ≥ 3.2 scores	23 (69.7%)	4 (28.6%)	**0.012**	5.75 (1.45–22.8)
Time < 432 s	23 (69.7%)	4 (28.6%)	**0.012**	5.75 (1.45–22.8)
Analytic economy ≥ 9 scores	20 (60.6%)	1 (7.1%)	**0.001**	20.0 (2.33–172)
Analytic distance ≥ 7.8 scores	22 (66.7%)	2 (14.3%)	**0.001**	12.0 (2.28–63.3)
Distance < 14.9 mm	20 (60.6%)	1 (7.1%)	**0.001**	20.0 (2.33–172)
Analytic smoothness ≥ 7.4 scores	14 (42.4%)	1 (7.1%)	**0.020**	9.58 (1.12–82.1)
Analytic acceleration ≥ 4.7 scores	25 (75.8%)	7 (50.0%)	0.100	3.12 (0.84–11.6)
Analytic jolt ≥ 8.7 scores	15 (45.5%)	1 (7.1%)	**0.017**	10.8 (1.27–92.7)
Analytic activity ≥ 4.5 scores	23 (69.7%)	8 (57.1%)	0.621	1.72 (0.47–6.28)
Analytic visibility ≥ 8.7 scores	17 (51.5%)	2 (14.3%)	**0.024**	6.37 (1.23–33.0)
Tools visible ≥ 98.7%	17 (51.5%)	2 (14.3%)	**0.024**	6.37 (1.23–33.0)
Average OSATS ≥ 3.25 scores	28 (82.4%)	5 (35.7%)	**0.005**	8.40 (2.06–34.2)
OSATS task success = 2	30 (90.9%)	11 (78.6%)	0.344	2.73 (0.48–15.6)
OSATS respect for tissue ≥ 3	28 (84.8%)	6 (42.9%)	**0.010**	7.47 (1.80–31.0)
Time and motion ≥ 3	31 (93.9%)	8 (57.1%)	**0.005**	11.6 (1.96–68.9)
Instrument handling ≥ 3.5	26 (78.8%)	4 (28.6%)	**0.002**	9.29 (2.23–38.7)
Flow of operation and forward planning ≥ 3.5	25 (75.8%)	11 (78.6%)	**0.023**	5.63 (1.45–21.7)

Table 5. The number (proportion) of course participants in the groups differing in the success of the Anastomosis and the results of exercises on the third day of the course, the results of independence tests and odds ratios (OR). The movement parameters were quantified using ROC curve analysis. Continuous and ordinal variables were transformed into dichotomous variables, allowing for the generation of ROC curves to evaluate the probability of successful anastomosis. *$N = 47$ because one person was not assessed for a 3rd day—surgical knot but has made the anastomosis.

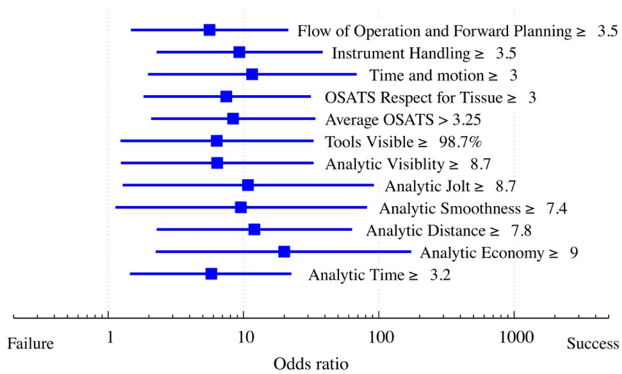


Fig. 6. The figure highlighted odds ratios (and 95% confidence intervals) of anastomotic success depending on the level of exercise performance scores on the 3rd day of the course.

Theoretical principles of suturing techniques, coupled with regular practical exercise on simulators, may facilitate learning optimization. While the three-day course revealed a consistent growth in suturing skill, it did not elucidate the current point of an individual learning-curve and the time required to achieve proficiency. The study's observational time constitutes a limitation. The strong side of the study is a relatively large cohort of surgeons of different specialties, with some experience in MIS techniques and motivated to learn. Uecker et al. reported the significant impact of the learning curve on surgical outcomes, underscoring the importance of efforts to minimize its effects on patient care[20].

The next issue to discuss is that the optimization of surgical skill training encounters some major challenges, primarily the necessity for a supervisor. In our study, we utilized both automatic simulator assessment, possible due to specific instrument sensors, and unified scoring of OSATS methodology. While the automatic simulator analysis focused on instrument movement parameters, time and distance, it did not evaluate the correctness of exercise performance, indicating its inability to fully replace human assessment. Conversely, OSATS is rather tailored for real surgeries assessment, offering parameters to evaluate familiarity with procedures and surgeon confidence, however with limited focus on suturing and instrument movement events. Wei Ch et al.

suggested the utility of the Moorthy checklist and laparoscopic skill competency assessment tool (LS–CAT) in laparoscopic suturing[21]. These metrics seem to correlate with the OSATS and could be an adjunct to OSATS for skill development. Nevertheless, our research revealed a strong positive correlation and coherence between scores generated by simulator analysis and those obtained from researchers' observation, as well as significant consistency between observations of both researchers. The combined use of these measuring tools suggests that simulation analysis could complement the expert assessment in the objective evaluation of MIS skills before transferring them into the operating theater[18]. Moreover, simulation analysis offers the potential for supervised distance training or even tele-mentoring, thereby expanding the scope of certificated MIS education programs[22,23].

Similarly, the literature reported that training on simulators can be an effective method to develop surgical endoscopic skills, especially in suturing[24–26]. Nowadays, various types of simulators exist, including those based on tissue-like materials, anatomically accurate organ models[27,28], and virtual reality simulators of complete surgical procedures[29,30]. However, training on tissue-representative models appears to be particularly advantageous for developing manual surgical competency. Deie K et al. highlighted the utility of disease-specific physical simulators, especially for pediatric surgeons dealing with rare conditions in newborn surgery[31]. Hong D et al. reported that the patient-specific, realistic 3D–printed phantom for video assisted thoracoscopic surgery (VATS), based on chest computed tomography, may offer a more comprehensive understanding the complex anatomical structures[32].

A systematic, comprehensive, and structured program of MIS education is prominent[27,33–35]. Such program may facilitate the transfer of skills acquired during simulation exercises to real surgical scenarios, along with potential impact on patient outcomes[31,33,34,36]. It should be noted that both technical skills improved during simulator training, and non-technical competencies such as decision-making impact on the surgical performance, thus effort should be made to develop all of them[35,37]. Bauman et al. emphasized that short training courses contribute to improvement in the perception of surgical skill and confidence, and 'exposure' courses play a role in skill maintenance[31,34,38].

Notably, one–third of the participants who attempted the Anastomosis were unsuccessful, and within this group, one–third did not perform any sliding–knot during the exercise. Among the participants who did not complete the Single Surgical Knot od Day 1, only two attendees (30%) succeeded in the final Anastomosis. However, no significant differences were found concerning their experience, the reference level of their healthcare facility, or the type of specialization. Consequently, it is essential to implement comprehensive and regular MIS training from the onset of surgical education, in conjunction with open surgery training, encompassing both large and small healthcare facilities, as well aa every type of surgical specialties.

The limitation of our study is that the simulator and materials utilized for performing anastomosis did not precisely replicate the conditions encountered during EA/TEF repair in newborns. This simplified model was designed to enable participants to practice the technical skills required for end-to-end anastomosis using the sliding-knot technique within a constrained space. The setup involved segments of Penrose drain secured to a designated exercise plate, which limited instrument movement to this specific area. While this model effectively reflects the principles of MIS suturing techniques, a more accurate EA/TEF model that closely resembles the conditions of actual surgery may provide a more reliable method of transferring skills to the operating theatre and fully realize the advantages of simulator training. Additionally, a limitation of the study is the small sample size.

Intensive simulation training significantly enhances MIS skills, particularly in the realm of endoscopic suturing. Advanced simulator tools such as instrument movement analysis and motion-tracking may be useful to distinguish between surgeons of different expertise[9–12,16]. Deliberate selection of appropriate exercises can also effectively improve specific instrument movement parameters, thereby facilitating advanced suturing skill development. Furthermore, the accessibility of simulator training, suturing education, and certified courses may broaden the applicability of minimally invasive procedures, including reconstructive surgeries. This would expand the range of indications for MIS over open surgery across various surgical departments and enhance proficiency in managing rare surgical diseases.

Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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Author contributions
DB contribution comprised: conceptualization, methodology, validation, formal analysis, investigation, visualization, writing—original draft, writing—review and editing. AW contribution comprised: software, formal analysis, investigation, resources, data curation, visualization. DP contribution comprised: conceptualization, methodology, investigation, validation, visualization, supervision and project administration.

Declarations

Competing interests
The authors declare no competing interests.

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