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Klok, J. W., Rahimi, M., Postema, R., Hardon, S., Bonjer, H. J., Daams, F., Dankelman, J., & Horeman, T. (2026). Effects of dynamic training on learning curves and skill transfer in a force-based laparoscopic task. *Minimally Invasive Therapy and Allied Technologies*. https://doi.org/10.1080/13645706.2026.2732156

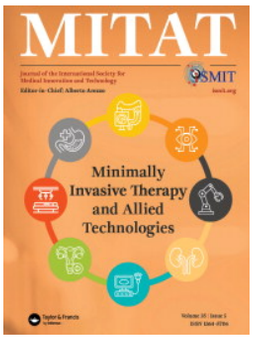
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Minimally Invasive Therapy & Allied Technologies

ISSN: 1364-5706 (Print) 1365-2931 (Online) Journal homepage: www.tandfonline.com/journals/imit20

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To cite this article: Jan-Willem Klok , Masie Rahimi , Roelf Postema , Sem Hardon , Hendrik Jaap Bonjer , Freek Daams , Jenny Dankelman & Tim Horeman (14 Oct 2026): Effects of dynamic training on learning curves and skill transfer in a force-based laparoscopic task, Minimally Invasive Therapy & Allied Technologies, DOI: 10.1080/13645706.2026.2732156

To link to this article: https://doi.org/10.1080/13645706.2026.2732156

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https://doi.org/10.1080/13645706.2026.2732156

ORIGINAL ARTICLE

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Effects of dynamic training on learning curves and skill transfer in a force-based laparoscopic task

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ABSTRACT

Background: Laparoscopic training is essential for developing safe and effective surgical skills. While most training tasks are performed in static environments, intra-abdominal conditions are inherently dynamic due to physiological motion. Although dynamic training may therefore enhance skill acquisition and transfer, its effects on force-based laparoscopic tasks remain unclear.

Methods: In this randomized controlled study, 18 novices performed a force-based wire chaser task in a laparoscopic box trainer. Participants were assigned to a Static or Dynamic training group. The Dynamic group trained on a moving platform, while the Static group trained without movement. All participants completed four training trials, followed by a dynamic test and a static test. Four key objective performance metrics (time, mean non-zero force, maximum force, and path length) were recorded. Primary analyses compared between-group differences. Secondary analyses assessed within-group learning (trial 1 vs 4) and transition effects (trial 4 vs dynamic and static tests).

Results: No significant differences between groups were observed at the predefined primary assessment points and both groups demonstrated significant learning effects during training. Transition analyses showed that participants trained statically exhibited increased force application and movement when performing the dynamic test, whereas no significant transition effects were observed in the Dynamic group. Conversely, limited improvements were observed when transitioning to the static task. Data distribution suggested that a subset of participants in the Dynamic group achieved relatively high performance during the dynamic test.

Conclusions: In this study, dynamic training did not result in superior overall performance compared to static training in this force-based task. However, it may influence learning strategies and adaptability, particularly for a subset of learners. Dynamic training may therefore serve as a complementary modality to increase task complexity and adaptability. Future research should investigate long-term effects on skill acquisition and explore the urgency for dynamic tasks in laparoscopic training curricula.

ARTICLE HISTORY
Received 18 May 2026
Accepted 1 August 2026

KEYWORDS
Dynamic training; intraoperative motion simulation; laparoscopic skills training; minimally invasive surgery; objective performance assessment

Introduction

Laparoscopic surgery requires extensive training to acquire proficiency in essential technical and procedural skills [1,2]. It is desirable to train these skills first in a safe simulation environment prior to performing on real patients in the operating room. Well-developed motor skills are related to a reduction in manipulation forces and completion time, which positively influence patient safety, complication rates, and healthcare costs [3,4].

Current laparoscopic training curricula incorporate various modalities, including box trainers, virtual reality or digital trainers, wet lab training, and proctoring. Practicing laparoscopic skills on a box trainer remains one of the most widely used training methods [5]. Extensive research has been conducted on the validation and learning curves associated with box trainers [6,7]. However, these studies primarily focus on static training tasks, while little research has been done on dynamic training tasks with objective parameters. Furthermore,

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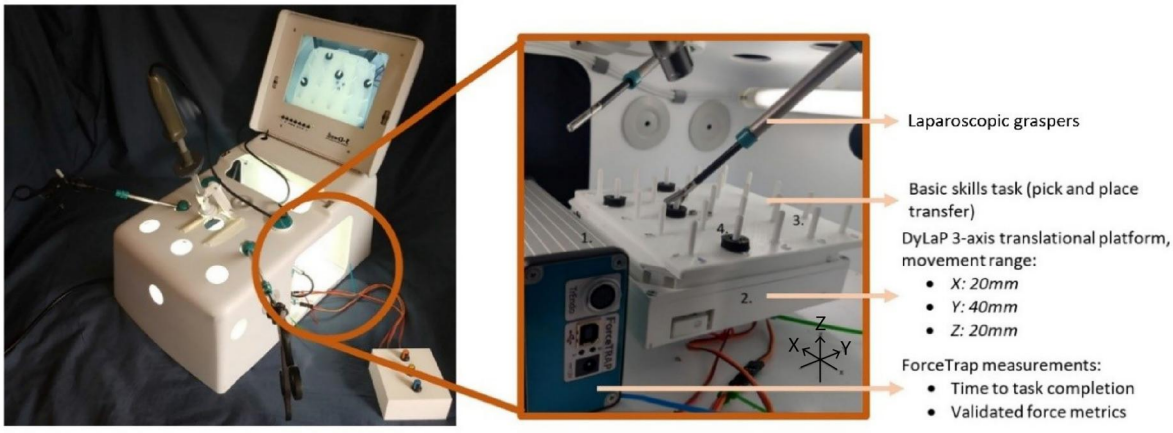


Figure 1. DyLaP integrated in the boxtrainer as used in the feasibility study.

ideally, learning curves and proficiency are assessed using a combination of both expert feedback and objective parameters: force measurements (tissue manipulation and instrument interaction forces), motion (efficiency), and time [5,8–11]. By introducing a moving platform, trainees are challenged to further develop their hand-eye coordination, depth perception, and bimanual dexterity. This approach allows all existing training tasks to be converted into dynamic training tasks, adding an extra level of difficulty.

To this end, the Dynamic Laparoscopic Platform (DyLaP, Figure 1) was previously developed and validated in a recent feasibility study [12]. It showed that skills acquisition is significantly different between statically trained novices and dynamically trained novices. The study was performed with a position-based peg transfer task, requiring only short instances of physical contact between the instruments and the task. However, these tasks are fundamentally different from force-based tasks that focus on the acquisition of tissue handling skills, as precise task motion mimicking during grasping is important at all times, while there is also the continuous need to apply sufficient grasping force in order to satisfy the skill parameters regarding time, force and movement [1,8]. A dynamic force-based task requires multi-tasking, which might increase mental load compared to a dynamic position-based task. Both task types are crucial for developing a comprehensive motoric skill set for laparoscopic surgery [13,14]. Therefore, the influence, relevance and impact of dynamic training in force-based tasks warrants further investigation.

Additionally, during laparoscopic procedures, the abdominal cavity is not static, as the targeted tissue is often moving [15,16]. Tissue movement has various causes and can be categorized into two groups: induced by tissue-instrument interaction (1) and induced by physiological processes in the patient (2). The motion due to tissue-instrument interaction is predictable, as it is mostly caused by the surgeon. Motion induced by physiological processes is more challenging to predict. The different tissue structures in the abdominal cavity repetitively move due to lung, heart and bowel movements, combined with unexpected motions caused by muscle contractions [17]. In surgery, respiratory motion has been identified as an important factor, especially for organs and tissues near the diaphragm [18–20]. For example, measurements of hepatic motion during deep inspiration showed a maximum amplitude of 55 mm, while liver tumors have been observed to move up to 35 mm [16,21]. During laparoscopic surgery, sudden and deep respiratory inspiration can occur. These motions stress the need for realistic and dynamic training environments.

The aim of this study was to analyze learning curves and transition effects when comparing a force-based, intermediate-level laparoscopic training task performed in both static and dynamic settings. By introducing a dynamic training environment, we aimed to add an additional dimension of difficulty and more closely mimic the conditions encountered in the abdominal cavity.

Based on the findings of the first DyLaP study, we hypothesized that training in a dynamic environment would lead to improved performance compared to static training, particularly in tasks requiring adaptation to motion. Furthermore, we expected that training in a dynamic environment would result in more favorable transition effects when participants were exposed to both dynamic and static test conditions.

Materials and methods

Study background

In preparation for this study, a video recording of a preparatory step during a liver resection was analyzed.

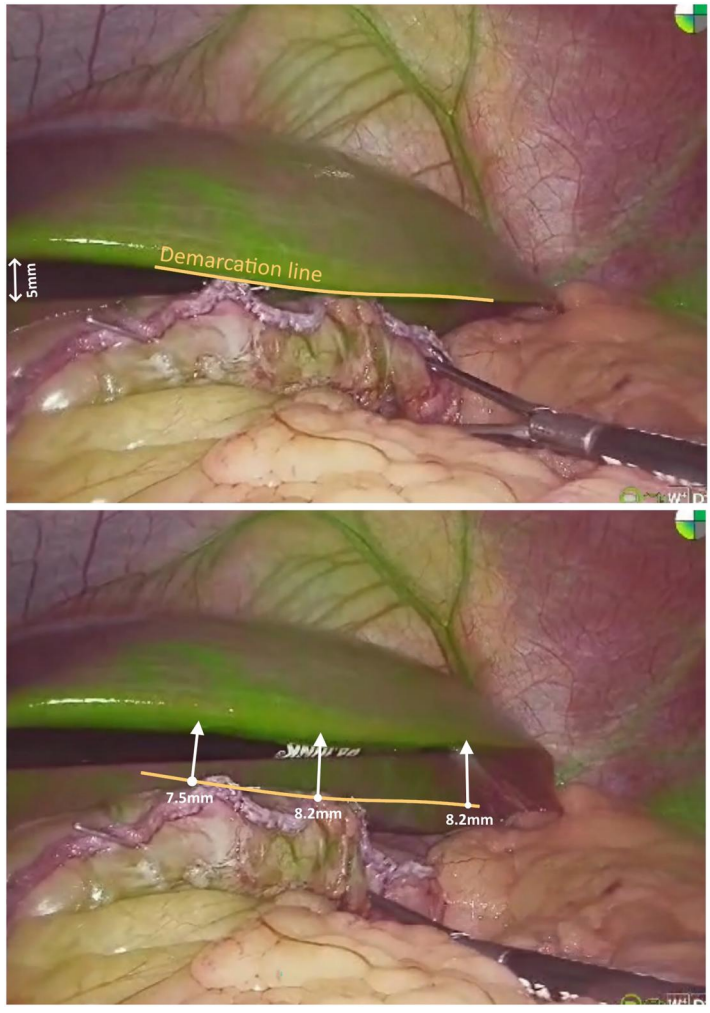


Figure 2. Representative laparoscopic video stills illustrating physiological liver motion. The upper image shows the reference position, whereas the lower image shows the maximum observed displacement used to estimate the motion amplitude applied in the DyLaP platform.

The known instrument diameter (5 mm) was used to determine the image scale. The analysis showed that, close to the diaphragm, liver tissue moved up to 8.3 mm in a direction parallel to the camera's image plane due to cardiac motion (Figure 2). Consequently, during this step, the instrument tip should follow the hepatic motion. In the video, the instrument tip moves with a maximum amplitude of 7.8 mm. Organ movements have a substantial impact on instrument movement.

Participants

The participants were recruited from the Dutch Surgical Society for Medical Students (VCMS). Eighteen participants were available for this study. Participants were required to have no prior experience with laparoscopic skills training and surgery. The study took place at the Amsterdam Skills Centre for Health Sciences (ASC).

System and materials

The DyLaP was mounted inside the Lapron box-trainer (ForceSense B.V., Delft, The Netherlands) on the ForceTRAP 3D force sensor (ForceSense B.V., Delft, The Netherlands) with a bracket (Figure 3a). The wire chaser task was mounted on the top of the DyLaP. The ForceTRAP measured the resultant interaction force transmitted from the laparoscopic instruments to the complete DyLaP and wire chaser assembly. Force measurements were corrected for the weight of the DyLaP and task assembly, such that the reported forces reflected interaction forces applied during task execution rather than the static load of the setup. The box trainer provided feedback

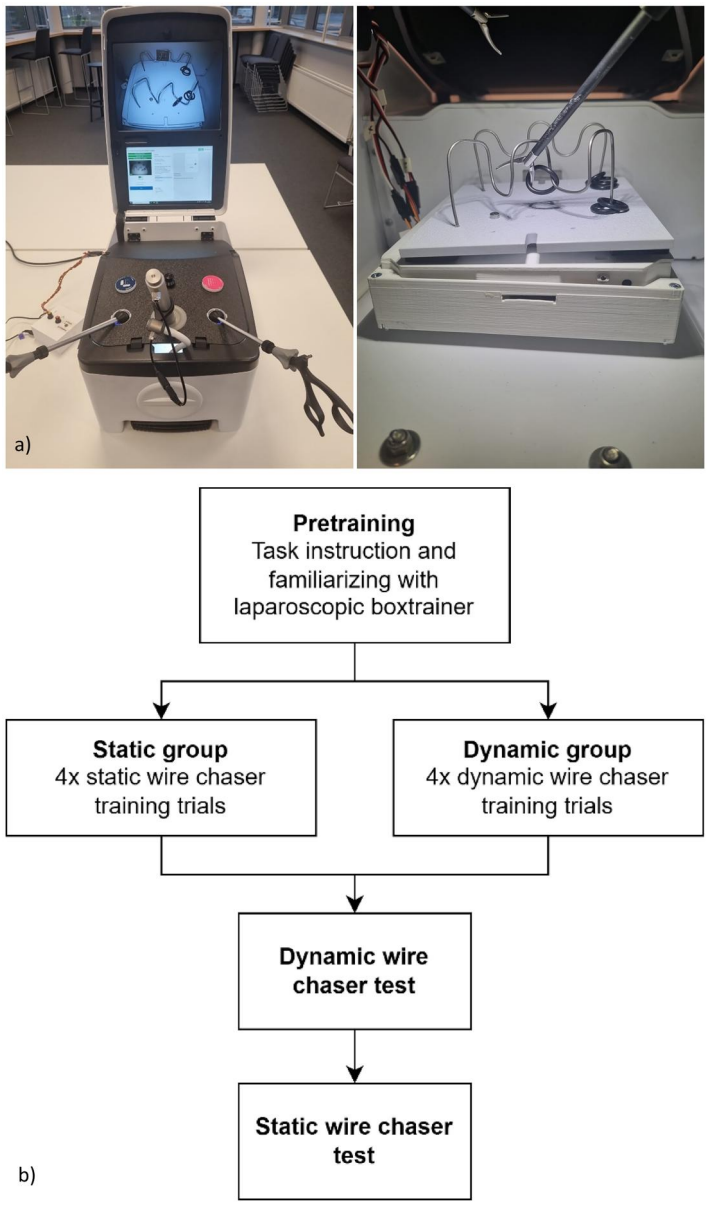


Figure 3. Experimental setup and study protocol. (a) The Lapron box trainer equipped with the DyLaP and the wire chaser task. (b) Overview of the randomized study design, including pretraining, four training trials, a dynamic test, and a static test.

on objective metrics of force (tissue manipulation), motion, and time (efficiency). Four key performance parameters (time to completion, mean non-zero force, maximum force, and path length) were selected for analysis, as they represent core aspects of laparoscopic performance, including efficiency, motion control, and tissue interaction [2,8]. For the experiments, the DyLaP movement was characterized by a three-dimensional asymmetric sinusoidal motion with a maximum amplitude of 41.5 mm. The tasks were performed using two curved Maryland grasping forceps (Aesculap, B. Braun, Melsungen, Germany).

Study protocol

A randomized controlled trial (RCT) study design was used (Figure 3b). Written informed consent was acquired from the participants and participation was voluntary. They were randomly divided into two groups: the static group and the dynamic group. Both groups were instructed on the use of the box trainer and allowed to perform a short pre-training to familiarize with the box trainer and the wire chaser task, during which they were instructed on how to use the instruments and execute the task. Then all participants performed four training trials, followed by a dynamic test and a static test. During the training

trials in the dynamic group, the wire chaser task, mounted on the DyLaP platform, was moved in an asymmetric sinusoidal pattern, requiring participants to continuously adapt their instrument movements to the task motion. In contrast, the DyLaP remained stationary in the static group. Participant age and sex data were collected. The aforementioned objective performance parameters were measured, representing tissue manipulation and instrument handling skills [1,8]. The study design was approved under Human Research Ethics Committee (Delft University of Technology HREC) application number 132767.

Statistical tests

The data were collected in the ForceSense online database (ForceSense B.V., Delft, The Netherlands). Data from the ForceSense software were analysed using RStudio (Posit Software, Boston, MA). Primary analyses assessed between-group differences at three predefined assessment points: the first trial and the dynamic and static tests in the post-training phase. Secondary analyses assessed within-group learning effects from training trial 1 to trial 4 and transition effects from trial 4 to the dynamic and static test conditions. Normality of the data was assessed using the Shapiro–Wilk test and visual inspection of Q–Q plots. As the data were normally distributed, descriptive statistics are presented as mean ± standard deviation. However, given the small sample size, non-parametric tests were used for inferential analysis. Between-group differences were assessed using the Wilcoxon rank-sum test (Mann–Whitney U test), while within-group comparisons were assessed using the Wilcoxon signed-rank test. To account for multiple comparisons, p-values were adjusted using the Holm–Bonferroni method. Differences were considered statistically significant if $p < 0.05$.

Results

There were 18 participants (12 females and six males, mean age 20.8, standard deviation 1.34) included in the study. All participants had no experience in

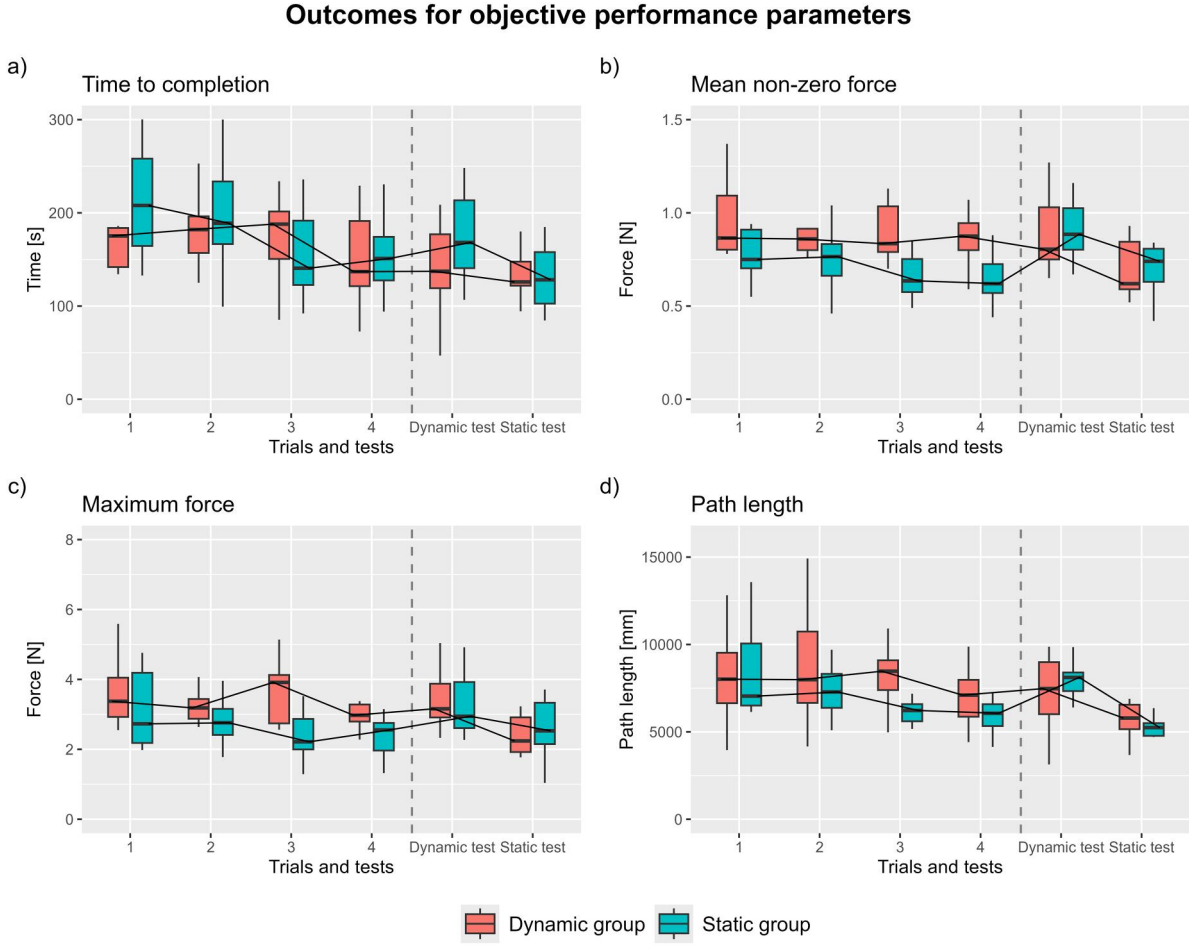


Figure 4. Learning curves and post-training test performance for the four objective performance parameters. Boxplots show time to completion (a), mean non-zero force (b), maximum force (c) and instrument path length (d) objective performance parameters.

surgical training. Figure 4a–d shows the learning curve as well as the dynamic and static test results for selected objective performance parameters (time to completion, mean (non-zero) force, maximum force and instrument path length). The means and standard deviations of all outcome parameters are reported in Table 1.

Primary outcomes

No significant differences between the Static and Dynamic groups were observed at the predefined primary assessment points (first trial, dynamic test, and static test) for any of the evaluated parameters (Table 1).

Secondary outcomes

Within-group learning and transition effects were identified in the secondary analyses. Learning effects are presented in Table 2. Improvement of skill was evaluated by comparing the results of the first and last (fourth) training trial. Participants in the Static group showed significant improvements ($p < 0.05$) in time to completion, maximum force, mean non-zero force and path length. In the Dynamic group, significant improvements were observed in the mean non-zero force. Improvements were observed across more of the evaluated parameters in the Static group compared to the Dynamic group.

The effects of transition to the dynamic task execution were obtained by comparing the fourth training trial and the dynamic test results (Table 2). In the Static group, a significant increase was observed in maximum force, mean non-zero force, and path length. These findings indicate a significant increase in force application and instrument movement in the Static group. There were no significant differences in the Dynamic group. As a result, performance levels during the dynamic test were comparable between groups.

Effects of dynamic task execution on static performance were obtained by comparing the last training trial and the static test. A significant decrease was observed in time to completion in the Static group. In the Dynamic group, there was a significant difference in mean non-zero force.

Notably, the lower quartile for time to completion and path length extended further in the Dynamic group during the dynamic test, suggesting that a subset of participants achieved relatively high-performance levels.

Table 1. Descriptive statistics of the objective skills parameters (means and standard deviations) and between-group comparisons of the objective performance parameters (p-value, unpaired wilcoxon tests).

Parameter	Group	Trial 1	Trial 2	Trial 3	Trial 4	Dynamic test	Static test	p-value		
								Trial 1	Dynamic test	Static test
Time [s]	Static	211.4 ± 57.1	199.2 ± 57.8	155.4 ± 45.2	153.8 ± 38.8	176.5 ± 50.3	131.6 ± 34.1	0.298	0.298	0.880
	Dynamic	175.9 ± 63.0	182.6 ± 63.6	172.7 ± 47.1	149.0 ± 49.8	142.3 ± 48.5	137.5 ± 54.1			
Maximal force [N]	Static	3.77 ± 2.56	2.77 ± 0.97	2.45 ± 0.92	2.37 ± 0.62	3.25 ± 0.90	2.61 ± 0.85	0.608	0.650	0.608
	Dynamic	3.58 ± 0.93	3.29 ± 0.57	3.68 ± 0.93	2.98 ± 0.57	3.38 ± 0.89	2.54 ± 0.91			
Mean non-zero force [N]	Static	0.89 ± 0.45	0.76 ± 0.16	0.65 ± 0.12	0.64 ± 0.13	0.90 ± 0.16	0.73 ± 0.18	0.289	0.545	0.545
	Dynamic	0.96 ± 0.20	0.90 ± 0.15	0.90 ± 0.16	0.86 ± 0.14	0.89 ± 0.19	0.69 ± 0.16			
Path length [mm]	Static	8522.6 ± 2720.3	7345.0 ± 1366.6	6022.5 ± 939.4	5892.8 ± 1048.0	8043.2 ± 1565.1	5249.8 ± 920.7	0.880	0.880	0.870
	Dynamic	8261.1 ± 2562.1	8765.7 ± 3175.3	8386.7 ± 2076.3	7262.7 ± 2085.2	7284.7 ± 2162.2	5952.9 ± 1683.7			

Table 2. Within-group comparisons of the objective performance parameters (p-value, paired Wilcoxon tests). Bold value indicates significant effect ($p < 0.05$).

Objective skills parameter	Group	Trial 1 versus Trial 4	Trial 4 versus Dynamic test	Trial 4 versus Static test
Time to completion	Static	**0.007**	0.114	**0.033**
	Dynamic	0.285	0.482	0.508
Maximal force	Static	**0.028**	**0.025**	0.169
	Dynamic	0.059	0.333	0.185
Mean non-zero force	Static	**0.037**	**0.014**	0.126
	Dynamic	**0.038**	0.838	**0.030**
Path length	Static	**0.007**	**0.014**	0.114
	Dynamic	0.333	0.959	0.057

Discussion

The aim of this study was to investigate the effects of static and dynamic training on laparoscopic task performance. No significant differences between the groups were observed at the predefined primary assessment points, including baseline performance, the dynamic test, and the static test. The initial hypothesis that dynamic training would lead to improved overall performance compared to static training was not supported by the results. However, within-group analyses demonstrated learning effects during the training phase, and transition effects when moving from training to testing conditions. The expected favourable transition effects of dynamic training were only partially supported. While no overall performance differences between groups were observed, additional insight can be gained by examining the transition from dynamic training to the static test condition. In the static test, the static group showed improvements in time to completion and path length, whereas the dynamic group showed changes primarily in force-related parameters. These findings do not indicate a clear advantage of dynamic training but rather suggest that training under different conditions may lead to distinct adaptation strategies.

In this study, the novices performed a wire chaser task. This task requires continuous anticipation of movement, in contrast to the task in the first DyLaP study [12]. When training with a static task and switching to a dynamic task, participants exhibited a significant increase in force application and movement, likely as they adapted to the added challenge of motion. This indicates a clear difference in task difficulty between static and dynamic conditions. However, the relevance of this difference for laparoscopic training curricula remains unclear. The increase in force and motion parameters observed in the static group when transitioning to the dynamic condition primarily reflects adaptation to increased task demands, rather than an absolute deterioration in performance. Notably, these values approached those observed in the dynamic group during training. In contrast to the findings in the earlier pick-and-place task, where dynamic training showed beneficial effects, no overall performance advantage of dynamic training was observed in the present study. Therefore, the question of whether dynamic training provides added value for laparoscopic skill acquisition remains inconclusive.

These findings suggest that the effectiveness of dynamic training may depend on the type of task. Future training setups should aim to incorporate more realistic and clinically relevant scenarios, for example tasks that mimic surgical procedures in anatomically constrained regions such as near the diaphragm. This also suggests that untrained novices may be challenged by unexpected motion, which could be particularly relevant for tasks requiring precise tissue handling, such as needle driving.

Although the Dynamic group showed descriptively shorter completion times in several training trials, no statistically significant between-group differences were observed. Moreover, this pattern was already apparent during the first training trial, suggesting that baseline variation may have contributed. Completion time should therefore be interpreted alongside force and path length.

Although no overall between-group differences were observed, the distribution of performance outcomes suggests that dynamic training may benefit a subset of participants more strongly. This is reflected by lower quartile values for time to completion and path length during the dynamic test in the Dynamic group, indicating that some participants achieved relatively high-performance levels. This finding aligns with principles from motor learning and skill acquisition, where individuals may adopt different strategies and adapt at different rates when exposed to increased task complexity or variability. Dynamic training may impose higher cognitive and sensorimotor demands, potentially facilitating more effective skill transfer for certain individuals, while others may

require a more gradual progression. Such inter-individual variability has been described in motor learning literature [22,23], where variability in practice can enhance adaptability but does not uniformly benefit all learners. This may partly explain why no significant differences were observed at the group level, despite indications that dynamic training can lead to superior performance in a subset of participants. These findings are consistent with motor learning theories on variable practice and contextual interference, which suggest that increased variability may enhance adaptability and transfer, but does not uniformly improve short-term performance [24–26]. In short, individuals might benefit from more challenging or accelerated training paths.

This interpretation is supported by recent findings [27], which showed improved transfer after a workload-adapted training protocol with progressively increasing task difficulty. Together, these findings suggest that future dynamic laparoscopic training protocols may benefit from adapting task difficulty to the learner, consistent with principles from motor learning.

Both groups demonstrated learning effects for force, motion, and time parameters. In the Static group training, significant improvements were observed across both efficiency-related parameters (e.g. time to completion and path length) and force-related parameters, whereas in the Dynamic group, improvements were primarily limited to force-related measures. This pattern may suggest that the dynamic training task imposes higher cognitive and sensorimotor demands, resulting in novices prioritizing a limited subset of objective performance parameters, such as force control, over efficiency-related metrics.

However, alternative explanations should be considered. The dynamic training task may inherently constrain opportunities to improve efficiency due to its time-varying nature, or differences in measurement sensitivity and baseline performance may have influenced the observed patterns. Additionally, the prioritization of force control may reflect a safety-driven strategy rather than solely increased mental load.

Strengths and limitations

Several limitations should be considered. Firstly, the sample size was relatively small, resulting in limited statistical power to detect between-group differences. This should be considered when interpreting outcomes for which no statistically significant differences were observed. While consistent trends were observed across several performance measures, future studies including larger cohorts are warranted to confirm these findings and provide greater statistical power to detect between-group differences. Also, the study included novices, potentially limiting the generalizability of the findings to intermediate-level and expert-level trainees and to clinical practice. Secondly, multiple objective performance parameters were analysed, increasing the risk of type I error despite correction procedures. Thirdly, the study was conducted in novices using a simplified task, which may limit generalizability to clinical practice.

In addition, the dynamic task likely imposed a higher cognitive load on participants, requiring increased attention and continuous adaptation. This increased task demand may partly explain the observed differences in learning patterns between groups, as higher cognitive load can both facilitate skill acquisition through increased challenge and constrain performance, particularly in novice learners. However, cognitive load was not directly measured in this study, limiting the ability to disentangle its role in the observed effects.

Despite these limitations, this study has several strengths. It combines a dynamic training platform with the analysis of a comprehensive set of objectively measured force, motion, and time parameters, providing a detailed assessment of laparoscopic performance showing the risk related to unexpected movements on task execution. Furthermore, the study builds on previous work validating the DyLaP setup and extends this by investigating force-based task performance. Finally, the presented platform offers a flexible and reproducible method to introduce dynamic conditions into existing dry-lab training tasks, which may facilitate further research into adaptive and task-specific training strategies.

Future research

Our studies introduce a versatile dynamic training platform on which any dry lab task can be adapted to increase training difficulty. While dynamic training should not replace static training, our findings suggest it may have potential as a complementary training modality for laparoscopic training curricula, to increase task complexity and promote adaptability. However, this study is exploratory and did not focus on long-term effects and potential benefits of dynamic training. In future research this should be investigated. Future studies should include both surgical trainees and experienced surgeons to establish

reference performance levels, determine whether responses to task motion differ with expertise, and assess whether the observed learning and transition patterns generalize beyond novice users. Also, it might be beneficial for effective laparoscopic training curricula to foster appropriate motion strategies for manual motion tracking [28] through task design. More research is needed to translate this to laparoscopic skills training.

An interesting avenue for future research is the potential presence of a responsive subgroup within the dynamic training cohort. While no overall between-group differences were observed, the outcome distributions suggest that some individuals may benefit more strongly from dynamic training. Further studies could aim to identify such participants early in the learning process, for instance through baseline performance profiling or adaptation patterns. If reliably distinguishable, these individuals might profit from more demanding or accelerated training tracks. This could make laparoscopic training more efficient and personalized, which is a relevant goal given the time-intensive nature of current curricula. However, such applications remain speculative and require dedicated investigation.

Moreover, future research should focus on training tasks in which failure to adequately respond to unexpected motion can lead to clinically relevant risks. For example, tasks such as suture driving with large needles may result in unintended tissue puncture when motion is not properly compensated. Incorporating such high-risk, motion-sensitive tasks could further evaluate the value of dynamic training in improving surgical safety.

Conclusion

This study investigated the effects of static and dynamic training on laparoscopic task performance in novices using a force-based training task. No significant differences between groups were observed at the predefined primary assessment points. However, both groups demonstrated learning effects, and transition analyses revealed that static training was associated with increased force application and movement when switching to a dynamic task.

These findings suggest that dynamic training does not lead to superior overall performance compared to static training in this task but may influence how skills are acquired and applied. Notably, performance distributions indicated that a subset of participants may benefit more strongly from dynamic training, potentially reflecting differences in motor learning strategies and adaptability.

Dynamic training may therefore have value as a complementary training modality, particularly for increasing task complexity and promoting adaptability to changing conditions. However, its role within laparoscopic training curricula remains inconclusive. Future research should focus on long-term effects, individual learning trajectories, and the use of more clinically representative training tasks.

Author contributions

CRediT: **Jan-Willem Klok**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft; **Masie Rahimi**: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing; **Roelf Postema**: Conceptualization, Methodology, Writing – review & editing; **Sem Hardon**: Writing – review & editing; **Hendrik Jacob Bonjer**: Writing – review & editing; **Freek Daams**: Writing – review & editing; **Jenny Dankelman**: Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing; **Tim Horeman**: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

A dataset of this study is available at 4TU Researchdata repository (DOI: https://doi.org/10.4121/078413f5-c739-48d7-a664-2acb2557bec4)

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