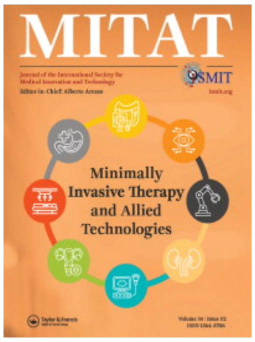

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ORIGINAL ARTICLE

The impact of simulated intra-abdominal movement on basic laparoscopic skills development: a feasibility study

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ABSTRACT

Background: Laparoscopic surgery requires a complex set of motor skills. Currently, basic laparoscopic skills training is performed in a static environment, while intraoperatively, abdominal tissue is often moving. The aim of this study was to develop a dynamic training platform and evaluate its impact on laparoscopic skills acquisition in a box trainer.

Methods: The Dynamic Laparoscopic Platform (DyLaP) includes a moving base which has been intergrated with the Lapron box trainer and the ForceSense objective measurement system. Dynamic training was evaluated in a comparative study where novices were divided into a static and dynamic training group, performing six training trials of a peg transfer task with the DyLaP. Afterwards, both groups performed a dynamic exam task. Task manipulation (force) and instrument efficiency (path length and time) were measured.

Results: Participants ($n = 12$) exhibited a significant difference ($p < 0.05$) in time, path length, and maximum force between the static and dynamic groups in the first trial. Learning curves were most prevalent in the dynamic group.

Conclusions: The DyLaP can be used to provide a challenging and realistic training environment. From the comparative peg transfer study, it can be concluded that dynamic training significantly affects laparoscopic skill acquisition. More research is needed to evaluate dynamic training effects in force-based training tasks.

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KEYWORDS
Minimally invasive surgery; laparoscopic skills training; intraoperative motion simulation; learning curve analysis; box trainer

Introduction

The evolution of surgical training has shown significant advancements since the advent of laparoscopic surgery, requiring the development of specialized skills in a minimally invasive environment to foster safe tissue handling. Traditional laparoscopic box trainers have long been a cornerstone in the acquisition of these skills, providing a static and controlled environment for trainees to practice and refine their techniques [1–4]. However, these static models fall short in replicating the dynamic nature of the intra-abdominal environment encountered during actual surgeries [5].

Intra-abdominal movements, including respiratory fluctuations, peristaltic waves, and patient-specific anatomical variations, present significant challenges during laparoscopic procedures [6,7]. Organ movements up to 55 mm can alter the position and orientation of organs, requiring surgeons to constantly adjust their techniques in real time. In robotic surgery, respiratory motion has been identified as a factor of importance, leading to the development of respiratory compensation algorithms for the performance of safer surgeries [6,7]. Several studies have quantified the motion of various organs in the abdominal cavity. Movement is predominant in tissue proximal to the diaphragm. A study involving magnetic resonance imaging-based motion tracking found that, when at rest, hepatic motion caused by respiratory action can reach up to 34 mm in the cranial-caudal direction [8]. Measurements of hepatic motion during deep inspiration showed a maximum amplitude of 55 mm [9,10], while it has been shown that liver tumors can move up to 35 mm [11]. The variability of the

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surgical environment is further compounded by differences in patient physiology, such as body mass index (BMI), age, and the presence of underlying conditions, which can impact tissue compliance and visibility [12]. Consequently, the static nature of traditional laparoscopic trainers fails to adequately prepare trainees for these dynamic conditions.

To address this issue, we introduce a novel laparoscopic box training system utilizing a dynamic platform designed to simulate intra-abdominal movements. This innovative approach aims to bridge the gap between static training models and the dynamic, unpredictable nature of live surgery, which demands not only a certain level of technical skill but also the ability to adapt and respond. We expect that exposure to a training environment that closely simulates the movement in real surgical conditions will improve the trainee's ability to handle the complexities of laparoscopic procedures more effectively than traditional static models. The aim is to enhance the preparedness and confidence of trainees in handling the intricate and dynamic nature of laparoscopic surgery, resulting in higher levels of technical skills at the end of training.

The dynamic platform should integrate motion control technology to mimic various intra-abdominal scenarios, such as respiratory movements and peristaltic waves, offering a more realistic and challenging training environment [13], whilst using real instruments that provide realistic haptic feedback.

The aim of the study is to develop a dynamic training platform and evaluate its effectiveness in enhancing the acquisition of laparoscopic skills in a box trainer.

Material and methods

Design

For the dynamic platform, we collaborated with expert surgeons to establish the following Design Requirements:

1. The platform should be suitable for various basic laparoscopic skill training tasks such as the peg transfer, zig-zag loop, wire chaser, and flap task;
2. The platform should move the training task in a box trainer in all three translational directions with a minimum amplitude of 20 mm and at least one degree of freedom with a minimum amplitude of 40 mm;
3. To simulate sudden and deep respiratory inspiration, the maximum speed per axis should be at least 100 mm/s;
4. The frequency, amplitude, and pattern of the individual translations must be independently adjustable;
5. Furthermore, the platform interface should be suitable for use with the ForceSense objective measurement system (ForceSense, Amsterdam Universitair Medische Centra (UMC) and Amsterdam Skills Centre, Amsterdam, The Netherlands) and basic laparoscopic skills tasks;
6. The platform should be attachable to the ForceTRAP sensor interface (ForceSense, Amsterdam UMC and Amsterdam Skills Centre, Amsterdam, The Netherlands) using the already existing slide-on mounting mechanism;
7. The platform's weight should not exceed 300 grams to prevent the ForceTRAP force sensor from exceeding its normal working range [6];
8. The platform should be reusable for a box trainer setting, while the total cost of the platform components should be lower than 150 euros.

An 'independent stage' concept was designed to generate movements in three directions. The design features two servo-driven stages for the horizontal movements of the table and one servo-driven stage integrated with a scissors lift mechanism for the vertical movement. To ensure realistic motion, the movement parameters such as velocity, amplitude, and cyclicity were initially confirmed by surgeons involved in this study who compared the movement parameters to relevant data in scientific literature and their surgical experience.

Technical validation

The maximum amplitude was validated by measuring the largest possible movement range of all three degrees of freedom. The maximum speed of a single degree of freedom was calculated using the maximum rotational servo speed and the transmission ratio:

$$v = \dot{\alpha}_{s,\max} r_1 \frac{n_1}{n_2} \tag{1}$$

With $\dot{\alpha}_{s,\max}$ being the maximum rotational servo speed, r_1 the servo gear radius, n_1 the number of teeth on the servo gear, and n_2 the number of teeth on the belt gear.

As tasks are placed upon the moving platform their position in the box trainer increases. This slightly alters the box trainer camera perspective, which might create issues regarding instrument reach. Therefore, in collaboration with the surgeons involved in this study, it was confirmed whether the training tasks outlined in Design Requirement 1 remained feasible to complete with the platform installed.

Peg transfer test

The Dynamic Laparoscopic Platform (DyLaP) was tested for feasibility and evaluated to assess the influence of movement on laparoscopic skills with a basic training task: the peg transfer task. The DyLaP was mounted using a bracket onto the ForceTRAP 3D force sensor inside the Lapron box trainer (ForceSense, Amsterdam UMC and Amsterdam Skills Centre, Amsterdam, The Netherlands). The training task was mounted on top of the DyLaP. Objective force, time, and instrument path parameters were measured, representing tissue manipulation and instrument handling skills [14,15]. For the experiments, the DyLaP movement was characterized by a 3D asymmetric sinusoidal pattern with a maximum amplitude of 41.5 mm. The tasks were performed using two curved Maryland grasping forceps (Aesculap, B. Braun, Melsungen, Germany).

The participants were recruited from the faculty of Mechanical Engineering at the Delft University of Technology. A minimum of ten participants was required for this feasibility study. Participants were required to have no prior experience in laparoscopic skills training and surgery. Participation was voluntary and written informed consent was obtained. Participants were randomly divided into two groups: the static group and the dynamic group (Figure 1). Both groups were instructed on the use of the box trainer and allowed a short pre-training session to familiarize with the box trainer and peg transfer task, during which they were instructed on how to use the instruments and execute the task. Then, all participants performed six training trials followed by an exam. In the dynamic group, the task was moving during the training trials; in the static group, the DyLaP did not move. Afterwards, both groups performed the same dynamic (moving) exam. Participants were given instructions and familiarized themselves with the laparoscopic graspers and the box trainer. During each trial, participants were asked to move four soft pegs from one peg to another in a prescribed way. All four pegs had to be transferred twice per trial. For each trial, the prescribed start and end locations were different, but task difficulty did not differ between the trials. Participant age and sex data were collected. Time to completion, instrument tip path length, and exerted forces were measured and the learning curves of the static and dynamic group were compared.

These data were collected and analysed in an online database. The data were tested for normal distribution using the Shapiro-Wilk test. Statistical analysis was performed using the MATLAB statistical toolkit (The Mathworks Inc., Natick, MA, USA). Normal distribution of the differences between the groups could not be assumed, therefore significance of the measured effect was tested with the Wilcoxon signed-rank test.

The study design was approved under Human Research Ethics Committee (HREC) application number 3441.

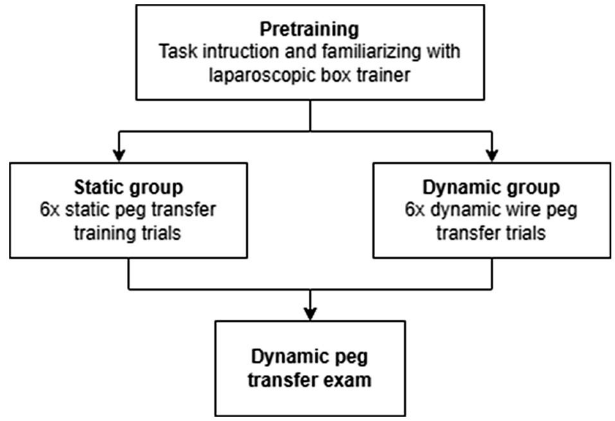

Figure 1. Flow chart of the pick and place task study design.

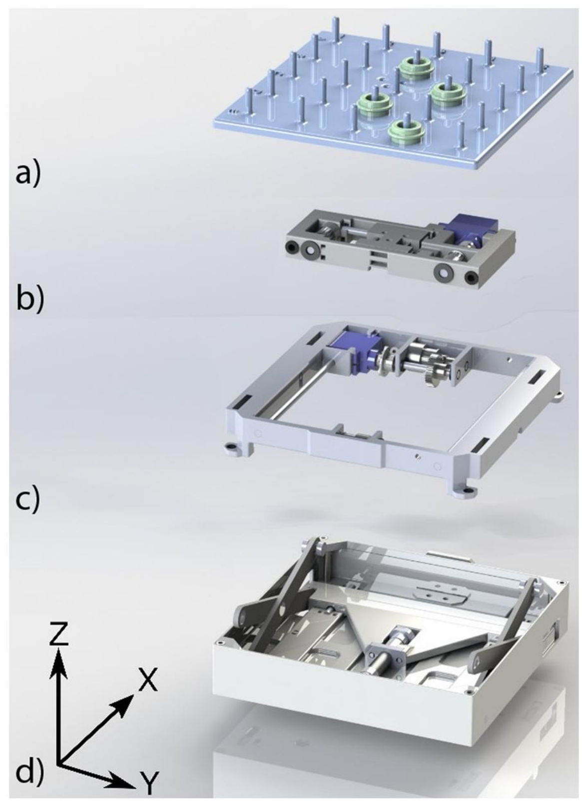

Figure 2. Exploded view of the DyLaP design, with the training task **(a)** on top, the stages for the movement in the X-direction **(b)**, Y-direction **(c)** and Z-direction **(d)**.

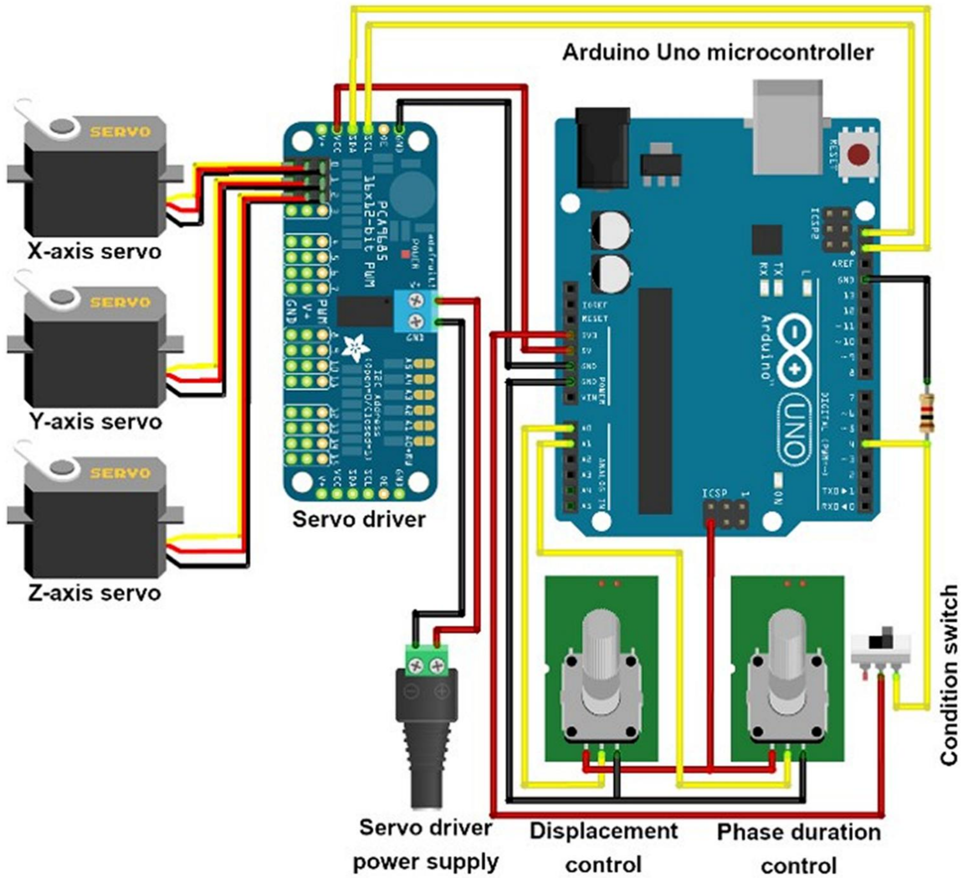

Figure 3. Electronics schematic with microcontroller, servo driver, servos, and control unit. The yellow wires are signal wires, red is power supply and black is ground wire.

Results

Design

The detailed prototype design of the DyLaP consists of three independently actuated linear stages, each moving the task (Figure 2a) over an axis of translation. The stages are independently guided using two guiding rods for each stage, and are actuated by SG92R servos (Tower Pro Pte Ltd, Singapore). The maximum amplitude for the x, y, and z axes is 20 mm, 40 mm, and 20 mm, respectively. The servos for the x-axis movement (Figure 2b) and y-axis movement (Figure 2c) use a belt transmission. The servo for the z-axis movement is connected to both a spindle and a scissors mechanism (Figure 2d). The servos are controlled by an Arduino Uno programmable microcontroller (Arduino, Turin, Italy) and a PCA9685 servo driver (NXP Semiconductors, Eindhoven, The Netherlands) (Figure 3). An asymmetric sinusoidal pattern was programmed. A control panel was implemented allowing for displacement magnitude and phase duration to be adjusted, as well as a toggle switch to change between experiment conditions. Surgeons involved in this project stated that, during initial testing, they perceived the DyLaP movements as truthfully simulating intraoperative movements, including amplitude, speed, and cyclicity.

Technical validation

The DyLaP was suitable for various basic laparoscopic skills training tasks, with the increased task height creating no issues regarding instrument reach. The DyLaP was able to perform all necessary movements and was successfully integrated with the Lapron box trainer and the ForceSense objective measurement system (Figure 4). The maximum absolute displacement of the DyLaP is 53 mm. The maximum displacement of the individual degrees of freedom (X, Y, and Z) is 20 mm, 21 mm, and 45 mm, respectively. Substituting these values into Equation 1 yielded maximum speeds of 5.4 m/s, 12.6 m/s, and 5.4 mm/s for X, Y, and Z, respectively. The frequency, amplitude, and pattern of the individual translations were independently adjustable using the Arduino interface. Furthermore, it was compatible with the ForceTRAP measurement system. The total platform weight is 280

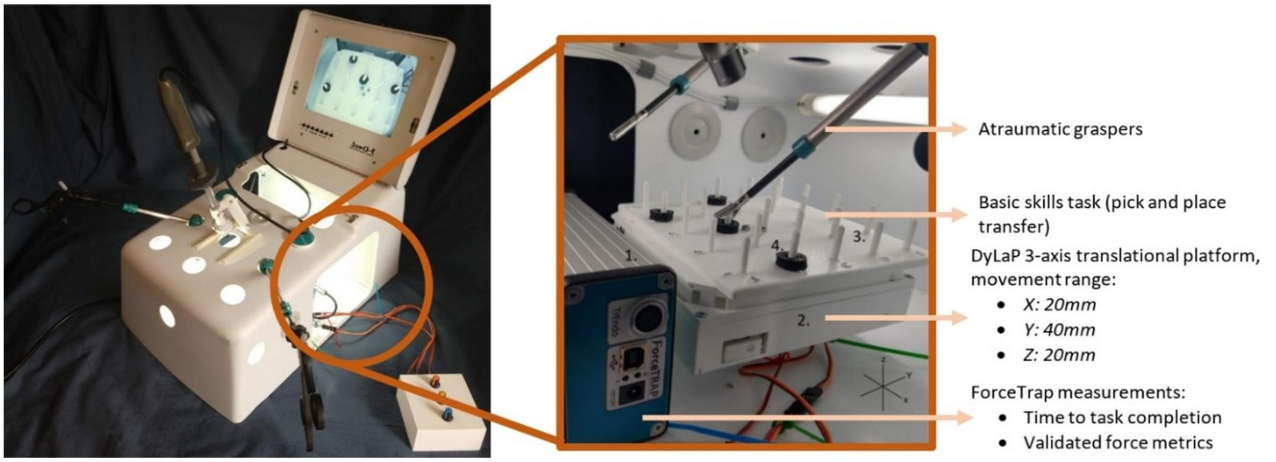

Figure 4. Overview of the DyLaP, mounted in a boxtrainer.

grams. The cost of the DyLaP system parts was 117.09 euros.

Peg transfer test

The total number of participants was 12 (four females and eight males; mean age, 27.8 ± 2.7). All participants had no experience in surgical training. In Table 1, the results of the performance parameters of all six trials and the dynamic exam are shown. There was a significant difference ($p < 0.05$) in time, path length, and maximum force between the static and dynamic groups in the first trial (Trial 1). Learning curve effects were observed from the comparison between the first and last training trial (Trial 1 vs. Trial 6) in both groups. There was a significant difference in time (static and dynamic group), path length (dynamic group), and max force (dynamic group). Learning curves (Figure 5a–d) show that performance of the static and dynamic groups converged after three trials. There was a significant difference in time (Figure 5a) between the static and dynamic groups in the dynamic exam.

The conversion from the static training to the dynamic exam resulted in significant differences as well. The static group had a significantly higher time to completion (Figure 5a) and instrument path length (Figure 5b) in the dynamic exam compared to Trial 6. Conversion from static to dynamic yielded no significant differences in mean force (Figure 5c) and maximum force (Figure 5d) for the static group. In the dynamic group there were no differences at all between the sixth training trial and the exam.

It was observed that, during the training trials, participants of the dynamic group learned to use the short static moments in the cyclic movement as windows of opportunity to transfer the pegs.

Discussion

The DyLaP, a modular and dynamic laparoscopic training task platform, was developed and successfully met the criteria and requirements when tested on a fundamental laparoscopic training task, fulfilling Design Requirement 1. The DyLaP is able to move in all three translational directions and its movement patterns can simulate intraoperative tissue movement characteristics found in scientific literature. Organ movements can alter the position and orientation of organs by up to 55 mm [6–11,16]. The maximum absolute displacement of the DyLaP is 53 mm, fulfilling Design Requirement 2. Aditionally, the maximum speed of the DyLaP is 12.6 m/s, greatly exceeding Design Requirement 3. The platform is able to simulate tissue motion in terms of displacement, motion, and frequency. Furthermore, the frequency, amplitude, and pattern of the movements are adjustable, fulfilling Design Requirement 4. The DyLaP was also compatible with the ForceSense objective measurement system (Design Requirement 5) and attachable to the ForceTRAP sensor interface (Design Requirement 6). Weighing 280 grams, it remains well below the maximum weight limit of 300 grams stated in Design Requirement 7. Lastly, the DyLaP prototype cost €117.09 to manufacture, fulfilling Design Requirement 8.

In the peg transfer task results, a clear learning curve could be observed in both the static and dynamic groups, while the results of the first trial between both groups regarding time to completion, path length and maximum force were significantly different. However, skill ceased to improve after the third trial. Both observations indicate that the difficulty of the dynamic and static peg transfer task was significantly different, but dynamically trained participants adapted to the training environment as quickly

Table 1. Results of the performance parameters of the peg transfer task.

			Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Dynamic exam	*p*-values			
										Trial 1 vs 6	Trial 6 vs Dynamic exam	Trial 1, static vs dynamic	Dynamic exam, static vs dynamic
Time [s]	Static	Mean	222.0	200.8	158.8	154.5	157.7	126.9	206.1	**0.002**	**0.004**	**0.01**	**0.009**
		SD	88.2	79.4	59.8	44.2	41.5	35.2	51.0				
	Dynamic	Mean	331.8	265.3	201.6	191.7	189.7	134.5	152.9	**0.0009**	0.15		
		SD	97.8	66.2	131.9	56.7	36.5	43.9	41.9				
Path length [mm]	Static	Mean	8144	7989	6761	6392	6365	5753	9899	0.10	**0.003**	**0.0005**	0.11
		SD	3241	3429	2866	2197	2134	2693	3843				
	Dynamic	Mean	14779	12044	17620	9666	9252	6574	7543	**0.0002**	0.12		
		SD	3502	2887	31283	3779	2458	1782	2179				
Mean force (non-zero) [N]	Static	Mean	0.70	0.69	0.65	0.68	0.67	0.67	0.70	0.93	0.72	0.29	0.89
		SD	0.30	0.26	0.17	0.20	0.22	0.24	0.16				
	Dynamic	Mean	0.81	0.92	0.77	0.79	0.74	0.79	0.74	0.69	0.27		
		SD	0.33	0.42	0.26	0.25	0.21	0.25	0.22				
Maximum force [N]	Static	Mean	2.48	2.40	2.13	2.45	1.99	2.19	2.37	0.97	0.33	**0.03**	0.29
		SD	1.46	1.28	1.14	1.02	0.79	0.93	0.71				
	Dynamic	Mean	3.66	3.71	2.42	2.94	2.56	2.34	2.67	**0.01**	0.15		
		SD	1.54	2.13	0.97	1.37	0.87	1.07	0.63				

Bold values represent statistically significant effects.

as the statically trained participants, showing a steeper increase in performance during the first trials. Therefore, when presented with a more challenging environment, novices were able to speed up their skill acquisition. Regarding learning curve effects, there were more significant differences in the dynamic group than in the static group (three vs. one, respectively).

During the exam trial, the static group was confronted with task movement and had to learn to anticipate, which was reflected in the significantly longer total completion time. It was observed that participants used stationary moments of the cyclic motion as windows of opportunity to place the rings. In general, introducing simulated movement during laparoscopic training influenced skill acquisition. Anticipation of movement can also be trained alongside basic skills training.

In the static group, the conversion from static training to the dynamic exam yielded significant differences in time to completion and path length, whereas in the dynamic group, it did not. For the static group, the conversion required a higher level of dexterity to compensate for the unexpected DyLaP movements. Movement thus had two effects on surgical novices when training laparoscopic technical skills in this training task: firstly, surgical novices compensated for movement with coping strategies (waiting for window of opportunity). With this strategy, participants attempted to minimize the increase in difficulty. This led to the increase in time. When asked about this after exam trial completion, participants confirmed that they used this strategy to reduce difficulty and consequently complete the task with minimal errors. Secondly, in precise training tasks where dexterity is important and movements must be made quickly, the degree of difficulty increases considerably. This was evident in the group differences observed during the initial trials. Novices with no prior experience performed significantly better in the static group as they did not have to overcome the added challenge of movement.

Further research

During laparoscopic surgery, sudden and deep respiratory inspiration or unexpected muscle traction can occur. This can result in surgical errors, such as tissue slipping while grasping or complications like tissue perforation when surgeons fail to anticipate sudden movements. Surgical residents who have been trained with dynamic methods might have better

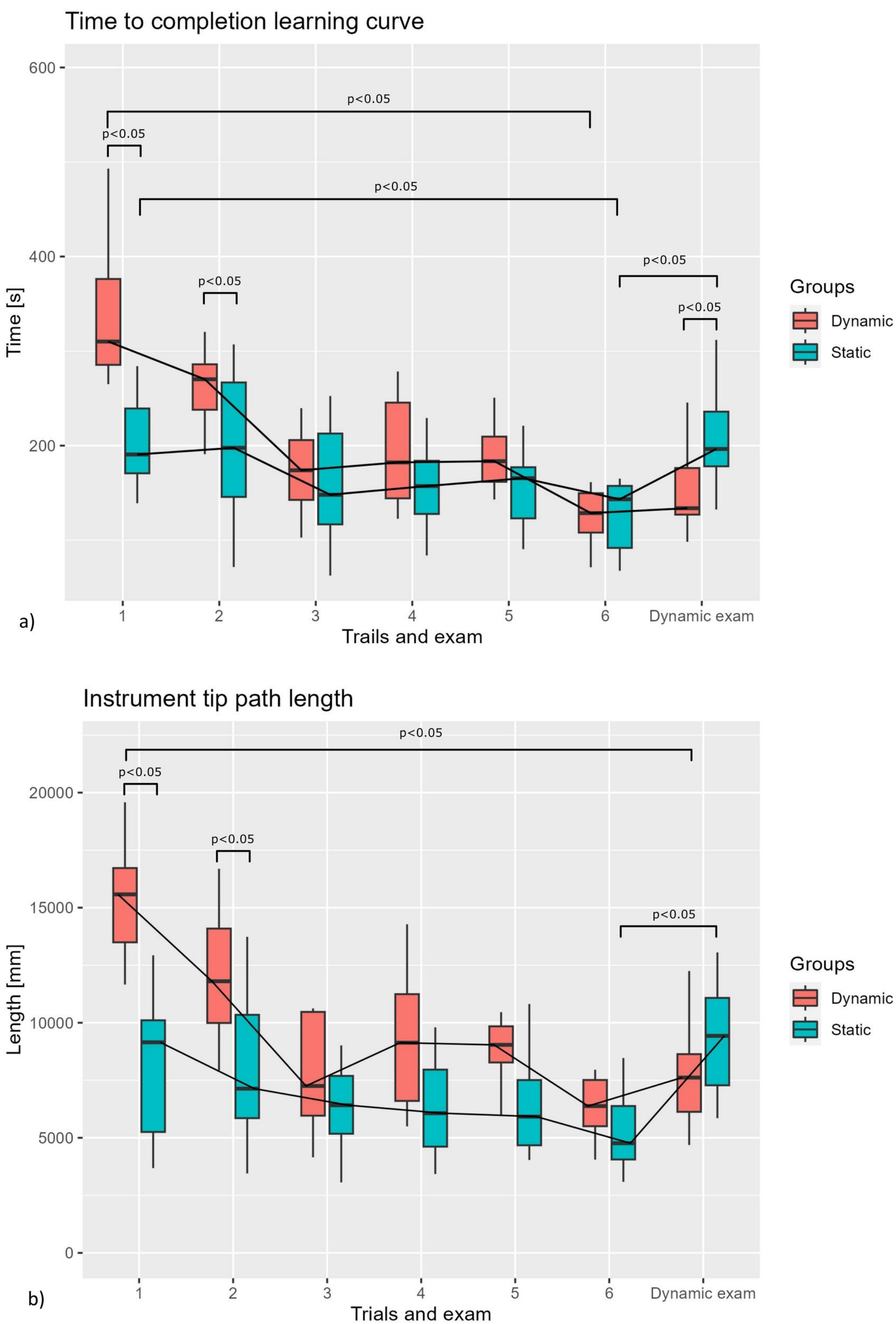

Figure 5. Results of the time to completion **(a)**, instrument tip path length **(b)**, mean force (non-zero) **(c)** and maximum force **(d)** learning curves.

anticipatory responses to these sudden movements. However, further research on specific skill tasks, such as grasping and suturing, is needed to validate this.

In this study, the exam test was not fundamentally different for the dynamic group. This was done to exclude all other effects on the objective parameters

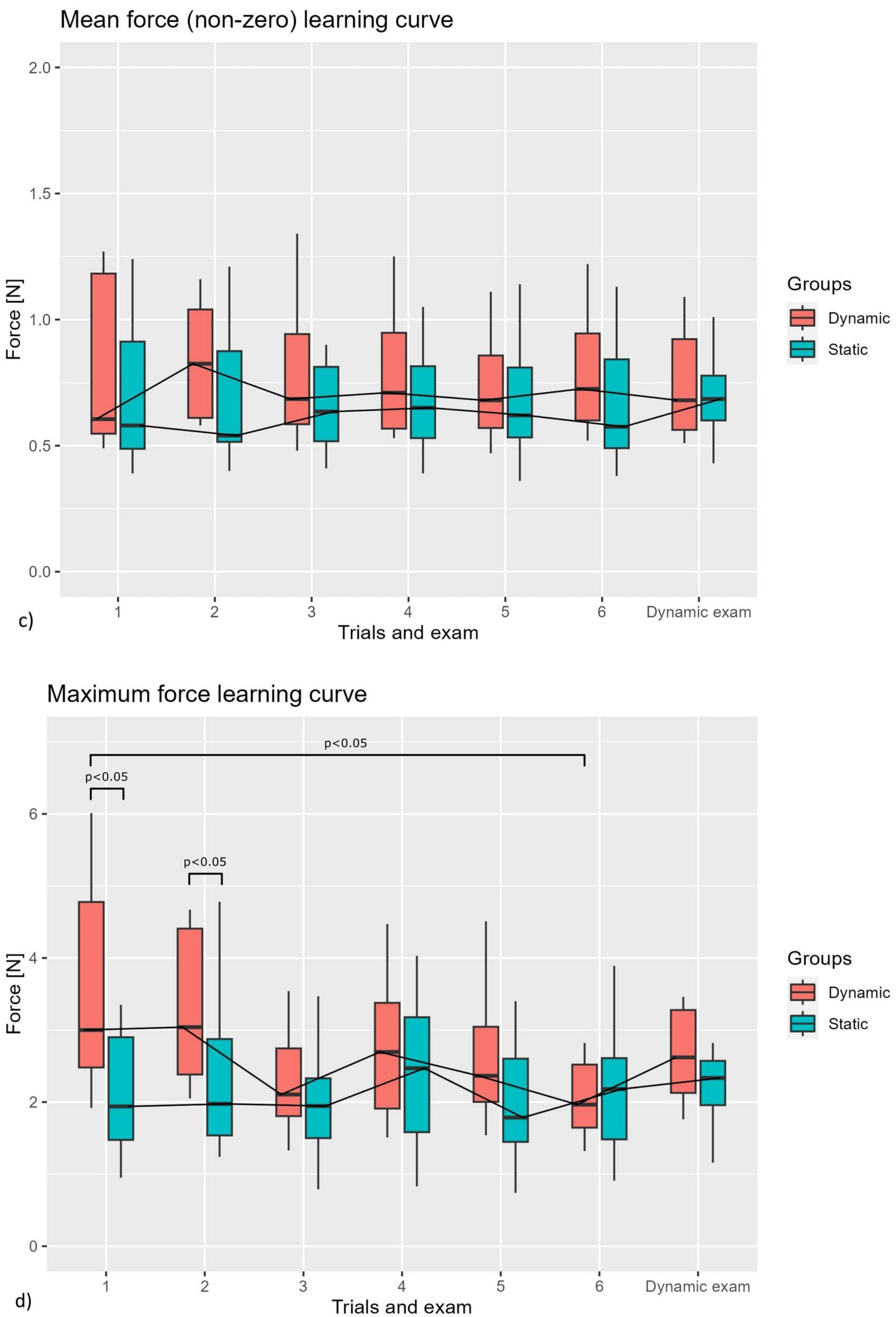

Figure 5. Continued.

but at the same time limited the study's scope. In future research, a different exam task could be performed to gain more knowledge on the transferable effects of skills gained through dynamic training. Alternatively, both groups can perform a subsequent dynamic and static exam to study conversion effects.

Residents trained in dynamic tasks may exhibit different skill levels in a static condition due to their training in a more motorically-challenging environment. Therefore, the influence of dynamic training on the objective performance parameters in static training conditions should be investigated.

To establish a baseline comparison in static and dynamic training, all participants in this study had no prior experience in laparoscopy or laparoscopic training. Comparing task performance of dynamically trained surgical residents with (expert) surgeons might give valuable insights on the value of implementing dynamic tasks in laparoscopic skills training.

In this study, a peg transfer task was evaluated. This is a position-based task, in which participants only briefly interact with the moving task while removing or placing the pegs. The need to anticipate movement arises only in these instances. In contrast, force-based tasks such as the flap task or wire chaser [17] require continuous instrument contact, which makes them fundamentally different. In this case, precise task motion mimicry during grasping is important at all times, while there is also the continuous need to apply sufficient grasping force in order to satisfy the task objectives regarding time and instrument path length. If the motion mimicry is suboptimal, then slipping may occur. Thus, 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 [18,19]. Therefore, the influence, relevance, and impact of dynamic training in force-based tasks should be further investigated.

Conclusion

The Dynamic Laparoscopic Platform (DyLaP), a modular and dynamic laparoscopic training task platform, was successfully developed and used in multiple user experiments. The DyLaP was sufficient in moving in all three translational directions; the movements' frequency, displacement, and pattern were adjustable. In the peg transfer exam test, the dynamic group was significantly faster in completing the task than in the static group. The static group showed a significant drop in performance when transitioning from the static training set-up to the dynamic exam. Adding movement to laparoscopic technical skills training introduces additional difficulty and challenge, ultimately enhancing skill development. Further research is needed to investigate sudden movements, possible implementation in laparoscopic training curricula, and the role of dynamic training in force-based tasks that require intermediate laparoscopy motor handling skills.

Disclosure statement

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

Data availability statement

The dataset from this study is available at 4TU Research Data Repository (doi: 10.4121/a7922e8d-a61b-432f-b5a4-85cfce286478).

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