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ORIGINAL ARTICLE

Faster acquisition of laparoscopic skills in virtual reality with haptic feedback and 3D vision

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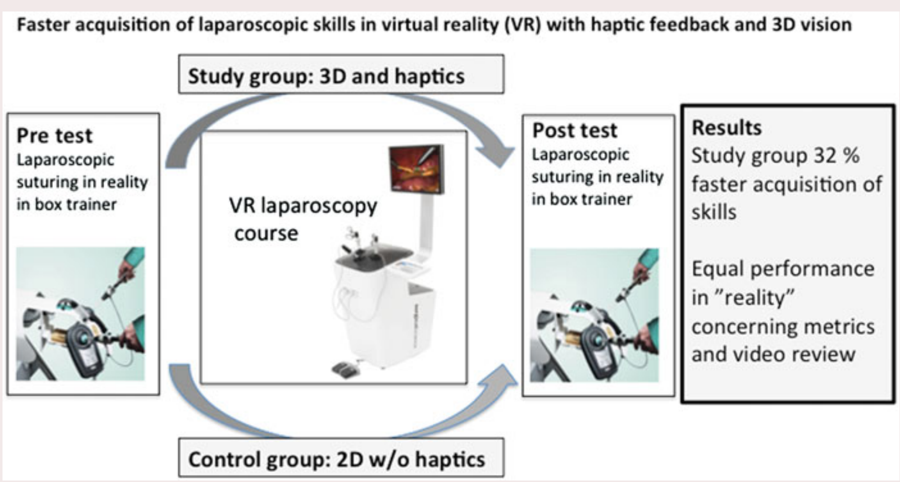
ABSTRACT

Background: The study investigated whether 3D vision and haptic feedback in combination in a virtual reality environment leads to more efficient learning of laparoscopic skills in novices.
Material and methods: Twenty novices were allocated to two groups. All completed a training course in the LapSim® virtual reality trainer consisting of four tasks: 'instrument navigation', 'grasping', 'fine dissection' and 'suturing'. The study group performed with haptic feedback and 3D vision and the control group without. Before and after the LapSim® course, the participants' metrics were recorded when tying a laparoscopic knot in the 2D video box trainer Simball® Box.
Results: The study group completed the training course in 146 (100–291) minutes compared to 215 (175–489) minutes in the control group ($p = .002$). The number of attempts to reach proficiency was significantly lower. The study group had significantly faster learning of skills in three out of four individual tasks; instrument navigation, grasping and suturing. Using the Simball® Box, no difference in laparoscopic knot tying after the LapSim® course was noted when comparing the groups.
Conclusions: Laparoscopic training in virtual reality with 3D vision and haptic feedback made training more time efficient and did not negatively affect later video box-performance in 2D.



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Haptic feedback; laparoscopy; surgical education; virtual reality; 3D vision

Introduction

The LapSim® Virtual Reality simulator (LapSim® VR; Surgical Science, Göteborg, Sweden) is designed to teach basic skills as well as some procedures in laparoscopic surgery. The simulator has been validated in several studies and has been shown to distinguish experts from novices and to predict operative skills following curriculum training. In addition, transferability of VR surgical skills to the operating theatre has been shown (1–4).

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Recently, an updated version was released with features of 3D vision and haptic feedback. Since advanced laparoscopic procedures that require complex skills are frequently performed, there is a need for laparoscopic training with objective feedback of instrument movements. Previous studies have evaluated earlier versions of LapSim® (5), but none have reported on the hardware set-up with haptic feedback and 3D vision used in this study. One pilot study performed on LapSim with an earlier software version (2011) and a different 3D monitor than the current set-up, did not show improved novice performance with 3D (6). Another study using LapSim with haptic feedback handles from Xitact IHP (Xitact, Lausanne, Switzerland) was unable to establish construct validity, and the results were partly explained by the participants experiencing unrealistic trocar friction (7).

VR simulators have been criticized for poor illustration of organs, tasks and lack of haptics (8–14). Previous VR models developed to provide haptic feedback have not been shown to do so convincingly and have therefore not added clinical value to VR training (7,15–18). A challenge in simulating laparoscopic surgery is the difficulty of providing authentic haptic feedback. Providing too little or too much feedback will probably lead to negative effects of training (19). A recent study on a laparoscopic grasper tip force model showed promising results but has not yet been tested in a VR environment (20). Studies have shown that tasks that rely on force application, such as stretching and grasping, are better performed when true haptic feedback is provided in a video box trainer (21,22). In addition, residents seem to prefer box trainers to VR trainers (13,14).

An environment with 3D vision offers a higher degree of realism with depth perception and conceivably reduced visual misperceptions. In a recent review of randomized control trials, laparoscopic simulators with 2D or 3D vision were compared. In this review, 28 of 31 studies were conducted in a simulated environment and a majority included novices (23). Of the 19 trials published from 2004 to 2014, ten studies showed a reduced performance time, 12 of 19 trials reported a lower rate of errors and two trials reported more accurate performance in favour of 3D vision (23). A diversity of 3D vision systems were used and the results were not consistent, though some studies showed a benefit of 3D for accuracy, reduction in errors and time (23). Four studies found no additional benefit of 3D (6,24–26). Another recent review investigating 3D and 2D laparoscopy concluded that conflicting evidence for the benefit of 3D visualisation greatly depends on stereovisual ability and viewing conditions in the test set-up (27).

Considering the high cost of VR simulators with 3D vision and haptic feedback, it is important to evaluate the possible advantages of these added features for laparoscopic training. There is a trade-off between fidelity and cost, and ultra-high fidelity might not always be necessary to gain relevant training benefits (19). There are no current published studies investigating the combination of 3D and haptic feedback in simulated environments.

The study aimed to investigate whether 3D vision and haptic feedback in combination lead to more efficient learning in novices. A secondary aim was to investigate whether there is a difference between novices trained with and without 3D and haptic feedback when tested in a 2D environment.

Material and methods

Participants

A single-blinded controlled trial was carried out, with equal numbers of participants in each group, stratified according to sex, video game habits, self-perceived motor coordination skills and handedness. Self-perceived motor coordination skills were graded on a scale 1–5, where 1 equals not very skilled, 3 ordinary skills and 5 highly skilled.

The participants were not allowed to have practised laparoscopic surgical knot tying or suturing, nor witnessed live laparoscopic surgery and had to be able to perceive picture depth in 3D cinema movies. All participants gave informed consent and were informed that they could leave the study at any time.

Simulators

LapSim® on SimFrame (LapSim®, Surgical Science Sweden AB, Göteborg, Sweden) is a virtual reality simulator designed to teach basic skills and some laparoscopic procedures (Figure 1(a)). The version used in the present study was launched in 2013 and uses a haptic hardware platform together with 3D vision. The FUJITSU 3D Display (P23T-6 FPR) attached to the SimFrame uses the Film Patterned Retarder (FPR) 3D technology, developed by LG Corporation (Fujitsu Sweden AB, Kista, Sweden). The monitor displays separate images to the left and right eye through the FPR in different circularly polarized patterns. These images are perceived by the viewer as 3D when seen through left-and-right-polarized glasses, commonly known as cinema 3D (28).

Figure 1. (a) LapSim® on SimFrame virtual reality simulator with haptic feedback and 3D vision. (b) Simball® Box video trainer delivering objective metrics on performance using ordinary laparoscopic instruments. (c) Close-up on the Simball® Box laser-marked pattern in the trocar responsible for recording metrics.

Simball® Box (Simball®, G-coder Systems, Västra Frölunda, Sweden) is a video box trainer with 2D vision (3D vision possible but not used in this setup) that provides metrics on performance using standard laparoscopic surgical instruments through a potentiometer and with a patented laser-marked pattern in the trocars (Figure 1(b,c)) (29).

The Simball® Box is under validation. The first results show that Simball® Box metrics (time, linear and angular distance, average acceleration and average speed) mirror progression when performing laparoscopic suturing (30).

Study design

Each participant was introduced to LapSim® on SimFrame (Figure 1(a)) and Simball® Box (Figure 1(b,c)). The participants received introduction to laparoscopic knot tying and were allowed three attempts to practice a surgeon's knot in the Simball® Box. During these attempts, they were coached to tie a knot with only verbal instructions. Subsequently, the participants were granted one attempt to tie the knot with video and metrics recording in the Simball® Box.

The novices fulfilled a training course in LapSim® consisting of four tasks from the basic skills program to a predetermined proficiency level: 'instrument navigation', 'grasping', 'fine dissection' and 'suturing' (Configuration and proficiency settings, Appendices A and B). The study group performed the LapSim® course with haptic feedback and 3D vision and without the control group. After completing the LapSim® course, the participants were allowed to practice three knots in the Simball® Box before a second video and metrics recording of the knot tying was carried out.

Two 5th-year medical students educated in laparoscopic suturing, LapSim® on SimFrame and Simball® Box coached all study participants individually. The training sessions were limited to six hours with regular breaks, and a maximum of seven days were allowed to pass between each training session.

A laparoscopic surgeon, who had performed more than 200 laparoscopic procedures, complemented the automatically recorded metrics in the Simball® Box with a qualitative review of all recorded video performances to ensure correctness of the knot together with performance levels comparing the first and second attempt. The videos were reviewed with regard to the number of times the instruments were out of view or outside the suture pad zone, whether the needle was outside suture pad zone, the correctness of knot choreography and whether the knot was sufficient. This reviewer was blinded to the allocated groups.

Statistics

The parameters registered in the LapSim® and Simball® Box were calculated for each participant. Data were saved and stored in Microsoft Excel© 2010. For statistical analyses, data were transferred and analysed by using GraphPad Prism© version 6.0f for Mac (GraphPad Software, Inc., La Jolla, CA). All data are expressed as median and range. Data were considered nonparametric and a Mann–Whitney *U*-test was performed to compare the two groups.

Change in Simball® Box-performance was calculated by comparing the performance parameters before and after the LapSim® course. A Fishers' exact test was performed to compare the two. A p value of $<.05$ was considered significant.

Results

Forty-seven novices attending the first, second or third year of medical school expressed interest in participating in the study and answered the questionnaires used for recruitment. Twenty-one novices were excluded due to previous practice in either open or laparoscopic knot tying or suturing. Four novices could not participate due to scheduling reasons. Two novices declined participation. Twenty novices, mean age 21 (19–28) years, were finally included in the study and divided into two equal groups ($n = 10$) (Table 1). All participants stated that they were able to perceive cinema 3D vision.

The study group performed the LapSim® course with haptic feedback and 3D vision and completed the training course in 146 (100–291) minutes compared to 215 (175–489) minutes in the control group ($p = .002$), which was 69 minutes (32%) faster than the control group (Figure 1).

Table 1. Demography of study participants.

Variables	Study group	Control group	p value[a]
Total subjects	10	10	–
Sex			
Female	5	5	–
Male	5	5	–
Age (year)	21 (19–28)	21 (19–27)	.606
Dominant hand (#)			
Right	9	9	–
Left	1	1	–
Video games (hours/week)	4,5 (0–14)	1 (0–11)	.559
Stated psychomotor skills by participants (scale 1–5)	3 (2–5)	3 (2–5)	.720

[a]Mann–Whitney *U*-test.

The study group was significantly faster in three out of four tasks; instrument navigation, grasping and suturing (Table 2). In the 'instrument navigation' task, all parameters except 'total instrument misses' showed a superior performance by the study group compared to the control group (Table 2). In the study group, the number of attempts to reach proficiency was significantly lower for instrument navigation with a median of 27 (13–79) attempts compared to 65 (29–196) attempts in the control group ($p = .005$) (Table 2). The number of attempts in the grasping task was fewer for the study group with 19 (10–34) attempts compared with 29 (19–36) attempts in the control group ($p = .017$) (Table 2). For the 'suturing task', the corresponding figures were 24 (15–73) attempts and 41 (30–93) attempts, for the study group and control group, respectively ($p = .011$) (Table 2). However, total training course instrument path length and total training course instrument angular path parameters for the study group were similar to those of the control group (Table 2).

Subanalysis

Total path length was lower in the study group in the 'instrument navigation' ($p = .003$) and 'suturing task' ($p = .030$) (Table 2). Angular path length was found to be significantly shorter in the study group in 'instrument navigation' ($p = .007$) (Table 2).

Total tissue damage parameter was similar in both groups, although the novices in the study group performed superiorly regarding total maximum damage in 'instrument navigation' and 'grasping task' ($p = .003$ and $p = .019$, respectively). The results from the 'fine dissection task' did not differ between the two groups. A better performance was observed in the

Table 2. Task parameters of the LapSim® training course.

Course task	Study group Median (range)	Control group Median (range)	*p* value[a]
Instrument navigation			
Total attempts (#)	27 (13–79)	65 (29–196)	.005[c]
Total time (min)	19 (9–52)	46 (20–149)	.003[c]
Total instrument path length (m)	41 (17–136)	94 (43–331)	.007[c]
Total instrument angular path (degrees)	7606 (3529–27301)	17,490 (8133–60,693)	.007[c]
Total tissue damage (#)	138 (42–739)	347 (95–1550)	.015[a]
Total maximum damage (mm)	109 (60–1048)	422 (92–1834)	.003[c]
Total instrument misses (%)	2,2 (0–8)	1,5 (0–3)	.288
Grasping			
Total attempts (#)	19 (10–34)	29 (19–36)	.017[b]
Total time (min)	29 (16–55)	49 (30–65)	.007[c]
Total instrument path length (m)	83 (30–226)	104 (55–152)	.306
Total instrument angular path (degrees)	15,660 (5932–44,600)	19,648 (10,471–29,054)	.347
Total tissue damage (#)	155 (40–396)	254 (103–537)	.188
Total maximum damage (mm)	178 (45–380)	390 (107–847)	.019[b]
Total instrument misses (%)	22 (18–27)	14 (16–31)	.183
Fine dissection			
Total attempts (#)	7 (5–22)	8 (3–21)	.236
Total time (min)	22 (13–40)	13 (5–55)	.060
Total instrument path length (m)	12 (7–38)	8 (2–29)	.071
Total instrument angular path (degrees)	2858 (1778–10,210)	1882 (441–6992)	.089
Total instruments outside view (#)	3 (0–16)	4 (0–12)	.864
Total instruments outside view (s)	4 (0–49)	7 (0–37)	.927
Total ripped or burned blood vessels (%)	7 (0–25)	16 (0–43)	.088
Total energy damage on blood vessels (%)	7 (1–26)	5 (0–25)	.469
Total ripped small vessels (%)	5 (0–14)	12 (0–26)	.127
Total burned small vessels (%)	94 (83–97)	88 (73–100)	.287
Total burned small vessels without stretch (%)	0 (0–15)	0 (0–3)	.249
Suturing			
Total attempts (#)	24 (15–73)	41 (30–93)	.011[b]
Total time (min)	62 (40–194)	115 (67–265)	.007[c]
Total instrument path length (m)	99 (50–500)	169 (86–516)	.030[b]
Total instrument angular path (degrees)	20,191 (10,375–100,768)	36,027 (17,387–92,798)	.052
Total target error (mm)	55 (15–90)	41 (1–195)	.645
Total knot error (%)	42 (27–59)	41 (34–52)	.725
Total training course parameters			
Total training course time (min)	146 (100–291)	215 (175–489)	.002[c]
Total training course instrument path length (m)	237 (134–683)	356 (216–976)	.063
Total training course instrument angular path (degrees)	47,511 (27,891–137,858)	70,566 (42,982–177,728)	.063

[a]Mann–Whitney *U*-test,
[b]Statistical significance =0.050,
[c]Statistical significance =0.010

Table 3 Simball box® metrics. Change (in per cent) $\Delta = \frac{\text{(pre course value − post course value)}}{\text{pre course value}} \times 100$ of obtained metrics in Simball Box® pre and post LapSim® training course (median and range).

Parameters	Study group	Control group	*p* value[a]
Δ Total time (%)	26.9 (2.4–61.2)	19.7 (−2.5–51.5)	.326
Δ Linear distance (%)	14.2 (−5.3–56.9)	6.7 (−34.8–54.6)	.151
Δ Angular distance (%)	13.7 (−22.6–66.5)	8.0 (−76.2–55.1)	.364
Δ Average acceleration (%)[b]	−12.3 (−55.8–32.5)	−22.6 (−54.0–30.1)	.545
Δ Average speed (%)	9.7 (−40.4–51.2)	1.1 (−34.4–82.8)	1.000
Δ Motion smoothness (%)	5.9 (−55.5–46.6)	2.1 (−27.5–50.0)	.940

[a]Mann–Whitney *U*-test.
[b]A negative value implies that the acceleration is increased in the post-course performance.

study group concerning time, attempts and path length parameters in the 'suturing task' (Table 2).

After completing the virtual reality course in LapSim®, analysis of the knot tying test in Simball® box did not show any difference in performance pre- and post the LapSim® course in the provided metrics or as rated by the video reviewer (Tables 3 and 4). One video in the control group was corrupted and could not be analysed.

Discussion

The main aim of this study was to investigate whether virtual reality with 3D vision and haptic feedback leads to faster acquisition of laparoscopic skills in novices. The current study showed that the study group's performance was superior to the control group in total time spent in the simulator to reach the set proficiency level. The novices training with 3D vision and haptic feedback reached the proficiency

Table 4. Video review of performance in Simball Box®.

Parameters	Study group $N = 10$ improved/no improvement	Control group $N = 9^{b}$ improved/no improvement	p value[a]
Instrument outside of view	9/1	9/0	1.000
Instrument outside of zone	10/0	7/2	.476
Needle outside of zone	9/1	9/0	1.000
Correct knot choreography (yes/no)	10/0	7/2	.211
Sufficient knot (yes/no)	10/0	8/1	.474

Comparison of performance before and after Lapsim® VR training with or without 3D and haptic settings.
[a]Fisher's exact test.
[b]One video could not be analysed due to corrupt video file.

level 32% faster than the control group. Hence, novices in laparoscopy may shorten the learning curve when 3D vision and haptic feedback are added to the VR simulator.

For the 'instrument navigation' task about half as much time was needed to reach proficiency in the study group compared to the control group. For this task, haptic feedback is of little relevance and consequently the better results are in all probability due to 3D vision.

In the 'grasping task', the study group used less total time and number of attempts. In addition, the study group novices had less maximum tissue damage. This may be interpreted as the study group benefited from the haptic feedback or had a better perception of picture depth.

Early exposure to haptic feedback during surgical simulator training has been suggested to improve basic skill acquisition and performance for novices (17,22). These findings provide support for the integration of haptic feedback in VR simulators.

Possibly due to low complexity of the task, the results from the 'fine dissection task' did not differ between the study and control group. Previous studies on laparoscopic performance in a VR simulator have suggested that a certain complexity of the task is required to affect outcome, a so-called ceiling effect (16,22). If the 'fine dissection task' was too easy, it is reasonable to assume that the 3D vision and haptic feedback would have no effect on performance.

In the 'suturing task', the study group performed better than the control group concerning time, attempts and path length. Suturing was the most complex task in the LapSim® course and requires depth perception and advanced instrument coordination. An interpretation could be that the more complex the task, the larger the benefit of 3D vision and haptic feedback.

Some previous investigations have suggested that practicing with 3D vision gives superior performance compared to standard 2D vision (31–33). Another study has shown a reduced rate of task errors for inexperienced individuals when practicing in 3D and a positive transfer of motor skills when switching to 2D vision (34). In the present investigation, the post-course test in the 2D environment did not detect differences in performance between the study and the control group. Hence, it may be hypothesized that training with 3D vision does not affect performance, neither to the better nor to the worse, when later performing 2D laparoscopy.

As the trainees advance, many find the VR trainers less useful because of the lack of visual and haptic reality and therefore avoid using them after having acquired the most basic skills (13,14). A study of training perseverance, using VR simulators and comparing standard to those with these added features, would therefore be of interest.

There are some limitations of the present study that should be acknowledged. The study cohort is relatively small. No correction for confounders could be made with the current number of participants, and consequently, excluding potential outliers was not possible. To compensate for lack of Gaussian distribution, the groups were demographically stratified. Excluding participants with experience of surgical knot tying or laparoscopic procedures reduced the number of confounders. All participants reached the same level of proficiency in performing a laparoscopic surgical knot before commencing the VR simulator training course. Hence, the baseline of this skill was fairly equal. There were no exclusion criteria to sort out participants with physical impairments or illnesses. The participants were not specifically tested for their 3D perception abilities and the ability was self-reported. The study did not compensate for height and hand size of the participants. Although the instructors were not laparoscopic experts, using senior medical students to coach their peers has previously been deemed eligible (35).

Other VR simulators use different hardware to provide haptic feedback and the results of the present study may not be comparable to other studies using other simulators. Studies using other simulators have failed to support positive skill acquisition effects of haptic feedback (18,19). The fidelity of previous models of haptic feedback in VR simulators has been questioned (7,19). Hence, a general conclusion of the usefulness of haptic feedback in VR simulators cannot be drawn.

It might be hypothesized that the superior performance of the study group may be accredited to the 3D vision due to the lack of evidence supporting an added value of haptic feedback. No effort was made to discriminate between the contributing roles of 3D and haptic feedback in the current study since these features in combination are standard in the newest version of LapSim®. The synergistic effect of 3D vision and haptic feedback seen in the current study is relevant from a practical point of view when constructing training of novices. Future studies are needed to reveal whether the same effect is noticed in surgical trainees with previous experience in laparoscopy.

Within the context of these limitations, the current study suggests that training in virtual reality with 3D vision in combination with haptic feedback provides a time-efficient acquisition of laparoscopic proficiency compared with 2D without haptic feedback. In addition, the present study shows that training with 3D vision is not a disadvantage when later performing an authentic laparoscopic task in 2D.

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Declaration of interest

Drs. Anderberg, Bergenfelz, Ekelund, Hagelsteen, Langegård and Lantz have no conflicts of interest or financial ties to disclose. This statement covers all parts of the study and includes no attachment, in any aspect, to the manufacturers of LapSim® or Simball®.

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Appendix A. LapSim® task configurations settings.

Parameter description	Instrument navigation	Grasping	Fine dissection	Suturing[a]
Randomize				
Random sequence (#)	45638954	685798	1234	–
Spread wide	Yes	Yes	–	–
Camera options				
Rotate degree	0	0	0	0
Use moving camera	Y	No	No	No
Object options				
Left objects (#)	6	7	–	–
Right objects (#)	6	7	–	–
Object size (mm)	6	8	–	–
Timing				
Use object timeout	Yes	Yes	No	Yes
Timeout after (S)	10	15	1000	180
Target options				
Target size (mm)	–	15	–	–
Vessel options				
Number of blood vessels	–	–	2	–
Number of small vessels	–	–	3	–
Stretch sensitivity (easy–hard)	–	–	2	–
Instrument options				
Cutter instrument	–	–	Thermo hook	–
Easy grip and knot	–	–	–	No
Needle size (mm)	–	–	–	15
Suture length (mm)	–	–	–	150
Environment options				
Environment	–	–	–	Realistic
Stitching options				
Target area diameter (mm)	–	–	–	10
Maximum stretch sensitivity (mm)	–	–	–	20
Knot detection (easy–hard)	–	–	–	Easy

[a]Configuration settings according to Ahlberg et al (3).

Appendix B. Proficiency-level settings in LapSim®

Parameters	Instrument navigation	Grasping	Fine dissection	Suturing[a]
Total instrument time (s)[b]	34.0	110	160	120
Right	17.0	55	–	–
Left	17.0	55	–	–
Total instrument path length (m)[b]	2.0	4.4	–	3.0
Right	1.0	2.2	–	1.5
Left	1.0	2.2	–	1.5
Total instrument angular path (degrees)[b]	280	740	–	800
Right	140	370	–	400
Left	140	370	–	400
Tissue damage (#)	1.0	3.0	–	–
Maximum damage (mm)	2.0	5.0	–	–
Average instrument misses (%)	0.0	6.0	–	–
Right	0.0	3.0	–	–
Left	0.0	3.0	–	–
Total instruments outside view (#)[b]	–	–	1.0	–
Right	–	–	1.0	–
Left	–	–	0.0	–
Total instruments outside view (s)[b]	–	–	5.0	–
Right	–	–	5.0	–
Left	–	–	0.0	–
Vessel options				
Ripped or burned blood vessels (%)	–	–	0.0	–
Energy damage on blood vessels (%)	–	–	20.0	–
Ripped small vessels (%)	–	–	0.0	–
Burned small vessels (%)	–	–	100.0	–
Burned small vessels w/o stretch (%)	–	–	25.0	–
Cutter angular path (degrees)	–	–	200	–
Cutter outside view (#)	–	–	1	–
Cutter outside view (s)	–	–	5	–
Cutter path length (m)	–	–	0.9	–
Grasper options				
Grasper angular path (degrees)	–	–	60	–
Grasper outside view (#)	–	–	0	–
Grasper outside view (s)	–	–	0	–
Grasper path length (m)	–	–	0.3	–
Maximum target error (mm)	–	–	–	0.0
Knot error (%)	–	–	–	0.0

[a]Right and left instrument parameters are measured separately in the LapSim® software.
[b]According to Ahlberg et al. (3).
Total parameters are the sum of right and left instrument parameters.
Total parameter values were used for statistical analysis.