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SURGICAL ENDOSCOPY
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The influence of experience and camera holding on laparoscopic instrument movements measured with the TrEndo tracking system

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Abstract
Background: Eye–hand coordination problems occur during laparoscopy. This study aimed to investigate the difference in instrument movements between the surgeon him- or herself holding the camera and an assistant holding the camera during performance of a laparoscopic task and to check whether experience of the surgeon plays a role in this issue.
Methods: The participants were divided into three groups: experts, residents, and novices. Each participant performed positioning tasks using the right (R) and left (L) hands. During these tasks, the camera was manipulated either by the participant (C_{self}) or by an assistant ($C_{assistant}$). Movements of instruments were recorded with the authors' new TrEndo tracking system. The performance was analyzed using five kinematic parameters: time, path length, three-dimensional (3D) motion smoothness, 1D motion smoothness (along the axis), and depth perception.
Results: A total of 46 participants contributed. Three tests were performed: test 1-LC_{self}, test 2-$LC_{assistant}$, and test 3-$RC_{assistant}$. In all the tests, the experts performed better than the residents and novices in terms of time, path length, and depth perception. The novices performed better in tests 1-LC_{self} and 2-$LC_{assistant}$ than in test 3-$RC_{assistant}$ in terms of path length, 3D motion smoothness, and depth perception.
Conclusions: Laparoscopic experience and the camera-holding factor influenced the performance of laparoscopic tasks on the simulator. Time, path length, and depth perception clearly discriminate between different levels of experience in laparoscopy, whereas 3D and 1D motion smoothness play a limited role. Novices experienced more difficulties when an assistant held the camera. Therefore, self-manipulation of the camera seems to improve novices' eye–hand coordination.

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Key words: Endoscope — Eye–hand coordination: motion analysis — Laparoscopy: training

Minimally invasive surgery (MIS, e.g., laparoscopy) currently is widely used for therapeutic purposes. It is well known that laparoscopy has many advantages for the patient such as reduced morbidity, shorter hospitalization, better cosmetic results, and earlier return to normal activity [6]. Laparoscopic surgery, however, requires expertise in psychomotor skills different from those needed to perform open surgical procedures and results in longer learning curves [8]. These skills include a shift from a three-dimensional (3D) operating field to a 2D monitor display, judgment of altered depth perception and spatial relationships, distorted eye–hand coordination, adaptation to the fulcrum effect, manipulation of long surgical instruments while adjusting for amplified tremor, diminished tactile feedback, and fewer degrees of freedom [12]. To guarantee safe performance of laparoscopy, surgeons must be properly trained, and the procedures must be assessed thoroughly [1] (e.g., as in flight simulators for pilots) [13].

Most laparoscopic procedures require the use of an operating team that includes not only a surgeon, but also at least one operating assistant [2]. The surgeon and the operating assistant must be comfortable with the entire laparoscopic setup. Depending on the preference of the surgeon, the assistant can manipulate the camera and an additional instrument (e.g., while stretching the tissue or holding an organ) during the procedure. In gynecology, however, laparoscopic procedures often are performed using one hand (not necessarily the dominant hand) to operate and the other hand to hold the camera (e.g., laparoscopic sterilization).

Because of the change in the position of the camera, the view of the operating field (side, angle, and scale) can change. Such a change, especially when combined with replacement of the camera operator, can result in disturbed eye–hand coordination of the operator (even an experienced one). Therefore, in both general surgery and gynecology, surgeons must be able to perform the laparoscopy under two conditions: when manipulating the endoscope themselves and when the assistant manipulates the camera.

No study was found that investigated whether holding the camera has an influence on the eye–hand coordination, and consequently on the instruments' movements during the performance of laparoscopic tasks. Also the influence of different experience levels under different camera-holding conditions is unknown. Therefore, the primary purpose of the current study was to investigate the influence of camera holding (by the participant or by an assistant) on instrument movements during the performance of MIS tasks. A second objective was to test whether the experience of the surgeon is a significant factor in the aforementioned issue.

To test these objectives, we compared the performance of participants with different levels of MIS experience who completed three MIS tests in a box trainer. During these tests, the camera was manipulated by the participants or by the assistant. The task used during the tests represents a basic MIS task used to train eye–hand coordination. Our new tracking system, TrEndo, was used to measure the movements of the laparoscopic instrument [4]. The performances of the participants were analyzed and compared using five kinematic parameters: time, path length, 3D motion smoothness, 1D motion smoothness (along the axis), and depth perception [5].

Materials and methods

Participants

Gynecologists and gynecologic residents from various hospitals in the Netherlands together with interns from the Department of Gynaecology at Leiden University Medical Center were invited to participate. Each participant voluntarily enrolled in this study and was asked to complete a short questionnaire detailing demographic information and prior experience in laparoscopy. The participants were divided into three groups: experts, residents, and novices. The group of experts consisted of gynecologists with experience comprising more than 100 laparoscopic procedures. The group of residents consisted of gynecologic residents with experience performing 10 to 100 laparoscopic procedures. The group of novices consisted of interns with no previous experience in laparoscopic procedures. The assistant was always the same person.

Task

All the participants performed a one-hand positioning task in a box trainer. The positioning task required touching the top of eight cylinders with the tip of the laparoscopic instrument in a box trainer (Fig. 1). All eight cylinders were situated in various positions in 3D. The start/end position of the instrument and the order for touching all the cylinders (indicated by numbers located next to the cylinders) were the same for all the participants. Every correctly touched cylinder resulted in lighting up of a lamp corresponding to this cylinder.

To provide the same conditions for all the participants, we standardized the position of the task and the position of the camera in the box trainer. The image of a 0° laparoscope was presented on a monitor.

Fig. 1. Positioning task. This task requires touching the top of eight cylinders (in varying three-dimensional positions) with the tip of the minimally invasive surgery (MIS) instrument. A correctly touched cylinder results in the lighting up of a lamp (above in the picture) corresponding to this cylinder.

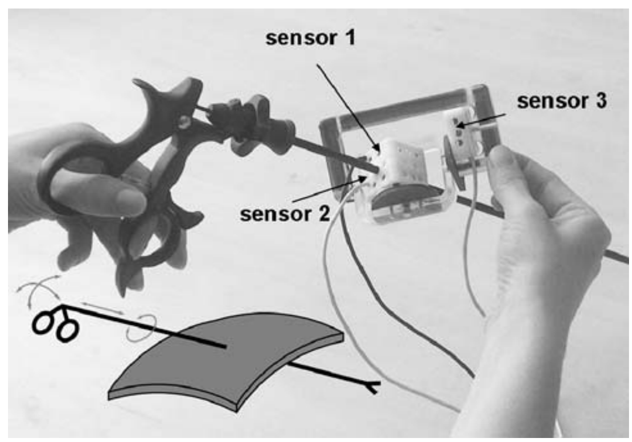

Fig. 2. The TrEndo device for tracking the movements of the endoscopic instrument. Sensor 1 tracks the insertion–retraction and the rotation of the minimally invasive surgery (MIS) instrument around its own axis. Sensors 2 and 3 track the left–right and the forward–backward rotations of the instrument around the incision point, respectively.

Tracking system

All the tests were performed in a box trainer (video trainer) with a built-in tracking system. This combination allowed realistic movements of the MIS instrument in four degrees of freedom and real-time recording of the instrument's movements. The main principle of our newly developed TrEndo tracking system involves tracking the movements of the MIS instrument [4]. The TrEndo consists of a two-axis gimbal mechanism with three optical mouse sensors (Fig. 2). The role of the gimbal mechanism is to guide the MIS instrument in four degrees of freedom: translation of the instrument along its axis, rotation of the instrument around its axis, and left–right and forward–backward rotations around the incision point. The optical sensors enable contactless measurement of the movements of standard laparoscopic instruments. Motions of the laparoscopic instrument during the tests were measured with a sample frequency of 100 Hz.

Experimental protocol

Most gynecologists perform MIS while standing on the left side of the patient. To mimic the *in vivo* situation, the influence of camera holding

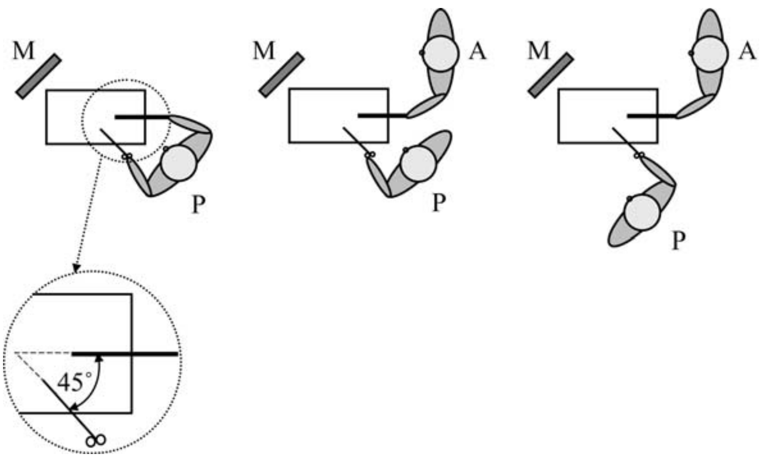

Fig. 3. Schematic drawings of the three test configurations: test 1-LC_{self}, test 2-$LC_{assistant}$, and test 3-$RC_{assistant}$. In test 1-LC_{self} (left), the participant performs the positioning task with the left hand and holds the camera in the right hand. In test 2-$LC_{assistant}$ (middle), the participant performs the task with the left hand, and the camera is held by an assistant. In test 3-$RC_{assistant}$ (right), the participant performs the task with the right hand, and the camera is held by an assistant. P, participant; A, assistant; M, monitor

and experience on instrument movements was investigated using three test configurations:

- Test 1-LC_{self}: Participants performed the positioning task with their left hand while holding the camera themselves in the right hand.
- Test 2-$LC_{assistant}$: Participants performed the positioning task with their left hand while the camera was held by an assistant.
- Test 3-$RC_{assistant}$: Participants performed the positioning task with their right hand while the camera was held by an assistant (Fig. 3).

During all the tasks, the camera was situated on the right side of the participants in the same initial position (90° to the surgeon's line of sight). At the start of each test, the angle between the instrument and the camera was 45° (Fig. 3).

During tests 2-$LC_{assistant}$ and 3-$RC_{assistant}$, the assistant moved the camera to follow the movements of the MIS instrument and to keep the instrument in the center of the view. The participants could ask the assistant to zoom the view in or out. Before measurements, all the participants were instructed on how to perform the positioning task. They also were allowed to perform one trial before testing. To avoid the influence of a task-learning effect on the results of the study, all the participants performed the tasks in a random order.

Parameters

On the basis of the literature, the following four kinematic parameters were chosen for assessing the performance of all the participants [5]:

- *Time:* The total time (t) taken to perform the positioning task (in seconds).
- *Path length:* The length (p) of the curve described by the tip of the instrument during performance of the positioning task (in cm).
- *3D Motion smoothness:* A parameter based on the third time-derivative of position, which represents a change in acceleration, defined as

$$j = \sqrt{\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^2}$$

(in cm/s^3). Motion smoothness is derived from the integrated squared jerk as follows:

$$J = \sqrt{\frac{1}{2}\int_0^T j^2 dt}.$$

- *Depth perception:* The total distance (d) traveled by the instrument along its axis (in cm).
- 1D *Motion smoothness along the axis:* A parameter based on the third derivative of the position of the instrument moving along its axis (direction h), which represents a change in acceleration, defined as

$$j = \sqrt{\left(\frac{d^3h}{dt^3}\right)^2}$$

(in cm/s^3). One-dimensional motion smoothness is derived from the integrated squared jerk as follows:

$$J = \sqrt{\frac{1}{2}\int_0^T j^2 dt}.$$

Statistical analysis

Recorded data were analyzed using the Statistics Toolbox of MATLAB 7: The MathWorks, Inc., Natick, MA, USA. Statistical analysis was performed using one-way analysis of variance (ANOVA) and Wilcoxon tests. A p value less than 0.05 was considered statistically significant.

Results

Participants

All 46 participants enrolled in this study were right-handed. The participants were divided into three groups: experts ($n = 11$), residents ($n = 21$), and novices ($n = 14$). The group of experts consisted of 5 female and 6 male gynecologists ranging in age from 35 to 59 years. The group of residents consisted of 12 female and 9 male gynecologic residents ranging in age from 29 to 41 years. The group of novices consisted of 11 female and 3 male interns ranging in age from 23 to 30 years. All the participants completed the questionnaire and the tests. Five novices did not finish test 2-$LC_{assistant}$.

Influence of the experience level

Figure 4 presents typical instrument trajectories for an expert and a novice performing test 1-LC_{self} (instrument in the left hand and camera in the right hand). As shown, the motions of the expert separate eight points more distinctly than the motions of the novice.

Figure 5 shows the influence of the experience level under the different camera-holding conditions on the kinematic parameters for all three test configurations.

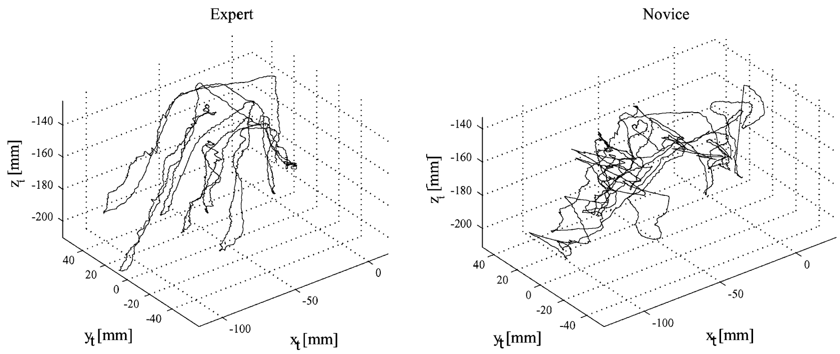

Fig. 4. Typical instrument trajectories of an expert gynecologist (*left*) and a novice (*right*) performing test 1-LC_{self} (instrument in the left hand and camera in the right hand).

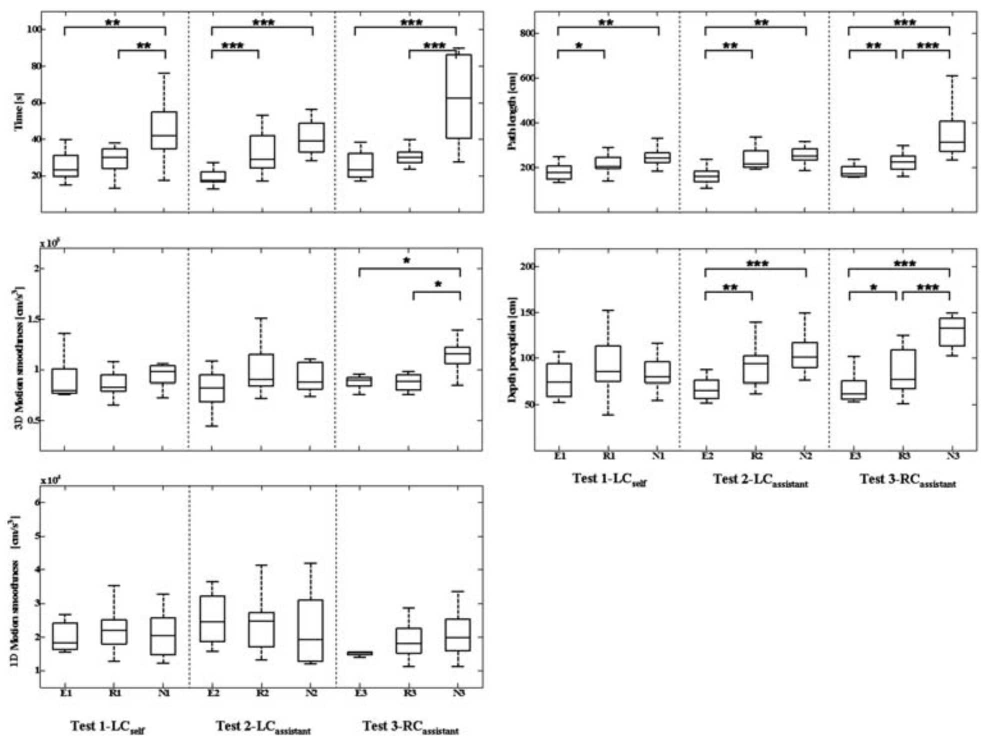

Fig. 5. The influence of the experience level on the kinematic parameters for all three tests: test 1-LC_{self}, test 2-$LC_{assistant}$, and test 3-$RC_{assistant}$. The results are presented as box and whisker plots, in which every box has a line at every quartile, median, and upper quartile value. The whiskers are presented as lines that extend from each end of the box to show the extent of the remaining data. A few extreme outliers are excluded from the plots to omit excessive compression of the y-axis. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. E, experts; R, residents; N, novices

An influence of experience on time and path length was found in all three tests (Table 1). In tests 2-$LC_{assistant}$ and 3-$RC_{assistant}$, the depth perception of the experts was better than that of the residents and novices. In test 3-$RC_{assistant}$, the 3D motions of the novices were less smooth than the motions of the experts and residents (Table 1). No influence of experience on 1D motion smoothness was found.

Influence of camera holding

Figure 6 presents the influence of camera holding on the performance of the experts, residents, and novices. The data in Fig. 6 are the same as the data in Fig. 5, but are presented per group. An influence of the camera holding on the instrument movements was observed only for the novices. The novices' path length was longer in test 3-$RC_{assistant}$ than in tests 1-LC_{self} and 2-$LC_{assistant}$ (Table 2). The novices' 3D motions were less smooth in test 3-$RC_{assistant}$ than in tests 1-LC_{self} and 2-$LC_{assistant}$. The novices showed better depth perception while performing test 1-LC_{self} than while performing the two other tests (Table 2). The experts' and residents' 1D motion smoothness was better in test 3-$RC_{assistant}$ than in tests 1-LC_{self} and 2-$LC_{assistant}$.

Discussion

The experts performed better than the residents and novices in terms of time, path length, and depth perception. Three-dimensional motion smoothness could discriminate only between different levels of experience when the positioning task was performed with the right hand and the camera was held by an assistant.

The results of the camera-holding test show that the 1D motions of the experts and residents were smoother during test 3-$RC_{assistant}$ (performed with the right hand) than during the other tests, in which the tasks were performed with the left hand (tests 1-LC_{self} and 2_$LC_{assistant}$). Because all the experts and residents were right-handed, we can conclude that, independent of

Table 1. Influence of the experience level on instrument movements during the performance of minimally invasive surgery (MIS)

Test	Parameter	Exp–Res % (p)	Exp–Nov % (p)	Res–Nov % (p)
Test 1-LC_{self}	Time	NS	42 (<0.01)	31 (<0.01)
	Path length	19[a] (<0.05)	25 (<0.01)	NS
	3D Motion smoothness	NS	NS	NS
	Depth perception	NS	NS	NS
	1D Motion smoothness	NS	NS	NS
Test 2-$LC_{assistant}$	Time	41 (<0.001)	53 (<0.001)	NS
	Path length	32 (<0.01)	36 (<0.01)	NS
	3D Motion smoothness	NS	NS	NS
	Depth perception	28 (<0.01)	36 (<0.001)	NS
	1D Motion smoothness	NS	NS	NS
Test 3-$RC_{assistant}$	Time	NS	63 (<0.001)	54 (<0.001)
	Path length	20 (<0.01)	53 (<0.001)	40 (<0.001)
	3D Motion smoothness	NS	25 (<0.05)	19 (<0.05)
	Depth perception	22 (<0.05)	51 (<0.001)	38 (<0.001)
	1D Motion smoothness	NS	NS	NS

Exp, experts; Res, residents; Nov, novices; NS, not significant; 3D, three-dimensional; 1D, one-dimensional
[a] Difference between mean values given as percentage

camera holding, 1D motions performed with the dominant hand are smoother than motions performed with the nondominant hand. This effect was not found for the novices, probably because the problems that novices had with depth perception were overruled by the camera-holding effect. Furthermore, we found an influence of the camera holding on the performance of the laparoscopic task in terms of path length, 3D motion smoothness, and depth perception for the novices.

Breedveld et al. [3] found that motion parallax can be a cue for depth perception. Motion parallax is a phenomenon in which objects in the environment appear to move due to a motion of an external influence (e.g., the camera in MIS). Objects closer to the observer "move" faster and farther than more distant objects. By observing motion parallax, it is possible to estimate a relative distance between the observer and various objects in the visual field.

In our study, the novices' depth perception (defined as the total distance [h] traveled by the instrument along its axis) was improved when novices manipulated the camera themselves during task performance. Hence, self-manipulation of the camera improved novices' performance. This probably was caused by the fact that the novices, when self-manipulating the camera, estimated the relative distances better.

Studies have demonstrated that in addition to time and errors, motion analysis can be a valuable assessment tool for the training of MIS skills [5, 7, 10, 11, 14]. In our study, we were able to discriminate between different levels of experience in laparoscopy using the kinematic factors described by Cotin et al. [5]. Cotin et al. [5] described kinematic parameters that can be used to assess performance while relying on the motion of the instrument [5]. A parameter related to the number of rotations the instrument makes around its axis does not play a role in the positioning task and was therefore not taken into account. Our study confirms that motion analysis can be used as an objective tool for assessing performance in MIS. We noted that one parameter alone (e.g., time) cannot be used to assess the entire performance or the level of experience. Moreover, time alone cannot be used to assess the difficulty of the MIS task either.

Cotin et al. [5] used a combination of five kinematic parameters to define a score. This score was validated by comparing the movements of expert and novice surgeons. However, the study did not validate the five individual parameters, so it still is unclear which parameters should be used to discriminate between different levels of experience. Others have found that motion smoothness (as defined by Cotin) cannot successfully distinguish between different levels of experience in laparoscopy [9].

Our study confirms this finding. Experience in laparoscopy did not clearly influence the 3D and 1D motion smoothness (Fig. 5). However, we found that the camera holding influences 1D motion smoothness (Fig. 6). Moreover, we found a difference in the influence of experience level on depth perception only when an assistant was holding the camera. Hence, it seems that the setting (e.g., position of the camera, camera operator) also is very important when the parameters that can discriminate between levels of experience are determined.

Because MIS is performed in a limited working area, with limited tactile perception and difficult handling of the instruments, it is necessary to find correct parameters that can measure the quality of actions for objective evaluation of the basic laparoscopic skills. Moreover, it is necessary to find the way these parameters should be combined. Only with the correct parameters will it be possible to provide information about the level of basic laparoscopic skills and the nature of the weak points. Such information will lead to goal-oriented training curricula because it can be used to give feedback to the residents about their basic skills that require improvement. Additionally, this feedback may increase motivation and efficiency of learning.

This study can be seen as a beginning of seeking and analyzing kinematic parameters. We found that some parameters can be used to differentiate between experience levels (e.g. time, path length, depth perception), whereas other parameters may be more dependent on

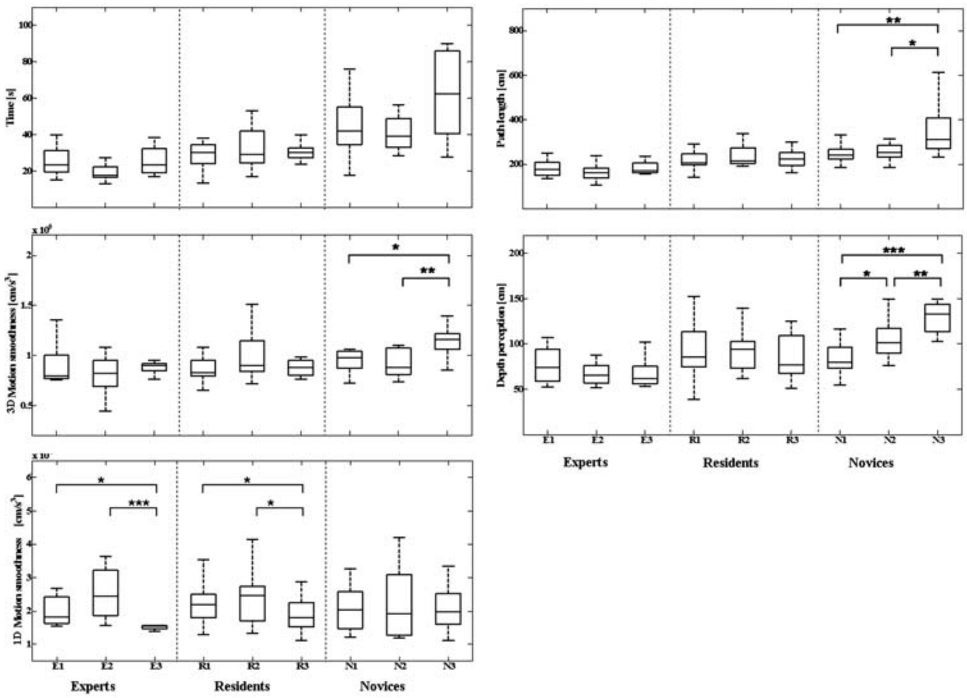

Fig. 6. The influence of camera holding on the kinematic parameters for all three tests: test 1-LC_{self}, test $2\text{-LC}_{assistant}$, and test $3\text{-RC}_{assistant}$. The data presented in this figure are the same as the data in Fig. 4, but are arranged per group. $^{*}p < 0.05$, $^{**}p < 0.01$

Table 2. Influence of camera holding on instrument movements during performing minimally invasive surgery (MIS)

Test	Parameter	Tests 1 and 2 % (*p*)	Tests 1 and 3 % (*p*)	Tests 2 and 3 % (*p*)
Experts	Time	NS	NS	NS
	Path length	NS	NS	NS
	3D Motion smoothness	NS	NS	NS
	Depth perception	NS	NS	NS
	1D Motion smoothness	NS	20[a] (< 0.05)	54 (< 0.001)
Residents	Time	NS	NS	NS
	Path length	NS	NS	NS
	3D Motion smoothness	NS	NS	NS
	Depth perception	NS	NS	NS
	1D Motion smoothness	NS	17 (< 0.05)	30 (< 0.05)
Novices	Time	NS	NS	NS
	Path length	NS	38 (< 0.01)	34 (< 0.05)
	3D Motion smoothness	NS	16 (< 0.05)	22 (< 0.01)
	Depth perception	14 (< 0.05)	45 (< 0.001)	24 (< 0.01)
	1D Motion smoothness	NS	NS	NS

Exp, experts; Res, residents; Nov, novices; NS, not significant; 3D, three-dimensional; 1D, one-dimensional
[a] Difference between mean values given as percentage

task complexity (e.g. depth perception, 1D motion smoothness).

Conclusion

Experience has an influence on laparoscopic task performance. Time, path length, and depth perception clearly discriminate between different levels of experience in basic laparoscopic skills, whereas 3D motion smoothness and 1D motion smoothness have a less clear effect. Camera holding does influence 1D motion smoothness. Experts' and residents' movements of the instrument along its axis are smoother when they are performed with the dominant hand. However, this was not found for the novices, probably because they have more problems with depth perception when an assistant is holding the camera. Self-manipulation of the camera apparently improves novices' eye–hand coordination.

Our study confirms that motion analysis can be used as an objective tool for assessing basic laparoscopic skills. Therefore, to evaluate performance, it is necessary to find correct parameters that measure the quality of actions. It should not be forgotten that the setting (e.g., task, position of the camera, camera operator, MIS instruments) plays an important role in determining the parameters that can discriminate between levels of experience.

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