A biomechanical analysis of bi-manual coordination and depth perception in virtual laparoscopic surgery

F. Cavallo [a,b], G. Megali [a,b], S. Sinigaglia [a,b], O. Tonet [a,b], P. Dario [a,b], and A. Pietrabissa [b]
[a] *CRIM Lab – Scuola Superiore Sant'Anna, Pisa, Italy*
[b] *EndoCAS – Center for Computer Assisted Surgery, Pisa, Italy*

Abstract. Minimally invasive surgery (MIS) has become very common in recent years thanks to the many advantages that patients can obtain. However, due to the difficulties surgeons encounter to learn and master this technique, several training methods and metrics have been proposed in order to, respectively, improve the surgeon's abilities and assess his/her skills. In this context, this paper presents the estimation of some biomechanical parameters and a segmentation algorithm to deeply investigate the surgeon's movements and to divide them into sub-movements. Segmentation allows to identify different phases of the exercise and also to distinguish the hand which is actively used in the task from the hand that is just holding the instrument.

Keywords: Gesture analysis, surgical training, laparoscopy, biomechanics metric, segmentation.

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1. Introduction

MIS has assumed, in the medical scenario, a dominant role as a consequence to the remarkable social and economic improvement that it involves. While on one hand MIS procedures ensure many advantages to patients, on the other hand they require surgeons to undergo a long and difficult training in order to manage and master these techniques. In this context, a biomechanical analysis is crucial to establish efficient training exercises for enhancing surgeons' dexterity and to define objective metrics for assessing the surgeons' experience and performance. Mainly, surgeons encounter perceptual limitations (lack of stereoscopic view, limited field of view, and reduced force and tactile sensing), and motor limitations (reversed motion, movement scaling and limited degrees-of-freedom) [1]. The skills required for MIS are based on unique perceptual-motor relationships that make these skills very difficult to master. So, shifting from open surgery to MIS, new problems arise, related to the training of the surgeon. In order to enhance surgeons' dexterity, training procedures have been established and skill evaluation metrics have been used to assess the surgeons' experience and performance.

Many previous works in the field of surgical training in virtual environments are focused on the definition of metrics for an objective evaluation of surgical performance. One of the main objectives is to assess the abilities of surgeons and also to measure the skill level of experts and novices. Many kinematic parameters and various indexes have been proposed for different surgical exercises [2-4] and also segmentation procedures have been employed to characterize different phases of movement [5][6].

This work is focused on assessing the abilities of surgeons in coordination of bi-manual movements and in depth perception during a typical laparoscopic exercise. Our aim is to define parameters that allow us to deeply characterize the surgeon's movement during a surgical procedure, to see how subjects of different expertise rank in these parameters and also to distinguish expert surgeons from less experienced surgeons such as residents and novices.

The original contribution of our work is related to a new set of parameters useful to analyze the skills and improvements of surgeons and to an automatic and objective segmentation procedure, performed only with the acquired position data of laparoscopic instruments in the virtual surgical reference frame. The segmentation procedure gives the opportunity to deeply investigate the surgeon's gesture and allows to split it into basic sub-movements and is usually performed by means of a videotape review. Even if a videotaped segmentation gives the opportunity to annotate the time-line of the entire exercise and identify sub-movements, it remains rather subjective and not rigorous.

Using the virtual laparoscopic scenario and, hence, exactly knowing the position of the targets to be reached, we can split, with an appropriate algorithm which uses just the position of the instrument tips, the whole exercise in many consecutive sub-movements, each of them related to one reaching task.

2. Methods and instruments

A commercial laparoscopic simulator, LapSim Basic Skills 2.2 (Surgical Science AB, Göteborg, Sweden), was used to perform exercises in a virtual environment and to acquire data concerning instrument positions. This feature gives different subjects the possibility to execute identical exercises, allowing to elaborate generic and objective metrics independent from external variations, and gives the same subject the possibility to perform the same exercise at different times, allowing the monitoring of his/her learning curve.

A group of four novices and a group of two expert surgeons were asked to complete an experimental session of four consecutive trials, consisting of reaching, alternatively with the right and left instruments, ten balls which appeared one at a time in the virtual scenario. Once a ball was touched by the tip of the instrument, it disappeared and the next ball appeared to be reached with the other instrument. These exercises allow to train the surgeon's ability in the bi-manual movement coordination of surgical instruments and in depth perception using the laparoscopic view.

The tip positions of the two instruments, measured by three encoders embedded in the hardware interface and sampled at a frequency of 60 Hz, were off-line filtered, using a numerical fourth-order low-pass Butterworth filter (cut-off frequency of 25 Hz) for reducing noise and then further processed for analysing the movements during the exercises. Subsequently, a segmentation procedure is used to split the whole exercise in different sub-movements. Each of the sub-movements, alternatively referred to right and left hand, correspond to each ball to be reached in the exercise. There are five different sub-movements for both hands. The first sub-movement (right hand) starts at the beginning of the exercise and finishes as soon as the right tip touches the first ball. Next sub-movements start at the end of the previous ones and finish as soon as the tip touches the next ball.

By knowing the position of the ten spheres in the coordinate system of the virtual scenario, it is possible to detect the time when a tip touches a ball. The algorithm procedure, used to segment the entire exercise, evaluates the distance between the center of the ball and the position of the tip. The instant in which the distance is equal to the ball radius, the task is completed.

3. Results

The following parameters were computed and discussed for both the whole exercise and the single sub-movements: *duration* (total time spent by subjects to complete the exercise), *path length* (trajectory length carried out by the tip of the instruments during the exercise), *mean speed* (mean speed of the tips), *maximum speed* (maximum speed of the tips), *mean acceleration* (mean acceleration of the tips), *maximum acceleration* (maximum acceleration of the tips), *normalized jerk* (measure of the motion smoothness) and *energy expenditure* (integral of the magnitude of the total acceleration vector, correlated to the energy expenditure [9]).

The evaluation of parameters clearly permit to identify the expert surgeons, and also to characterize the improvements of novices during the entire session. Improvement in experts improvements is less than in novices. Experts generally appear faster than novices in completing the exercises, and also smoother in managing the instruments (Table 1).

Table 2 shows other parameters for each subject relative to both hands. The mean value of path length, speed (Vm) and acceleration (Am) and the maximum of speed (Vmax) and acceleration (Amax) on the whole session are presented. The path length, on average, was greater in novices and also the differences between right and left hand appeared to be higher. The mean speed was higher for experts and lower for novices, especially for those that scored better in the previous parameters and are therefore considered to be more able. The mean value of acceleration and maximum speed value for experts were in the middle between the more and less able novices. Furthermore maximum acceleration value typically was low for experts and able novices.

The entire set of calculated parameters was also analyzed with the Principal Components Analysis (PCA) methods. Referring to the exercise as a whole, the three principal components permit to distinguish the subjects in three main groups, i.e. the expert group, and the best and worst novice groups, so that a skill-based classification on the learning curve can be done (Fig. 1).

Table 1
Evaluation of Duration, Mean speed and Normalized Jerk for all subjects and for all trials in the experimental session. Mean speed and Normalized Jerk are averaged between right and left hand.

	Duration (s)				*Vm (cm/s)*				*Norm Jerk*			
	1°	2°	3°	4°	1°	2°	3°	4°	1°	2°	3°	4°
ine1	55,74	39,04	39,11	32,87	3,12	3,70	4,09	4,09	72,67	33,66	31,39	23,12
ine2	53,65	42,00	35,43	35,44	3,87	4,14	4,43	4,15	70,54	45,50	26,77	28,38
ine3	31,41	30,09	31,30	33,32	2,79	2,85	2,98	2,62	7,50	6,03	6,86	8,74
ine4	49,67	39,65	47,30	31,61	2,36	2,77	3,68	3,20	16,82	10,81	15,46	6,13
exp1	18,62	19,63	18,02	13,75	5,63	4,35	5,08	5,71	2,23	2,76	2,28	1,29
exp2	18,86	18,15	17,28	14,50	4,69	4,94	5,34	5,58	2,51	2,31	2,04	1,38

Table 2
Other kinematics parameters for both hands, averaged on the entire session.

	inex1		*inex2*		*inex3*		*inex4*		*exp1*		*exp2*	
	dx	*sx*	*dx*	*sx*	*dx*	*sx*	*dx*	*sx*	*dx*	*sx*	*dx*	*sx*
Path length (cm)	92.14	100.88	105.91	113.17	84.18	90.64	144.64	106.03	87.10	92.24	87.54	87.91
Vm (cm/s)	3.54	3.96	4.01	4.29	2.71	2.91	3.42	2.58	5.06	5.32	5.12	5.15
Vmax (cm/s)	52.77	67.66	103.32	70.30	26.16	35.09	32.45	43.00	48.81	43.89	51.14	42.15
Am (m/s^2)	2.39	2.63	2.66	2.87	1.04	1.11	1.17	0.95	1.84	1.92	1.82	1.82
Amax (m/s^2)	39.10	41.92	100.50	56.83	13.61	20.49	15.59	15.13	28.74	14.74	20.73	15.86

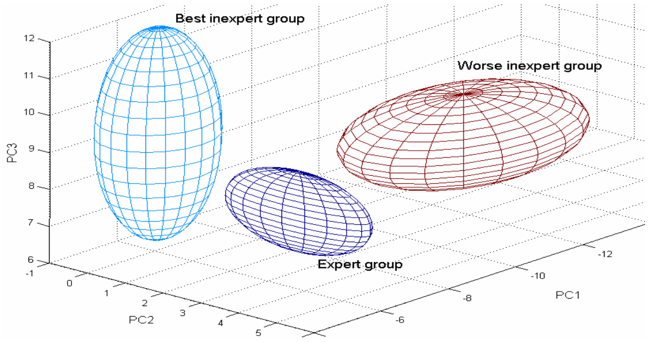

Fig. 1. PCA analysis that permits to distinguish three groups, based on the level of abilities.

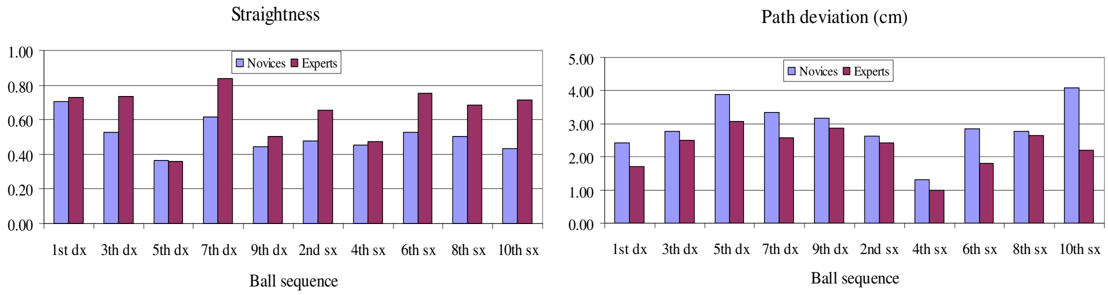

Fig. 2. Straightness and Path deviation for each single sub-movement and averaged on the novice and expert group.

Each segmented phase, related to a single sub-task, can be better characterized by two other parameters, previously not used for the whole exercise: the *straightness* (ratio of the straight line and the total distance of the hand travel between the start and end point of the task) and *path deviation* (maximum of perpendicular distance of the tip from the straight line). The use of these two parameters permits a wiser investigation in depth perception, because it take into account how the tips reach each single target, i.e. the movement of the instruments from a start to a end point of each single subtask, and does not involve the entire trajectory of the exercise. These parameters confirm the distinction between expert surgeons and novices and the greater improvements of novices during the session (Fig. 2).

Thanks to segmentation, the assessment of some parameters can be also focused on the hand that is not involved in the sub-task, and compared with the same parameters computed for the other hand, which is involved in the task. This allows not only to analyze the movement of the hand holding the instrument for the reaching task, but also the behaviour of the other hand, which only holds the instrument and waits for doing the next movement. This analysis of both hand motion showed substantial difference between experts and novices. In Fig. 3 this comparison is showed for the energy expenditure parameter and it is clear that surgeons have low energy consumption also for the hand that is not involved in the task.

4. Discussions and conclusions

In this paper, different parameters for the evaluation of surgical gesture were calculated for exercises, performed on a simulator, as a whole and for single sub-tasks. A segmentation procedure, based on tip coordinates processing, was used to split each exercise in consecutive sub-movements. Distinctions and evaluations have been also done between left and right hand behavior.

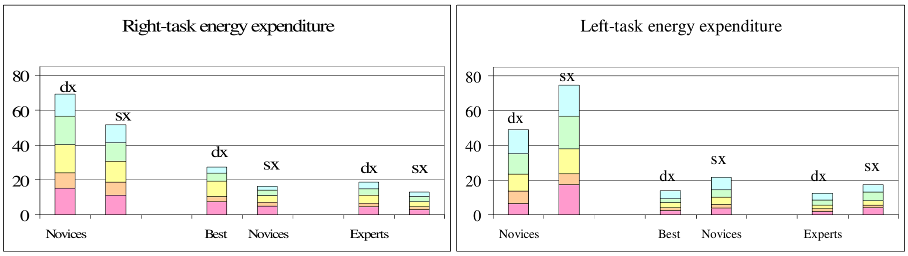

Fig. 3. Energy expenditure for whole exercise and single sub-task in both hands.

From this study we can observe different kind of subjects, each with a different approach to the laparoscopic task. Some novice subjects appear to be very unfamiliar with the instruments, but they show remarkable improvements during the session. Other novice subjects, instead, appear to be more similar to experts and very circumspect in using instruments. Finally the experts' group appears uniform in terms of ability levels, because of the high performance achieved with long periods of practice, while the group of novices appears more heterogeneous. The higher straightness and lower path deviation for experts denote that their path, covered during the exercise, is more straightly directed toward the target to be reached. Interestingly, straightness and path deviation appear to be very heterogeneous on all ten sub-tasks. We believe that this is due, firstly, to different depth perception of the balls in the virtual scenario framework, which in some case lead to more limited perception. Secondly, because of the constraint of trocars, subjects encounter more difficulty in performing a direct path from one task to another.

This work shows that an adequate and substantial set of parameters is necessary to investigate and analyze the surgeon's performance. Currently work is still in progress and our future commitment in this field is to continue to analyze the surgeon's gesture also for more complex procedures and with other sensor systems.

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