A biomechanical analysis of surgeon's gesture in a laparoscopic virtual scenario.

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Abstract. Minimally invasive surgery (MIS) has become very common in recent years thanks to many advantages that patients can get. However, due to the difficulties surgeons encounter to learn and manage this technique, several training methods and metrics have been proposed in order to, respectively, improve surgeon's abilities and assess his/her surgical skills. In this context, this paper presents a biomechanical analysis method of the surgeon's movements, during exercise involving instrument tip positioning and depth perception in a laparoscopic virtual environment. Estimation of some biomechanical parameters enables us to assess the abilities of surgeons and to distinguish an expert surgeon from a novice. A segmentation algorithm has been defined to deeply investigate the surgeon's movements and to divide them into many sub-movements.

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

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. 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) [6]. 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.

Most previous works in the field of surgical training in virtual environments revolve around the definition of metrics for an objective evaluation of the surgical performances. One of the main scope is to assess the abilities of surgeons and also to measure the skill level of experts and novices. Many kinematic parameters and various index have been proposed and also segmentation procedures have been employed to characterize different phases of movement [1]-[5]. The segmentation procedure is a more chance to deeply investigate the surgeon's gesture. It allows to split the surgeon's

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gesture into basic sub-movements: typical procedures include videotape review [3]-[4]. Unfortunately, even if a videotaped segmentation gives the opportunity to annotate the time-line of the entire exercise and identifies sub-movements, however it remains rather subjective and not rigorous.

In this paper the biomechanical parameters, computed from the motion of tip instruments during a typical Laparoscopic procedures, are presented. The scope of this work is, firstly, to investigate the relationship among several parameters, computed on the data concerning a whole exercise. Secondly, to asses the properties of single sub-movements, obtained by means of a segmentation procedure, based only on the tip coordinates. Our aim is to define parameters that allow us to deeply characterize the surgeon's movement during a surgical procedure, and also to distinguish expert surgeons from less experienced surgeons such as residents and novices. A careful consideration is done about the improvement of subjects during the session and their position on the learning curve.

1. Methods

We used the commercial laparoscopic simulator LapSim Basic Skills 2.2 (Surgical Science AB, Göteborg, Sweden) which allows to perform exercises in a virtual environment and easily 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. Each exercise consisted of reaching, alternatively with the right and left instruments, ten balls (spheres with radius of 15mm) which appeared one at a time in the virtual scenario. These exercises allow to train the surgeon's ability in the bi-manual movement coordination of surgical instruments and in depth perception using laparoscopic view.

1.1. Data processing and parameters

The tip positions of the two instruments, measured by the three encoders of the hardware interface, has been sampled at a frequency of 60 Hz, high enough to describe human gesture [7]. Components of both tips were off-line processed and the parameters listed below were computed. Only low-frequency components are present in surgeon's movements. However due to artefacts and some error of instruments, 3D position data is also contaminated by high-frequency noise. Since our data analysis involves first, second and third derivative, the acquired data are off-line filtered using a numerical fourth-order low-pass Butterworth filter, with cut-off frequency of 25 Hz.

Further a segmentation procedure is used to split the whole exercise in different sub-movements, which correspond to each ball to be reached in the exercise. 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 framework of the virtual scenario, it is possible to detect the time when a tip touches a ball. The algorithm procedure, used for segmentation, evaluates the distance between the centre of the ball and the position of the tip. When it is equal to the ball radius, then the task is completed.

- *Duration (T)*: that is the total time spent by subjects to complete the exercise (measured in seconds).
- *Path length (D)*: that is the length of the trajectory carried out by the tip of instrument during the trial. It is expressed in cm and is defined as:

$$D = \int_0^T \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2}\, dt \tag{1}$$

- *Mean speed (Vm)*: that is the speed of the tip, calculated with the finite-difference formula and averaged on the entire exercise (measured in cm/s).
- *Maximum speed (Vmax)*: that is the maximum value of the instrument speed during the whole session (cm/s).
- *Mean acceleration (Am)*: that is the acceleration of the tip, calculated with the finite-differences formula and averaged on the entire exercise (m/s^2).
- *Maximum acceleration (Amax)*: that is the maximum value of the instrument acceleration during the whole session (m/s^2).
- *Normalized jerk*: that is a measure of the motion smoothness during each trial and it is a rate of change in acceleration. It is normalized for different task durations and path lengths.

$$\mathrm{Jerk}_{\mathrm{norm}} = \sqrt{\frac{T^5}{2D^2} \int_0^T \left[\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^2\right] dt} \tag{2}$$

- *Straightness*: that is the ratio of the straight line, connecting the start and end of the task, and the actual tip path (total distance of the hand travel).
- *Path Deviation*: that is the maximum of perpendicular distance of the tip from the straight line connecting the start and end of the task (measured in cm).
- *IAV*: that is the integral of magnitude of the total acceleration vector (measured in m/s) and it represents a value correlated to the energy expenditure during the movement [9].

$$IAV = \int_0^T \sqrt{\left(\frac{d^2x}{dt^2}\right)^2 + \left(\frac{d^2y}{dt^2}\right)^2 + \left(\frac{d^2z}{dt^2}\right)^2}\, dt \tag{3}$$

2. Results

The time spent by subjects in each trials was useful to evaluate improvements in doing the task (Figure 1). Duration of whole experiments in novices was greatly inconstant and the duration trend from the first to the last trial was usually decreasing. In expert surgeons, the duration trend during the session was quite constant, with a mean value less than for the novices. This confirms the fact that experts' improvements usually are less than in the novices. However one of the novices had a constant trend, similar to experts, but with a duration mean value bigger then experts.

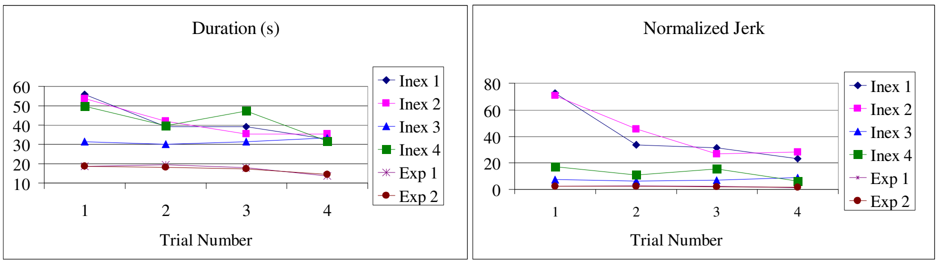

Figure 1. Durations of trial and normalized jerk (scaled by 10^6) for all subjects and trials.

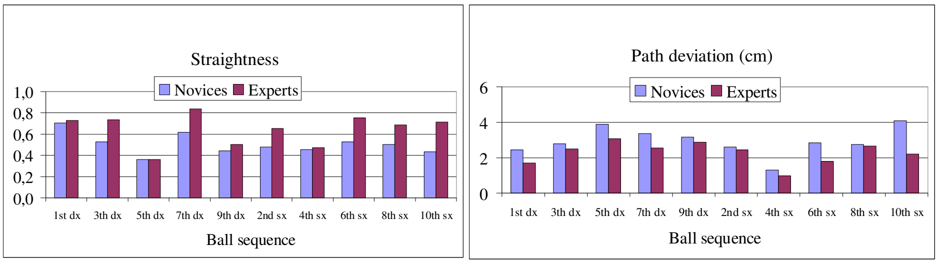

Figure 2. Straightness and path deviation for each single sub-movement.

In all subjects jerk values for both hands were quite similar. In Figure 1 normalized jerk, averaged for right and left hands, is shown for all subjects and trials. Expert surgeon movements appeared to be smoother than those of novices. In fact jerk values in experts were firmly low and constant, and are overlapping and difficult to distinguish in figure. Novices usually had high values, even if in some cases, when they are particularly able, their jerk values were similar to experts.

In Table 1 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 considered more able by seeing the previous parameters. 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.

In Figure 2, the straightness and the path deviation, calculated on the single sub-movement and averaged on both groups, are respectively shown. They appeared to be quite inconstant, depending on the single sub-task. On average, the straightness was higher in the expert group, while the path deviation was higher in the novice group.

Table 1. Kinematics parameters for both hands.

	Inex1		inex2		inex3		inex4		exp1		exp2	
	dx	sx	dx	Sx	dx	sx	dx	sx	dx	sx	dx	sx
Path (cm)	92.1	100.9	105.9	113.2	84.2	90.6	144.6	106.0	87.1	92.2	87.5	87.9
Vm (cm/s)	3.5	4.0	4.0	4.3	2.7	2.9	3.4	2.6	5.1	5.3	5.1	5.2
Vmax (cm/s)	52.8	67.7	103.3	70.3	26.2	35.1	32.4	43.0	48.8	43.9	51.1	42.2
Am (m/s^2)	2.4	2.6	2.7	2.9	1.0	1.1	1.2	0.9	1.8	1.9	1.8	1.8
Amax (m/s^2)	39.1	41.9	100.5	56.8	13.6	20.5	15.6	15.1	28.7	14.7	20.7	15.9

The IAV is a value greatly correlated to the energy expenditure of subject during the exercise [9]. In Figure 3, the level of energy expenditure in right and left-task, i.e.

when respectively the right and left hand is used to touch the balls and the other one is not used, are presented. On averaged, the energy expenditure is higher for the hand directly involved in the task, and for both hands it is higher in novices, even if best novices have a level consumption quite similar to experts. In Figure 3 the whole consumption is shown as a sum of consumption of each single sub-task.

3. Discussions

The proposed movement analysis in virtual laparoscopic scenario showed that it is complicated to find a distinctive threshold in the learning curve that permits to easily distinguish an expert from a novice. In fact, in the proposed exercise some inexpert subjects appear to be particularly able with respect to other novices and some of their estimated biomechanical parameters appear to be quite similar to those of experts. Consequently an adequate set of different biomechanical parameters has to be considered in order to estimate the skill level of expert and inexpert subjects.

In the inexpert group we found firstly different levels of ability, according to the personal skill and training experience, and secondly inexpert subjects faster than others to improve their abilities and capabilities during a whole session. Improvement of abilities reflects an high variability, i.e. standard deviation, of estimated parameters during all the trials included in the session. In the expert group, instead, the variability of estimated parameters during the whole session of experiments is low, according to the fact that, after a complete training procedure or a practise made, the level of ability for experts is more uniform.

High standard deviation and a decreasing trend of duration and jerk over the whole session suggests us that a subject is improving his performance and therefore that he is an inexpert surgeon. However subjects belonging to inexpert group with good abilities have shown a low standard deviation and a constant trend, showing a behaviour very similar to the experts, so that they can be confused as experts. This suggests the consideration that each parameter alone is not enough to evaluate the surgeon performances and that different parameters must necessarily be combined together. For example, if the estimation of duration and jerk standard deviation does not permit to assess that the third subject is an inexpert, because of that values are very similar to the expert subjects, however the averaged speed demonstrated how the third subject is actually the slowest one. As well, also the fourth subject has a jerk profile similar to the experts, but the averaged speed is lower and the duration is pretty long.

The mean speed appears to be higher in experts. In the inexpert group, instead, the mean speed is higher for the less able novices: this is due to the fact that more able novices are more circumspect in using instruments (lowest Amax and Vmax) and less able novices are characterized by possible unexpected and non-smooth movements (highest Amax and Vmax), typical of inexpert subjects. For the same reason, the mean acceleration is higher for less able novices and lower for more able.

Jerk values for experts has a low variability and lower mean value respect to the others. However some case of inexpert with a low variability and a similar mean value can be detect. Figure 1 seems to suggest us that there are four experts and two novices, but this is consequence of being very circumspect for novices that actually spent about ten seconds more than experts in completing task and have a little bit low mean speed.

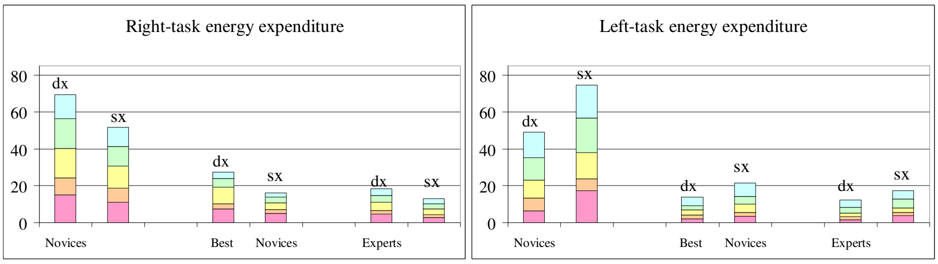

Figure 3. Energy expenditure for whole exercise and single sub-task in both hands.

The higher straightness and lower path deviation for experts denote that their path, covered during the trial, is more straight toward the task to be reached. Interestingly, straightness and path deviation appear to be very heterogeneous on all ten sub-tasks. We believe that it 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 difficult in performing a direct path from one task to another.

4. Conclusions

In this article a biomechanical analysis of the surgeon's gesture was performed and some parameters, calculated only using the coordinate of instrument tips, were defined to, firstly, assess the abilities of surgeons in the bi-manual movement of surgical instruments and in depth perception and, secondly, to find a criterion to distinguish experts from novices. Further a segmentation procedure, based on tip coordinates, was used to deeply investigate each single sub-movements of the gesture. This work shows that an adequate and substantial set of parameters is necessary to investigate and analyze the surgeon's performance. Actually this work is still in progress and our future commitment in this field is to analyze more complex surgical procedures with other sensor systems.

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