JOURNAL OF SURGICAL RESEARCH 188 (2014) 8–13

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.JournalofSurgicalResearch.com

Analysis of hand motion differentiates expert and novice surgeons

Munenori Uemura, MMedSci,[a] Morimasa Tomikawa, MD, PhD, FACS,[b] Ryuichi Kumashiro, MD,[b] Tiejun Miao, PhD,[c] Ryota Souzaki, MD, PhD,[b] Satoshi Ieiri, MD, PhD,[b] Kenoki Ohuchida, MD, PhD,[a] Alan T. Lefor, MD, MPH, FACS,[b] and Makoto Hashizume, MD, PhD, FACS[a,b,]*

[a] *Center for Advanced Medical Innovation, Kyushu University, Fukuoka, Japan*
[b] *Department of Advanced Medical Initiatives, Faculty of Medical Sciences, Kyushu University, Fukuoka, Japan*
[c] *TAOS Institute, Tokyo, Japan*

ARTICLE INFO

Article history:
Received 26 October 2013
Received in revised form
21 November 2013
Accepted 13 December 2013
Available online 19 December 2013

Keywords:
Clinical skills
Laparoscopic surgery
Surgical training
Kinematic analysis
Hand motion
Mathematical analysis

ABSTRACT

Background: The number of operations performed by a surgeon may be an indicator of surgical skill. The hand motions made by a surgeon also reflect skill and level of expertise. We hypothesized that the hand motions of expert and novice surgeons differ significantly, regardless of whether they are familiar with specific tasks during an operation.
Methods: This study compared 11 expert surgeons, each of whom had performed >100 laparoscopic procedures, and 27 young surgeons, each of whom had performed <15 laparoscopic procedures. Each examinee performed a specific skill assessment task, in which instrument motion was monitored using magnetic tracking system. We analyzed the paths of the centers of gravity of the tips of the needle holders and the relative paths of the tips using two mathematical methods of detrended fluctuation analysis and unstable periodic orbit analysis.
Results: Detrended fluctuation analysis showed that the exponent in the function describing the initial scaling exponent (α_1) differed significantly for experts and novices, being close to 1.0 and 1.5, respectively ($P < 0.01$). This indicated that the expert group had a greater long-range coherence with an intrinsic sequence and smooth continuity among a series of motions. Likewise, unstable periodic orbit analysis showed that the second period of unstable orbit was significantly longer for experts in comparison with novices ($P < 0.01$). This demonstrates mathematically that the hands of experts are more stable when performing laparoscopic procedures.
Conclusions: Objective evaluation of hand motion during a simulated laparoscopic procedure showed a significant difference between experts and novices.

* *Corresponding author*. Department of Advanced Medical Initiatives, Faculty of Medical Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka 812-8582, Japan. Tel.: +81 92 642 5992; fax: +81 92 642 5199.
E-mail address: mhashi@dem.med.kyushu-u.ac.jp (M. Hashizume).
0022-4804/$ – see front matter © 2014 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jss.2013.12.009

1. Introduction

Although laparoscopic surgery has many advantages, such as decreased scarring, faster recovery, and cosmetic advantages, laparoscopic surgical skills may be harder to learn for some surgeons, and in some ways differ from the techniques used in conventional open surgery. Specialized training is important and necessary for surgeons to perform laparoscopic surgery safely and accurately.

The number of operations performed by a surgeon is sometimes considered an indicator of surgical skill, and surgeons who have performed many operations are considered "expert surgeons." In addition to facilitating the safe and efficient conduct of an operative procedure, experience enables surgeons to seek strategic remedies when faced with difficulties during an operation. The hand motions made by a surgeon during an operation may also reflect the skill of a surgeon. It is sometimes said that surgeons seek "economy of motion" in reference to manipulating surgical instruments, but measuring this desirable trait is a complex matter. We hypothesized that the hand motions of expert surgeons differ significantly from those of novice surgeons, regardless of whether the expert surgeons are familiar with the specific tasks during a particular operation.

Ordinarily, expert surgeons are distinguished from novice surgeons by performance scores, which are based on performance time, the speed with which instruments are manipulated, and the number of errors made during an operation. Performance scores are frequently used to assess surgeons being trained to perform laparoscopic procedures [1–4] and have been used to distinguish experts from novices in the conduct of laparoscopic procedures. Performance scores alone, however, cannot assess the skills required for laparoscopic surgery. Other measures that may distinguish expert from novice surgeons being trained in laparoscopic procedures include psychomotor skills and eye–hand coordination [5–11], although these factors alone are neither necessary nor sufficient for distinguishing the skills of expert and novice surgeons in performing laparoscopic procedures.

The goal of this study was to identify latent factors possessed by experts in the conduct of laparoscopic procedures. Kinematic analysis of the motions made by a surgeon's forceps during a skill assessment task were evaluated, and two mathematical analysis techniques used to assign numerical values to features of surgical performance such as "fluctuation" and "unstable periodic orbits," which may at least in part describe the concepts attributed to "economy of motion."

2. Materials and methods

2.1. Study participants

Participants in this study included 38 surgeons who have taken a laparoscopic surgery training course held at Kyushu University Training Center for Minimally Invasive Surgery [1,12,13]. Examinees were divided into two groups. The expert group included 11 expert surgeons, each of whom had performed >100 laparoscopic surgical procedures and completed the skill assessment task, and the novice group had 27 young surgeons, each of whom had performed <15 laparoscopic surgeries and had not completed the skill assessment. Participants were given informed consent by staff of the Kyushu University Training Center for Minimally Invasive Surgery and voluntarily agreed to participate.

2.2. Assessment task and objective data collection

Figure 1 shows the skill assessment task, which was developed at the Kyushu University Training Center for Minimally Invasive Surgery to evaluate the skills of trainees who had taken the training course [14]. Two identical needle holders were set into the box. A six-degree-of-freedom magnetic tracking sensor was mounted onto the tip of each needle holder. The box contained a stretched rubber sheet, with a printed circle and eight pairs of dots (Fig. 1A). Each examinee was required to pick up and hold the needle correctly, tie two throws after the placement of the first suture at any pair of dots (Fig. 1B), and then continuously suture each pair of dots along the printed circle (Fig. 1C). Sutures were placed from an outer dot to the corresponding inner dot. The assessment task ends with the final two throws tied to the tail of the first suture (Fig. 1D). The entry and exit points of the needle had to be placed precisely on the center of the dots. The time allotted for the task was 7 min.

During the assessment, the path of the tip of each needle holder was tracked using the magnetic tracking sensor and the data recorded. The paths of the centers of gravity of both instruments (Fig. 2A) and the relative paths of the centers of movement of both tips (Fig. 2B) were then analyzed using two mathematical methods.

2.3. Mathematical analysis methods

2.3.1. Detrended fluctuation analysis

Detrended fluctuation analysis has several advantages over conventional methods, including its ability to detect long-range correlations embedded in nonstationary time series and the avoidance of spurious measurements, and has been previously described [15]. First, the signal time series is integrated to "mimic," a random walk after subtracting the mean value of the signal. Next, the integrated time series $y(n)$ is divided into boxes of equal length n. Within each box, a least-squares linear fit of the data, representing the trend within that box, is calculated. Subsequently, the integrated time series is detrended by subtracting the local trend in each box. Finally, the previously mentioned computations are repeated over all time scales (box size n) to yield a relationship between $F(n)$ and box size n (i.e., the observation window). A power-law relationship between the average root-mean-square fluctuation function $F(n)$ and the observation window size indicate scaling. Fluctuation correlations are characterized by a scaling exponent α as

$$F(n)\alpha n^{a} \quad (1)$$

We calculated the fluctuation function by increasing the value of n. Two different scaling regimes were characterized using the scaling exponents α_1 and α_2. Of these, we only used α_1 estimated for the range within 3.2 s in evaluating scaling behavior. A lower value of α_1 indicates less fluctuation.

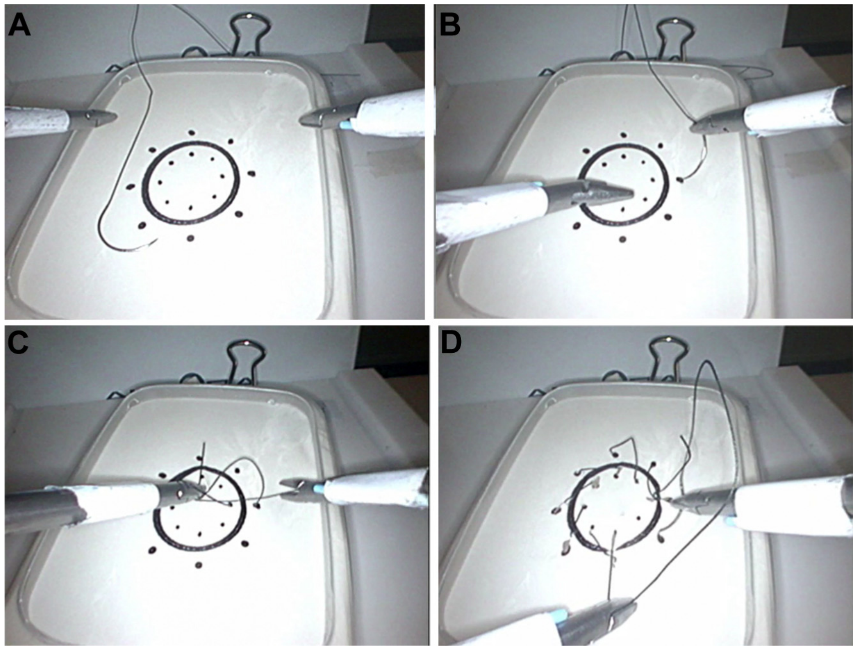

Fig. 1 – The skills assessment task. (A) A stretched rubber sheet, with a printed circle and eight pairs of dots, is placed in a simulation box. (B) Each examinee began by picking up the needle and holding it correctly. (C) Each examinee tied two throws, starting at any pair of dots and then continuously placing a suture at each pair of dots around the circle. Each suture was placed from an outer dot to the corresponding inner dot. (D) The final two throws were tied to the tail of the first suture. (Color version of figure is available online.)

2.3.2. *Unstable periodic orbits analysis*

We constructed a chaotic attractor to detect unstable periodic orbits in the experimental data. Properties such as the unstable period *T* are found to be characteristic of skill in laparoscopic surgeries. We used the recurrence method to extract unstable periodic orbits [16,17]. The procedure consists of first constructing the attractor from the time series, then taking the point $\mathbf{x}_i$ on the attractor. The dynamical steps follow as $\mathbf{x}_{i+1},\mathbf{x}_{i+2},\ldots,\mathbf{x}_j$ until the smallest index $j > i$ is found, such that $||\mathbf{x}_i-\mathbf{x}_j|| < e$, where e is a small predetermined distance below which two points on the attractor are considered to be coincident. If such a *j* exists, then $T = j - i$, and $\mathbf{x}_i$ represents a recurring point. The procedure is repeated for all points $i = 1,\ldots,N$ on the constructed attractor. Descriptions of detrended fluctuation analysis and unstable periodic orbit analysis are summarized in Table 1.

2.4. *Statistical analysis*

Results for the expert and novice groups were compared using the Mann-Whitney *U*-test. A *P* value <0.05 was defined as statistically significant.

3. Results

3.1. *Detrended fluctuation analysis*

We applied detrended fluctuation analysis to the center movement of both hands for all 38 participants. Figure 3A shows the plot for the initial scaling exponent, α_1. The exponent α_1 was significantly higher for the novice than for the expert group ($P < 0.01$), with α_1 for the novice group being about 1.5 and that for the expert group about 1.0 ($1/f$), indicative of Brown noise (i.e., no correlation). These results indicate that the expert group, with a lower value of α_1 was closer to "long-range coherence," implying an intrinsic sequence and smooth continuity among a series of motions.

3.2. *Unstable periodic orbits*

Figure 3B shows the result of unstable periodic orbit analysis. The period of unstable orbit 2 was significantly longer in the expert group than in the novice group ($P < 0.01$). Thus, compared with novices, the center gravity of the hands of experts stayed longer in unstable periodic orbit 2, indicating that the hands of experts were more stable in performing manipulation of the instruments in the laparoscopic simulation.

4. Discussion

The number of operations performed by a surgeon is sometimes considered an indication of surgical skill, and surgeons who perform large numbers of a particular type of surgery are often referred to as "expert surgeons" [18–20]. We have defined expert surgeons as those who previously performed >100 laparoscopic procedures. The aim of this study was to identify the unique characteristics of expert surgeons through a mathematical analysis of hand motion. We have applied mathematical analyses to objectively assess kinematic data

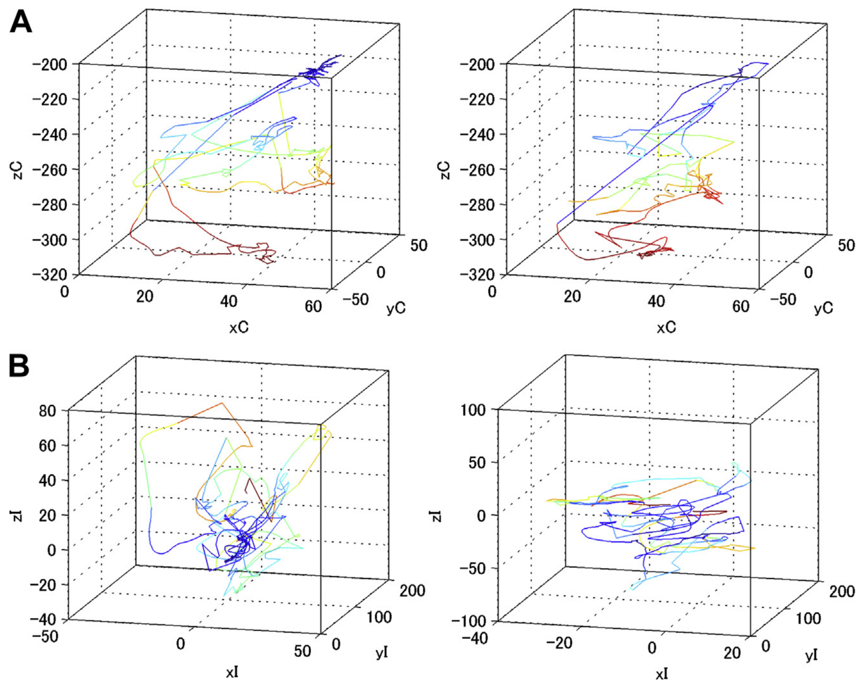

Fig. 2 – Examples of traced tracks of (A) center of gravity and (B) relative movement for two hands of an expert during doing the assessment task. (A) Plot a trajectory portrait in three-dimensional coordinates of (xC, yC, zC) for motions of center of gravity of two hands. The left panel shows the results of a novice and the right panel is an expert. The expert shows a more focused and flexible trajectory. (B) Plot a trajectory portrait in three-dimensional coordinates of (xI, yI, zI) for the relative motions of two hands. The left panel is a novice and right panel is an expert. The expert shows a more coherent and less noisy trajectory. (Color version of figure is available online.)

describing the motions of a surgeon's forceps during a skill assessment task suitable for a surgeon. These mathematical analysis techniques were originally applied to investigate the differences in body motion between experts and novices in the human motion field [21,22]. According to Nakayama *et al.* [22], the application of nonlinear time-series analysis, such as that conducted in this study, add additional evidence that reflects significant characteristics in motor control of trained movement. Nonlinear time-series analyses, together with other nonlinear methods, will provide us useful information on the spatiotemporal organization of human motion.

An ideal surgical procedure results in no complications, minimal bleeding, and no mistakes. This may be accomplished in part by beautiful and clever maneuvering, a concept as yet undefined. The findings of this study suggest that beautiful and clever surgical maneuvering is related to three factors including fluency of motion, flexibility, and stability. Fluency of motion can be defined as a lack of abrupt maneuvers or "jerkiness." In physics, a jerk, also known as a jolt, surge, or lurch, is the rate of change of acceleration; that is, the derivative of acceleration with respect to time, the second derivative of velocity, or the third derivative of position [23]. Flexibility is the ability to alter the center of motion in such a way as to be prepared to perform the next motion; for example, the way a boxer moves in the ring, or the manner in which a professional race car driver maneuvers the steering wheel. Stability can be defined as maintaining a center of gravity during constant motions, as exemplified by a marathon runner or judo expert.

Even in the expert surgeon group there are high and low outliers. This probably accurately reflects the variation that we all know exists in surgery. Some experienced surgeons are technically capable, but may not look graceful or skilled while operating, whereas others are clearly gifted in their manual

Table 1 – Method of analysis.

Method	DFA	UPO
Input	1. Time series data from center of gravity of two hands during a task 2. Time series data from relative movement of two hands during a task	1. Time series data from center of gravity of two hands during a task 2. Time series data from relative movement of two hands during a task
Output	Scaling exponent (α_1)	Period of unstable orbit (T)
Interpretation	Flexibility	Stability
	Smooth continuity among a series of motions	Stable in performing manipulation

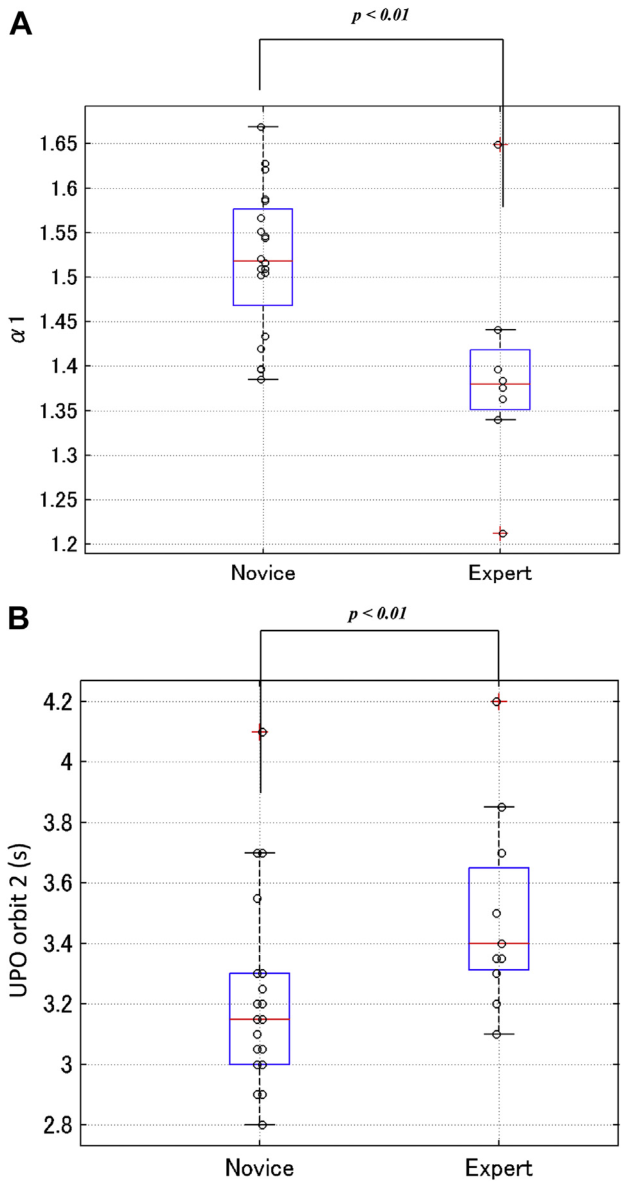

Fig. 3 – (A) Results of detrended fluctuation analysis showing the scaling exponents for both novice and expert groups. The exponent α_1 was significantly higher for the novice than for the expert group ($P < 0.01$), with α_1 for the novice group being about 1.5 (indicative of Brown noise) and that for the expert group about 1.0 (indicative of $1/f$). These results indicate that the expert group demonstrates an intrinsic sequence and smooth continuity among a series of motions. (B) Results of period of the second unstable periodic orbit for novice and expert groups. The period of unstable orbit 2 was significantly longer in the expert than in the novice group ($P < 0.01$). These results indicate that the hands of experts were more stable in performing manipulation of the instruments in the laparoscopic simulation than novices. (Color version of figure is available online.)

skills and make even the most difficult technical skills look relatively simple. This research tool is interesting, because it does not necessarily define competency, but rather quantifies the grace with which competency is performed. We think this is valuable to measure, but it remains unclear how this will ultimately be applied to the evaluation of surgical skill. It is still not clear that to do surgery, a surgeon does not only need to do it accurately and safely, but also has to look good while doing it. These results can be used to educate surgeons to accurately and safely perform laparoscopic surgery. Further studies are needed to identify the process by which a young surgeon develops surgical skill and will develop a new skill assessment system using these findings.

In this study, we applied detrended fluctuation analysis to the center of movement of both hands in the two groups of surgeons evaluated, which allowed a quantitative analysis of hand motion. We found that the expert group maintained better "long-range coherence," defined as an intrinsic sequence of a series of motions and smooth continuity among them, indicating that flexibility was greater in the expert than in the novice group. Unstable periodic orbits analysis showed that the period of unstable orbit 2 was significantly longer in the expert than in the novice group ($P < 0.01$). Thus, compared with novices, the center of gravity of the hand of experts stayed longer in unstable periodic orbits orbit 2, suggesting that the hand of an expert is more stable in performing laparoscopic procedures. Furthermore, "jerkiness" was less apparent in the expert than in the novice group [24]. These concepts do not come as a surprise, but the ability to study this in a quantitative manner through detrended fluctuation analysis and unstable periodic orbits analysis provides surgical educators with a new tool for training and assessment. Using a surgical skill assessment system based on these findings, trainees can evaluate their skill level. The results of these evaluations can be given back to the trainees, to help them gain awareness of opportunities for improvement.

In the field of robotics, Lin *et al*. [25] have reported differences between expert surgeons and novice surgeons in the posture of the surgeons, the angle of the surgeons' shoulders, and the angle of surgeons' hand rotations. These may be factors that correlate with laparoscopic surgical skills and also allow a quantitative assessment. Techniques used in other fields, such as assessment of the skill of engineers, may apply to skill assessment for laparoscopic surgery [26–28]. By using these mathematical analyses, we found that the expert group was superior in performing beautiful and clever surgical maneuvers.

5. Conclusions

These mathematical analyses provide a new way of quantitative differences in the hand motions of expert and novice surgeons during a simulated laparoscopic procedure. Further studies of these analytic techniques are indicated, and may provide a useful tool in both training and assessment of future laparoscopic surgeons.

Acknowledgment

Drs Uemura, Tomikawa, Kumashiro, Miao, Sozaki, Ieiri, Ohuchida, Lefor, and Hashizume have no conflicts of interest or financial ties to disclose.

REFERENCES

[1] Ieiri S, Ishii H, Souzaki R, et al. Development of an objective endoscopic surgical skill assessment system for pediatric surgeons: suture ligature model of the crura of the diaphragm in infant fundoplication. Pediatr Surg Int; 2013 (in press).

[2] Aggarwal R, Grantcharov T, Moorthy K, et al. A competency-based virtual reality training curriculum for the acquisition of laparoscopic psychomotor skill. Am J Surg 2006;191:128.

[3] McNatt SS, Smith CD. A computer-based laparoscopic skills assessment device differentiates experienced from novice laparoscopic surgeons. Surg Endosc 2001;15:1085.

[4] Brydges R, Farhat WA, El-Hout Y, Dubrowski A. Pediatric urology training: performance-based assessment using the fundamentals of laparoscopic surgery. J Surg Res 2010;161:240.

[5] Egi H, Okajima M, Kawahara T, et al. Scientific assessment of endoscopic surgical skills. Minim Invasive Ther Allied Technol 2010;19:30.

[6] Wilson MR, McGrath JS, Vine SJ, et al. Perceptual impairment and psychomotor control in virtual laparoscopic surgery. Surg Endosc 2011;25:2268.

[7] Gallagher AG, Smith CD, Bowers SP, et al. Psychomotor skills assessment in practicing surgeons experienced in performing advanced laparoscopic procedures. J Am Coll Surg 2003;197:479.

[8] Yamaguchi S, Konishi K, Yasunaga T, et al. Construct validity for eye-hand coordination skill on a virtual reality laparoscopic surgical simulator. Surg Endosc 2007;21:2253.

[9] Verdaasdonk EGG, Dankelman J, Lange JF, Stassen LPS. Transfer validity of laparoscopic knot-tying training on a VR simulator to a realistic environment: a randomized controlled trial. Surg Endosc 2008;22:1636.

[10] Iwata N, Fujiwara M, Kodera Y, et al. Construct validity of the LapVR virtual-reality surgical simulator. Surg Endosc 2011; 25:423.

[11] Hofstad EF, Våpenstad C, Chmarra MK, et al. A study of psychomotor skills in minimally invasive surgery: what differentiates expert and nonexpert performance. Surg Endosc 2013;27:854.

[12] Tanoue K, Ieiri S, Konishi K, et al. Effectiveness of endoscopic surgery training for medical students using a virtual reality simulator versus a box trainer: a randomized controlled trial. Surg Endosc 2008;22:985.

[13] Ieiri S, Nakatsuji T, Higashi M, et al. Effectiveness of basic endoscopic surgical skill training for pediatric surgeons. Pediatr Surg Int 2010;26:947.

[14] Yamaguchi S, Yoshida D, Kenmotsu H, et al. Objective assessment of laparoscopic suturing skills using a motion-tracking system. Surg Endosc 2011;25:771.

[15] Miao T, Hashiguchi T, Maruyama I. Nonlinear analysis of heart rate variability and plethysmogram in subjects with normal and abnormal cardiovascular function. 2006 IEEE International Conference on Systems, Man and Cybernetics. IEEE 2006;2885–2890

[16] Grebogi C, Ott E, Yorke JA. Unstable periodic orbits and the dimensions of multifractal chaotic attractors. Phys Rev A 1988;37:1711.

[17] Socolar J, Sukow D, Gauthier D. Stabilizing unstable periodic orbits in fast dynamical systems. Phys Rev E Stat Phys Plasmas Fluids Relat Interdicip Topics 1994;50: 3245.

[18] Aggarwal R, Grantcharov TP, Eriksen JR, et al. An evidence-based virtual reality training program for novice laparoscopic surgeons. Ann Surg 2006;244:310.

[19] Wilson M, McGrath J, Vine S, et al. Psychomotor control in a virtual laparoscopic surgery training environment: gaze control parameters differentiate novices from experts. Surg Endosc 2010;24:2458.

[20] Bell AK, Zhou M, Schwaitzberg SD, Cao CGL. Using a dynamic training environment to acquire laparoscopic surgery skill. Surg Endosc 2009;23:2356.

[21] Akay M, Sekine M, Tamura T, et al. Fractal dynamics of body motion in post-stroke hemiplegic patients during walking. J Neural Eng; 2004:111.

[22] Nakayama Y, Kudo K, Ohtsuki T. Variability and fluctuation in running gait cycle of trained runners and non-runners. Gait Posture; 2010:331.

[23] Liu D, Todorov E. Evidence for the flexible sensorimotor strategies predicted by optimal feedback control. J Neurosci 2007;27:9354.

[24] Kahol K, Satava RM, Ferrara J, Smith ML. Effect of short-term pretrial practice on surgical proficiency in simulated environments: a randomized trial of the “preoperative warm-up” effect. J Am Coll Surg 2009;208:255.

[25] Lin Z, Uemura M, Zecca M, et al. Objective skill evaluation for laparoscopic training based on motion analysis. IEEE Trans Biomed Eng 2013;60:977.

[26] Asada H, Izumi H Direct teaching and automatic program generation for the hybrid control of robot manipulators. Proceedings. 1987 IEEE International Conference on Robotics and Automation. Institute of Electrical and Electronics Engineers. 1987;1401

[27] Kawasaki H, Shimomura H, Shimizu Y. Educational–industrial complex development of an anthropomorphic robot hand “Gifu hand”. Adv Robotics 2001;15:357.

[28] Yamamoto M, Koshikawa K Human motion analysis based on a robot arm model. Proceedings. 1991 IEEE Computer Society Conference on Computer Vision and Pattern Recognition. IEEE Comput. Sco. Press, 1991;664–665