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Skills evaluation in minimally invasive surgery using force/torque signatures

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Abstract
Background: One of the more difficult tasks in surgical education is to teach the optimal application of instrument forces and torques necessary to facilitate the conduct of an operation. For laparoscopic surgery, this type of training has traditionally taken place in the operating room, reducing operating room efficiency and potentially affecting the safe conduct of the operation. The objective of the current study was to measure and compare forces and torques (F/T) applied at the tool/hand interface generated during laparoscopic surgery by novice (NS) and experienced (ES) surgeons using an instrumented laparoscopic grasper and to use this data for evaluating the skill level.
Methods: Ten surgeons (five-NS, five-ES) performed a cholecystectomy and Nissen fundoplication in a porcine model. An instrumented laparoscopic grasper with interchangeable standard surgical tips equipped with a three-axis F/T sensor located at the proximal end of the grasper tube was used to measure the F/T at the hand/tool interface. In addition, one axis force sensor located at the grasper's handle was used to measure the grasping force. F/T data synchronized with visual view of the tool operative maneuvers were collected simultaneously via a novel graphic user interface incorporated picture-in-picture video technology. Subsequent frame-by-frame video analysis of the operation allowed a definition of states associated with different tool/tissue interactions within each step of the operation. F/T measured within each state were further analyzed using vector quantization (VQ). The VQ analysis defines characteristic sets of F/T in the database that were defined as F/T signature.
Results: The magnitude of F/T applied by NS and ES were significantly different ($p < 0.05$) and varied based on the task being performed. Higher F/T magnitudes were applied by NS than by ES when performing tissue manipulation, whereas lower F/T magnitudes were applied by NS than by ES during tissue dissection. Furthermore, the time to complete the surgical procedure was longer for NS by a factor of 1.5–4.8 when compared to the time for ES. State analysis suggests that most of this time is consumed in an [idle] state, in which movements of the surgeon make no tissue contact.
Conclusions: Preliminary data suggest that F/T magnitudes associated with the tool/tissue interactions provide an objective means of distinguishing novices from skilled surgeons. Clinical F/T analysis using the proposed technology and methodology may be helpful in training, developing surgical simulators, and measuring technical proficiency during laparoscopic surgery.

Key words: Laparoscopy — Training — Technical Skills — Force-torque signatures — Haptics — Surgical simulators — Minimally invasive surgery

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One of the most difficult tasks in surgical education is to teach the optimal application of instrument handling necessary to conduct an operation. This is especially problematic in the field of minimally invasive surgery (MIS), where the teacher is one step removed from actual tissue contact. For laparoscopic surgery, this type of training has traditionally taken place in the operating room, thereby reducing operating room efficiency and potentially affecting the safe conduct of the operation.

The use of virtual reality models for teaching these complex surgical skills has been a long-term goal of numerous investigators [5, 6, 9]. The development of such a system would provide a less stressful learning environment for the surgical novice while eliminating risk to the patient, but it requires an understanding of the various components that comprise a realistic and useful training system [7]. Although other studies have focused on the tool-tip/tissue interaction and deformation [1, 3, 4, 8] this research measured the forces and torques (F/T) applied at the surgeon's hand/tool interface while performing minimally invasive surgery (MIS).

The objective of this study was to measure the F/T,

Table 1. Definitions of surgical procedure steps and type of tool tip used (bold steps performed but not recorded)

Procedure	Step	Description	Tool type	Hand	Video F/T
Laparoscopic Cholecystectomy	LC-1	Positioning gallbladder	Atraumatic grasper	L	+
	LC-2	Exposure of cyctic duct	Curved dissector	R	+
	LC-2**	Divide of cyctic duct	Scissors	R	–
	LC-3	Dissection of Gallbladder fossae	Curved dissector	R	+
	LC-4	Exposure of cyctic artery	Curved dissector	R	–
	LC-4*	Dividing artery	Scissors	R	–
Laparoscopic Nissen Fundoplication	LNF-1	Dissecting right crus	Surgiwand	R	–
	LNF-2	Dissecting left crus	Surgiwand	R	–
	LNF-3	Dissecting esophagus/blunt	Curved dissector	R	+
	LNF-4	Placing a wrap around the esophagus	Babcock grasper	R	+
	LNF-5	Suture wrap/intracorporeal knot tying with needle holder	Curved dissector	R	+
	LNF-6	Coronal sutures/intracorporeal knot tying	Endostitch	R	–

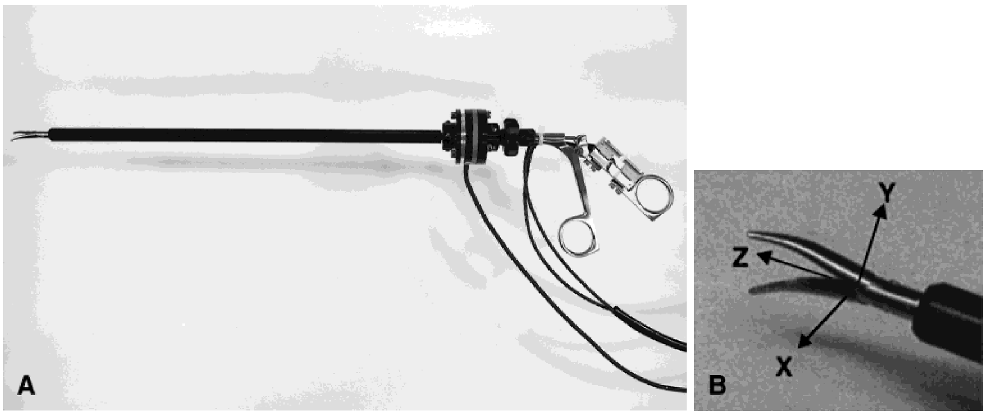

Fig. 1. The instrumented endoscopic grasper. **A** The grasper with the three-axis force/torque sensor implemented on the outer tube and a force sensor located on the instrument handle. **B** The tool tip and *x,y,z* frame aligned with the three-axis force/torque sensor.

identifying F/T signatures and analyzing how their signatures are distributed while performing laparoscopic surgery by novice (NS) and experienced (ES) surgeons using an instrumented endoscopic grasper. F/T signatures are a typical set of force and torque components associated with different tool-tip/tissue interactions that characterize cluster centers in a multidimensional database.

Statistical models of the quantitative knowledge gained in this study can be used to characterize surgical skills for training novice surgeons in performing laparoscopic procedures. Two areas in which the F/T signature database might be used are (a) virtual reality (VR) (developing haptic devices for realistic force feedback VR simulations of MIS procedures), and (b) minimally invasive surgical robotics (optimizing mechanisms and actuators).

Materials and methods

Subjects and protocol

Ten surgeons (five NS and five ES) performed a laparoscopic cholecystectomy and laparoscopic Nissen fundoplication in a porcine model. Protocols for anesthetic management, euthanasia, and survival procedures were reviewed and approved by the Animal Care Committee of the University of Washington and the Animal Use Review Division of the U.S. Army Veterinary Corps.

Each operation was subdivided into several steps (Table 1). Although all the steps were performed in each procedure, data were recorded only when the instrumented endoscopic tool was used with the following tool tips: atraumatic grasper, curved dissector, or Babcock grasper.

Experimental system setup

Two types of information were acquired while performing laparoscopic procedure: (a) F/T data measured at the surgeons' hand/tool interface, and (b) visual information about the tool tip's interaction with the tissues. The two sources of information were synchronized in time and recorded simultaneously for subsequent analysis using picture-in-picture video technology.

The F/T at the interface between the surgeon's hand and the endoscopic grasper handle were measured by two sensors. The first sensor was a three-axis F/T sensor (ATI mini-model), which was mounted into the outer tube (proximal end) of a standard reusable 10-mm endoscopic grasper (Karl Storz) (Fig. 1A). The sensor was capable of simultaneous measurements of three components of force (F_x ,F_y ,F_z) and three components of torque (T_x ,T_y ,T_z) in a Cartesian frame (Fig. 1B). The sum of the applied forces and torques at the tool-tip/tissue interface and the tool/trocar interface were transferred through the grasper structure to the surgeon's hand, as occurs in a normal instrument, and vice versa. The sensor orientation was such that the x and z axes formed a plane parallel to the tool's internal jaw contact surface with the jaw closed, and the y and z axes defined a plane perpendicular to that surface (Fig. 1B). A second force sensor was mounted to the endoscopic grasper handle to permit the measurement of grasping force (*Fg*) applied by the surgeon on the instrument.

The grasper had a reticulating feature that enabled the surgeon to change the orientation of the tool tip relative to the grasped tissue without changing the handle orientation. The alignment between tool tip origin relative to the sensor remained unchanged since the outer tube and the tool tip are linked mechanically.

The F/T data were integrated with the laparoscopic camera view of instrument activity (Fig. 2). The seven channels F/T data (F_x, F_y, F_z, T_x, T_y,

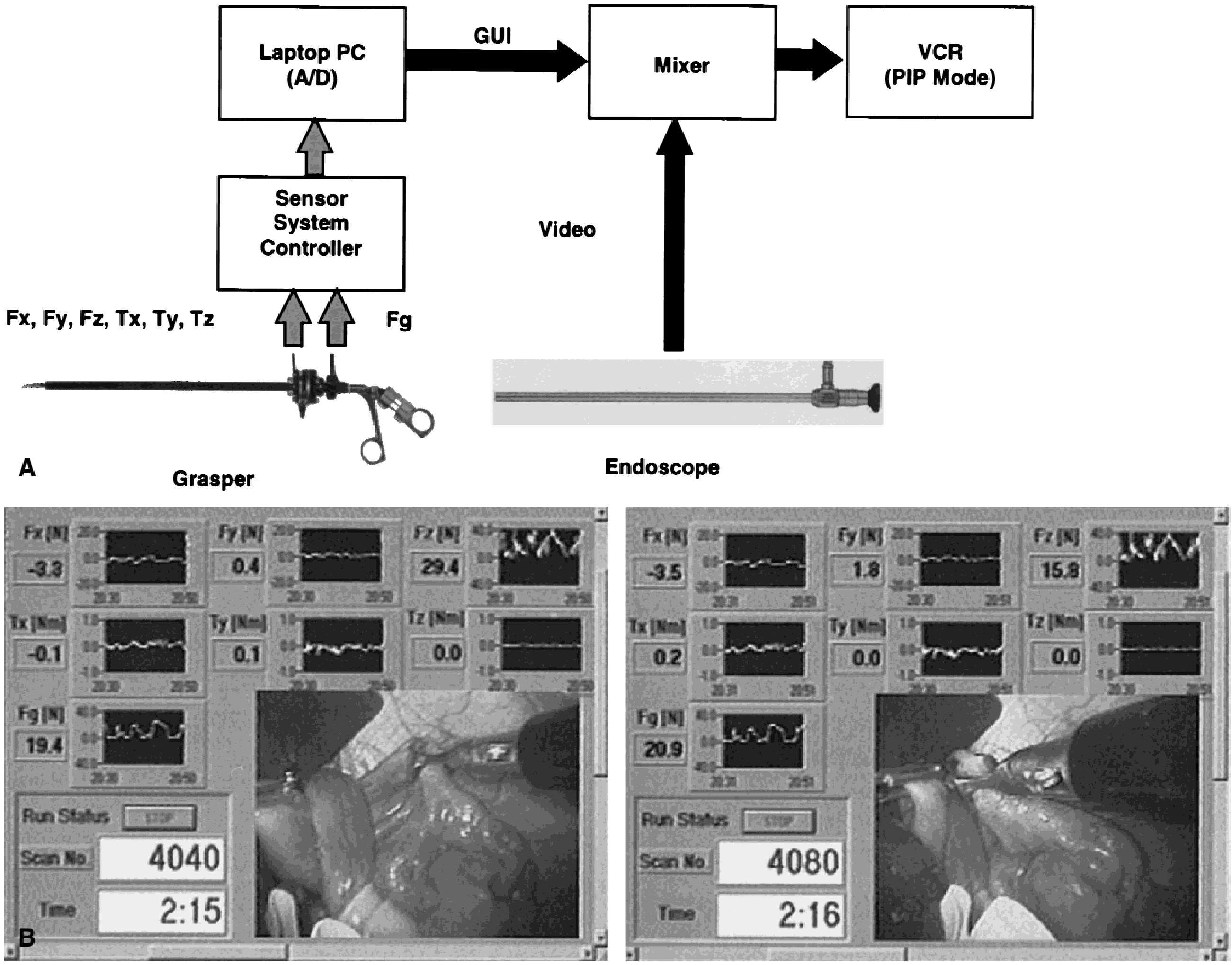

Fig. 2. Experimental setup. **A** Block diagram of the experimental setup integrating the force/torque data and the view from the endoscopic camera. **B** Real-time graphical user interface (GUI) of force/torque information synchronized with the endoscopic view of the procedure using picture-in-picture mode.

T_z, F_g) were sampled at 30 Hz using a laptop computer with a PCMCIA 12 bit A/D card (DAQCard 1200, National Instruments) (Fig. 2A). A LabView (National Instruments) application was developed with a graphical user interface for acquiring and visualizing the F/T data in real time (Fig. 2) during an actual operation. The visual view from the endoscopic camera that monitored the movement of the grasper's tip while interacting with the internal organs/tissues was integrated with the F/T data using a video mixer in a picture-in-picture mode, allowing correlation of the F/T data with instrument activity. The integrated interface was recorded during the operation for subsequent frame-by-frame analysis (Fig. 2B).

Data analysis

Two types of analysis were performed on the raw data: (a) video analysis encoding each step of the operation based on a predefined list of tool-tip/tissue interaction defining states, and (b) vector quantization (VQ) encoding the F/T data into signatures that were typical sets of F/T (F_x, F_y, F_z, T_x, T_y, T_z, F_g) representing cluster centers in the data. Each step of the operation was analyzed based on a total number of 14 different discrete tool-tissue interactions or states (Table 2). Upon further analysis, it became clear that each identified surgical maneuver (state) while interacting with the tissue had a unique F/T pattern. For example, isolation of the cystic duct and artery in laparoscopic cholecystectomy involves performing repeated pushing and spreading maneuvers, which in turn require application of pushing forces mainly along the z axis (F_z) and spreading forces (F_g) on the handle. Two expert surgeons independently performed frame-by-frame state analysis of the videotape with similar results.

The 14 states can be grouped into three broad types based on the number of movements performed simultaneously. Fundamental maneuvers were defined as type I and included the idle state (moving the tool in space without touching any structures within the insufflated abdomen). The forces and torques used in this state represent mainly the interaction of the trocar with the abdominal wall in addition to gravitational and inertial forces. In the grasping and spreading states, compression and tension were applied to tissue by closing/opening the grasper handle. In the pushing state, compression was applied on the tissue by moving the tool along the z axis. For sweeping, the tool was placed in one position while rotating around the x and y axes (trocar frame). Type II and type III were states defined as combinations of two or three states defined by group I (Table 2).

The F/T analysis used a VQ algorithm to define cluster centers in a multidimensional F/T data (F_x ,F_y ,F_z ,T_x ,T_y ,T_z ,F_g). This process was done using four steps.

During the first step, the 7D force/torque data vector was reduced to a 5D vector by calculating the magnitude of the forces and torques in the xy plane (F_{xy} ,T_{xy}).

During the second step, a pattern recognition analysis (clustering analysis) known as the K-means algorithm was used to define cluster centers and known F/T signatures for each state defined in Table 2. Each force/torque signature represented a cluster centered in a five-dimensional space. The F/T signatures are discrete symbols representing clusters in the database.

Table 2. Definition of states and the corresponding directions of forces and torques applied in laparoscopic cholecystectomy and Nissen fundoplication

Type	State name	State acronym	Force/torque Fx	Fy	Fz	Tx	Ty	Tz	Fg
I	Idle	ID	*	*	*	*	*	*	*
	Grasping	GR							+
	Spreading	SP							–
	Pushing	PS			–				
	Sweeping (lateral retraction)	SW	+/–	+/–		+/–	+/–		
II	Grasping - pulling	GR-PL			+				+
	Grasping - pushing	GR-PS			–				+
	Grasping - sweeping (grasping – lateral retraction)	GR-SW	+/–	+/–		+/–	+/–		+
	Pushing - spreading	PS-SP			–				–
	Pushing - sweeping	PS-SW	+/–	+/–	–	+/–	+/–		
	Sweeping - spreading	SW-SP	+/–	+/–		+/–	+/–		–
III	Grasping- pulling - sweeping	GR-PL-SW	+/–	+/–	+	+/–	+/–		+
	Grasping - pushing - sweeping	GR-PS-SW	+/–	+/–	–	+/–	+/–		+
	Pushing - sweeping - spreading	PS-SW-SP	+/–	+/–	–	+/–	+/–		–

During the third step, the entire database was encoded according to the predefined signatures so that in each time interval the F/T were associated with one of the signatures that were predefined based on minimizing the Euclidean distance between them. As a result, a one-dimensional list of symbols was generated, replacing the seven-dimensional vector. Each symbol represented a F/T magnitude associated with one of the tool/tissue interaction.

In final step, a statistical analysis of the F/T signatures magnitude distribution was performed. In order to perform the statistical analysis, the entire F/T database was lumped into two groups—the NS group and the ES group. The distribution of the F/T signatures for each tool/tissue interaction was then calculated for the NS and ES groups performing the different steps of the MIS procedures. The distributions of the F/T signatures applied by the NS and the ES were tested to identified tool/tissue interactions in which the F/T magnitude distributions of the two groups were significantly different using the median test (nonparametric method) combined with the fourfold point statistical procedure.

Using the human language as an analogy, the VQ was preformed to identify the basic “words” of the MIS “language” for creating a “dictionary.” Just as a single word is pronounced differently by different people, the same tool/tissue interaction is performed differently by different surgeons, yet they all share the same meaning, or outcome, as in the realm of surgery. The VQ was used to identify the typical F/T associated with each one of the tool/tissue interactions in the surgery “dictionary.” Or, using the language analogy, it characterized different pronunciations of a word.

Results

Each step of an operation can be interpreted as a series of states and transitions between states to achieve the goal of a particular step of an operation. A typical result of state analysis was summarized in the step of placing a fundal wrap around the esophagus while performing laparoscopic Nissen fundoplication. For this maneuver, the state transition diagram has the shape of a star, with the center point being the idle state (Fig. 3A). Each circle represents a different state characterized by a tool/tissue interaction; the arrows represent transitions between states. In some cases, the surgeon stays within the same state; this is depicted by an arrow to the same state.

This analysis clearly demonstrated several phenomena. First, expert and novice surgeons took different paths to reach the same goal (Fig. 3A). Each group utilized states and transitions not used by the other group. For example, in placing the fundal wrap, the novice used the state of sweeping-pushing, whereas the expert did not. Moreover, the transition between grasping-pulling and grasping-sweeping was performed only by NS and not by ES. Second, an assessment of the median completion time of the NS group and ES group showed a significant difference between these groups (p <0.05). The time to complete the surgical procedure was longer for NS by a factor of 1.5–4.8 when compared to ES. The difference between NS and ES was more profound in steps requiring greater dexterity and manual skill (e.g., LNF-5 in Fig. 3B) than in steps where a specific organ was placed in a specific position (e.g., LC-1). The main factor contributing to the significant difference in the completion times between NS and ES was the time spent in the idle state. NS spent significantly more time in the idle state than ES.

Typical raw data of forces and torques were plotted in a three-dimensional space showing the loads developed at the sensor location while dissecting the gallbladder fossae for 425 sec by an expert surgeon during laparoscopic cholecystectomy (Fig. 4). The black ellipsoid is a region that includes 95% of the F/T samples. The forces along the z axis (in/out of the trocar) were higher than the forces in the xy plane. On the other hand, torques developed by rotating the tool around the z axis were extremely low compared to the torques generated while rotating the tool along the x and y axis while sweeping the tissue or performing lateral retraction. Similar trends in terms of the F/T magnitude ratios between the x, y, and z axes were found in the data measured in other steps of the MIS procedures.

Using state analysis, each step of the operation was divided into states based on the tool/tissue interaction. By performing the VQ analysis on the F/T for each one of the tool/tissue interactions, 87 unique F/T signature were identified. For example, Fig. 5 represents nine F/T signatures associated with the grasping-pushing-sweeping (Table 2, GR-PS-SW) tool/tissue interaction. These nine signatures were dominated by positive values of F_g (grasping), negative values of F_z (pushing), and T_{xy} (sweeping the tissue in the xy plane). These nine pentagonal cluster centers found in the GR-PS-SW F/T data may represent the entire F/T at this specific tool/tissue interaction. The rest of the data associated with GR-PS-SW might be considered as a variation of these nine themes and can be correlated to one of these

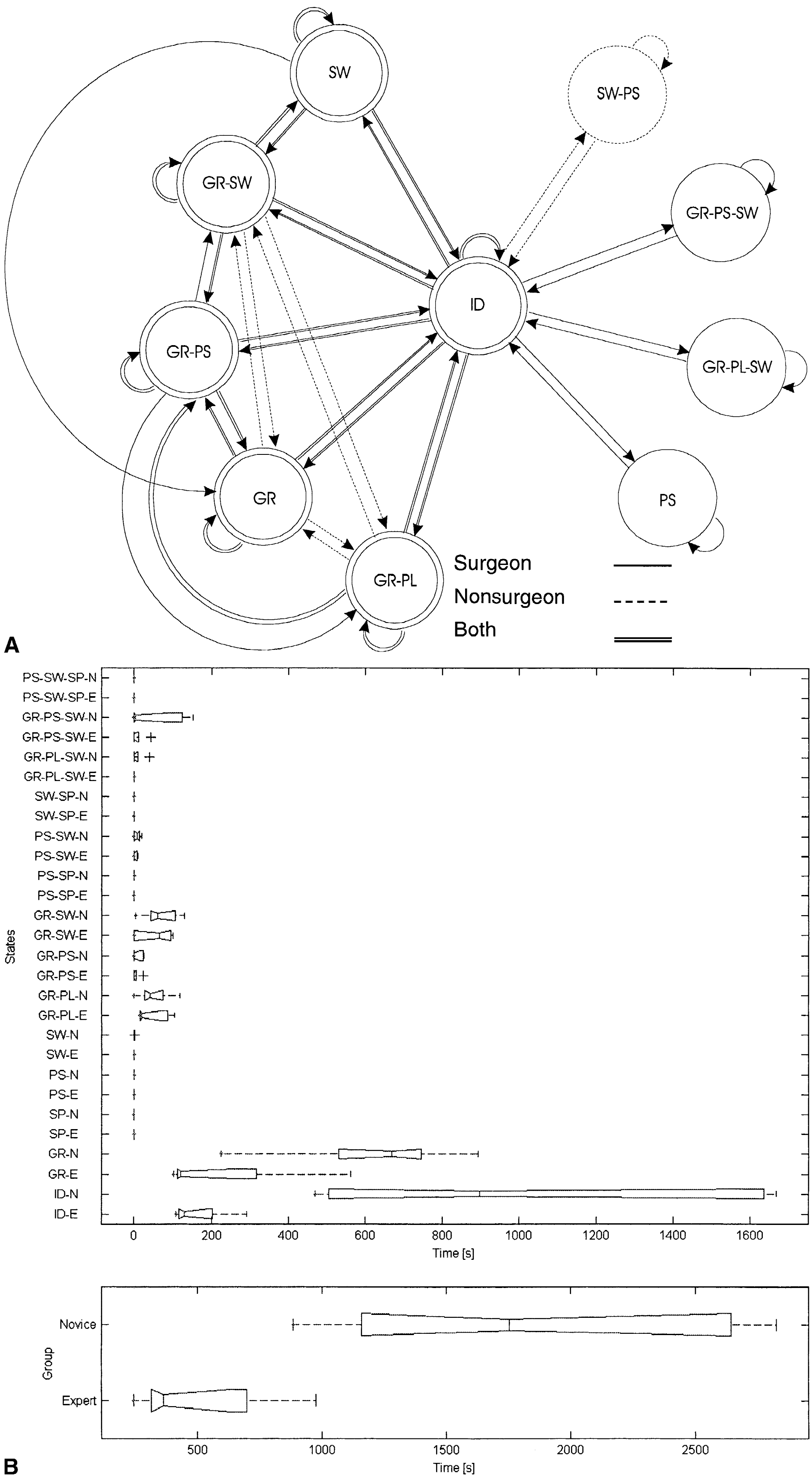

Fig. 3. State analysis of an MIS procedure. **A** State diagram of placing wrap around the esophagus during laparoscopic Nissen fundoplication showing differences between novice (dashed line) and expert (solid line) surgeons. The double lines represent states and transitions made by both groups. **B** Time spent at each tool/tissue interaction by novice surgeon (NS) and expert surgeon (ES) while performing suture wrap and intracorporeal knot tying with needle holder. The time distribution in each tool/tissue interaction of the 10 subjects is represented by a notch box plot. The lower and upper lines of the box are the 25th and 75th percentiles of the sample representing the interquartile range. The line in the middle of the box is the sample median. The notches in the box depicts the 95% confidence interval about the median of the sample. The lines extending above and below the box define the 95 percentiles of the sampled data.

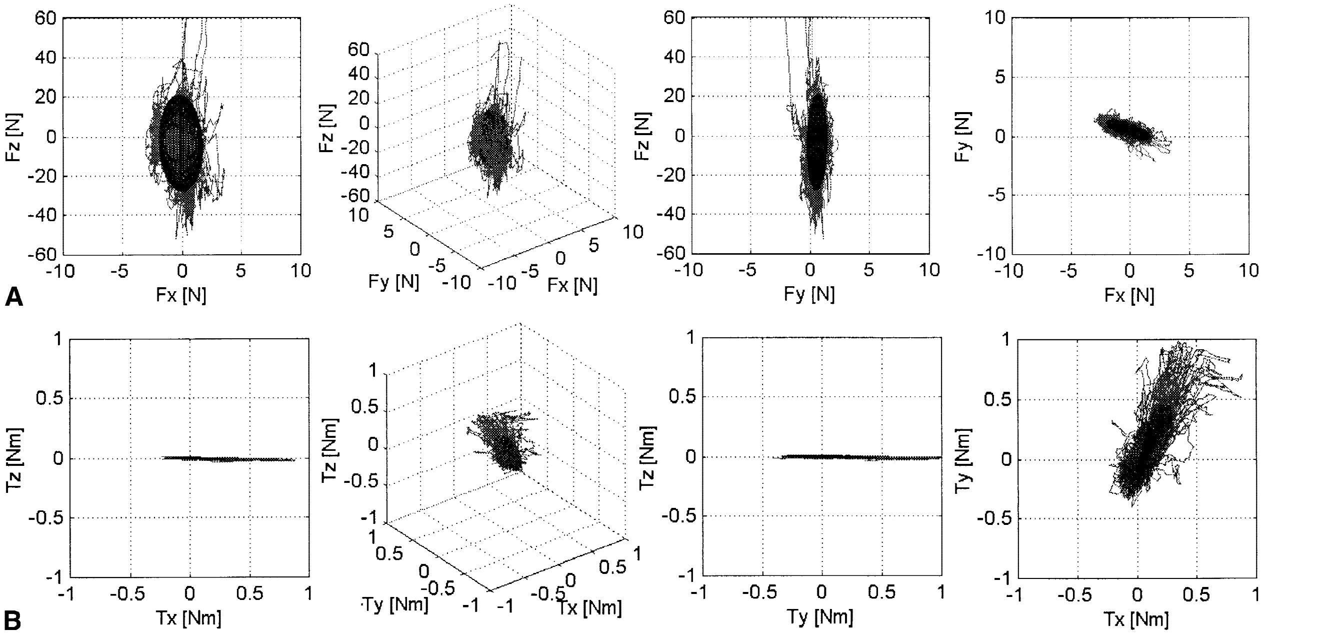

Fig. 4. Raw data of forces and torques measured at the surgeon's hand/tool interface while dissecting the gallbladder fossae during laparoscopic cholecystectomy. For the definitions of the *x,y,z* directions, see Fig. 1B—**A** forces and **B** torques.

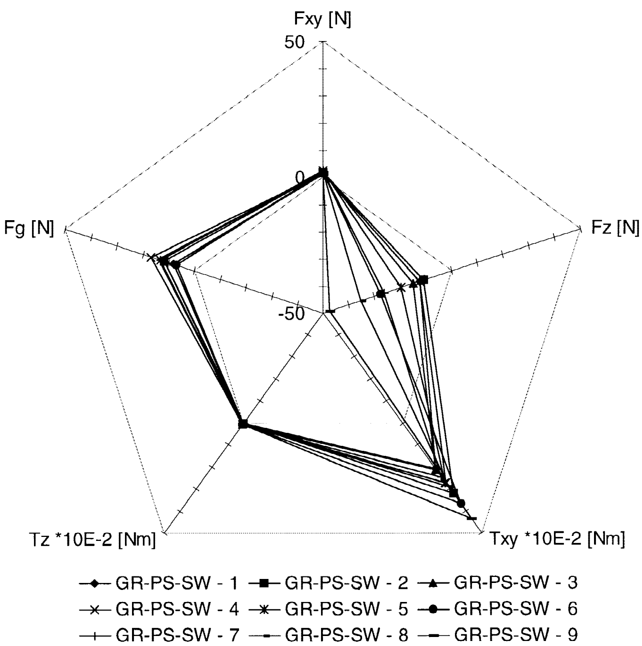

Fig. 5. Force/torque signatures of the grasping- pushing-swiping state.

signatures. Moreover, further analysis of this code book (87 F/T signatures) showed no overlap between signatures. There was at least one dimension (of the five) that differentiated each signature from the others.

Once the code book was defined, the entire database was encoded into the 87 F/T signatures. This encoding process allowed exploration of a new aspect regarding the differences between NS and ES. This new aspect was related to the magnitudes of F/T applied by NS and ES during each step of the MIS procedures for the different tool/tissue interactions (Table 2). The grand median analysis [2] showed that the F/T magnitudes applied by NS and ES in most of the tool/tissue interactions were significantly different ($p < 0.05$) (Fig. 6). Two steps of two surgical procedures were represented in Fig. 6 by two pie diagrams. The pie diagram on the left-hand side defines the tool/tissue interactions in which no significant difference was found (gray sector) between NS and ES and cases where a significant difference was observed (dotted sector). When a significant difference was identified, the pie diagram on the right hand side showed which group (NS, black sector; or ES, white sector) applied higher F/T in each one of the tool/tissue interactions. For example, in laparoscopic cholecystectomy step 3 (Fig. 6, LC-3), no significant difference in the F/T magnitude was identified in SW-SP, which is 8% of all the tool/tissue interactions. In the other 92% of tool/tissue interactions, a significant difference was identified (left-hand pie chart). Of the cases where a significant difference was observed, in 23% of the tool/tissue interactions (e.g., SW, GR-SW, PS-SW-SP) NS applied higher F/T magnitudes than ES; and in 69% of the cases (e.g., GR, SP, PS, GR-PL etc), ES applied higher F/T magnitudes than NS (right-hand pie chart) Fig. 6.

In general, a significant difference was identified in most of the tool/tissue interactions. Moreover, when the six surgical steps were divided according to the nature of the tool/tissue interactions—e.g., (a) tissue dissection (LC-2, LC-3, LNF-3), and (b) tissue manipulation (LC-1, LNF-4)—the results showed that higher magnitudes of F/T were applied by ES than by NS when dissecting the tissues, whereas lower magnitudes of F/T were applied by ES than by NS when manipulating the tissues.

Discussion

Minimally invasive surgery is a complex task that requires a synthesis between visual and haptic information. Analyz-

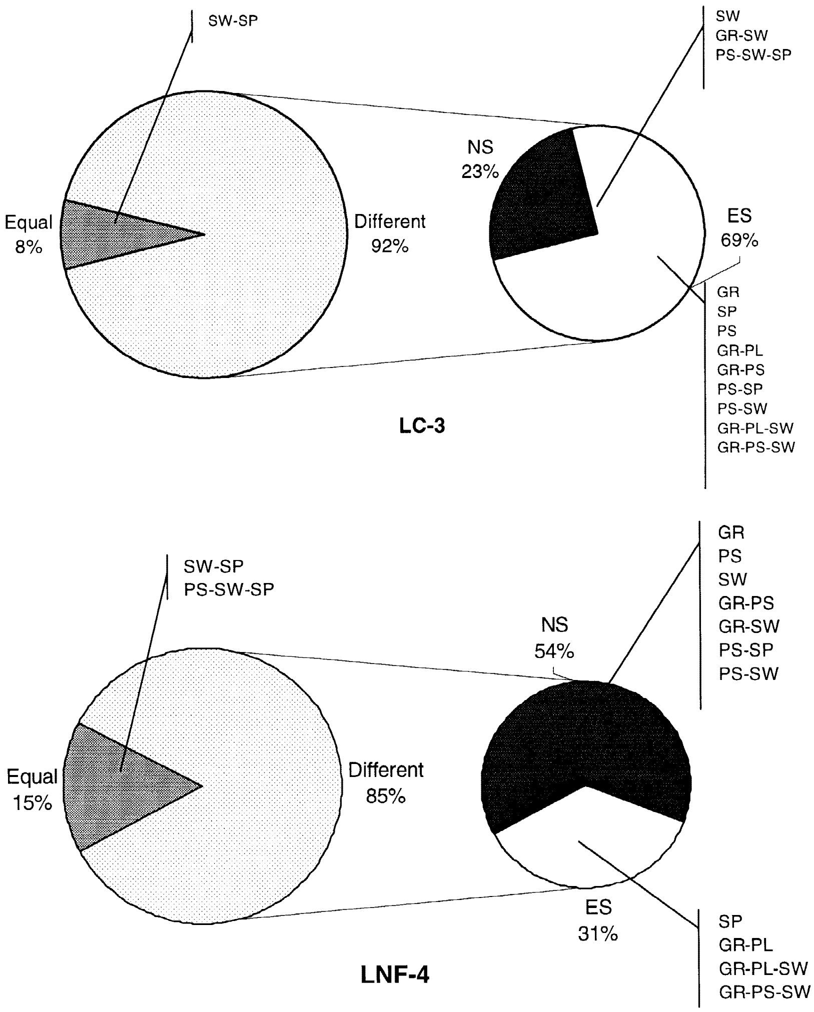

Fig. 6. F/T magnitude distributions at different tool/tissue interactions applied by novice (NS) and expert surgeons (ES) during steps of an endoscopic surgical procedures (for details, see Table 1). The pie bar on the left-hand side shows the distribution of tool/tissue interactions in which significant differences ($p < 0.05$) and nonsignificant differences ($p > 0.05$) in terms of the F/T were applied by NS and ES. In tool/tissue interactions, significant differences were identified between NS and ES (dotted sector). The pie diagram on the right-hand side shows the correspondence between high F/T magnitudes and the group of surgeons who applied them (black sector, NS; white sector, ES).

ing MIS in terms of these two sources of information is a key step toward developing objective criteria for training surgeons and evaluating the performance of master/slave robotic or teleoperated systems and virtual reality simulations with haptic devices. A synthesis of the visual and haptic information showed five areas in which the novice surgeon (NS) group was different from the expert surgeon (ES) group when performing MIS: (a) types of tool/tissue interaction being used, (b) transitions between tool/tissue interactions being applied, (c) time spent while performing each tool/tissue interaction (especially the idle state), (d) overall completion time, and (e) F/T magnitudes being applied by the surgeons on the endoscopic tools.

All of the criteria that differentiate the respective skill level of NS and ES were found to be related. In general, it took the expert surgeon less time to perform a typical procedure than the novice surgeon, who spent most of the extra time in the idle state. This time difference is probably due to a number of factors, including advanced knowledge of the anatomy, higher level of hand-eye coordination, and/or greater experience in handling the endoscopic surgical instrument. The magnitude of F/T applied by NS and ES varied based on the task being performed. Higher F/T magnitudes were applied by NS than by ES when performing tissue manipulation. This might be a result of insufficient dexterity of the NS, which could represent a potential for tissue damage and time consumption. However, lower F/T magnitudes were applied by NS than by ES during tissue dissection, which might indicate excessive caution to avoid irreversible tissue damage. More dissection movements were required by NS in order to tear the tissue, a process that substantially decreases the efficiency of the procedure and increases the time to complete the operation. Moreover, using the F/T information in real time during the course of learning as feedback information to the NS may improve the learning process, reduce soft tissue injury, and increase efficiency during endoscopic surgery.

The approach outlined in this study is part of an ongoing research project aimed at developing an objective skill scale for evaluating surgical performance. Moreover, an analysis of haptic and visual information, combined with other feedback data (e.g., tool position), could be used as a basis for developing teaching techniques that would optimize tool usage in MIS. A well-established methodology for evaluating skill level would allow novice surgeons to practice on animal models outside of the operating room or to use realistic virtual reality simulators until they had achieved a desired level of competence. It would also allow them to compare themselves to norms established by experienced surgeons and licensing organizations.

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