Surgeon-Tool Force/Torque Signatures - Evaluation of Surgical Skills in Minimally Invasive Surgery

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Abstract

The best method of training for laparoscopic surgical skills is controversial. Some advocate observation in the operating room, while others promote animal and simulated models or a combination of surgical related tasks. The mode of proficiency evaluation common to all of these methods has been subjective evaluation by a skilled surgeon. In order to define an objective means of evaluating performance, an instrumented laparoscopic grasper was developed measuring the force/torque at the surgeon hand/tool interface. The measured database demonstrated substantial differences between experienced and novice surgeon groups. Analyzing forces and torques combined with the state transition during surgical procedures allows an objective measurement of skill in MIS. Teaching the novice surgeon to limit excessive loads and improve movement efficiency during surgical procedures can potentially result in less injury to soft tissues and less wasted time during laparoscopic surgery. Moreover the force/torque database measured in this study may be used for developing realistic virtual reality simulators and optimization of medical robots performance.

1. Introduction

One of the more difficult tasks in surgical education is to teach the optimal application of instrument forces and torques 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 the actual 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 [1,2,3]. Developing such a system holds promise for providing a less stressful learning environment for the surgical student while eliminating any risk to the patient. In the development of such a system, it is important to understand the various components that comprise a realistic and useful training system [4]. While other studies have focused on the tool-tip/tissue interaction [5,6,7], the current research is aimed at analyzing the human/tool interface in MIS.

2. Purpose

The goal of this study is to create new quantitative knowledge of the forces and torques applied by surgeons on their instruments during minimally invasive surgery. Statistical models of this database can be used to characterized surgical skills for training advanced laparoscopic surgical procedures. Two areas in which this database might be applied are (*i*)Virtual Reality (developing haptic devices for realistic force feedback VR simulations of MIS procedures), and (*ii*) minimally invasive surgical robotics (optimizing mechanisms and actuators).

3. Methods

3.1 Experimental System Setup

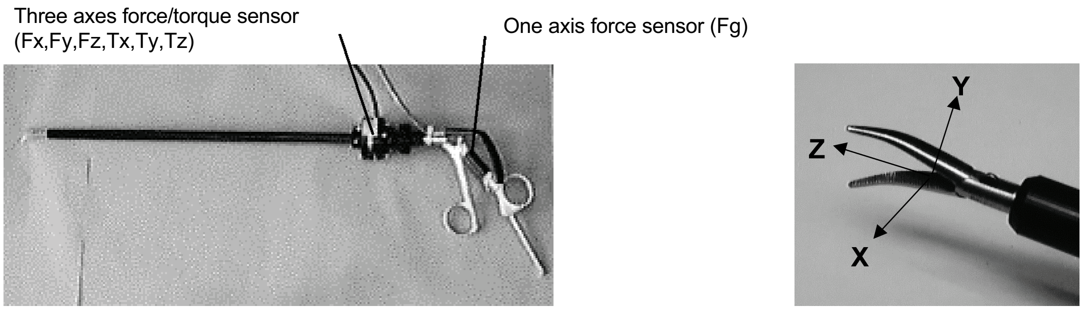
Two types of information were acquired while performing MIS on pigs: (*i*) force/torque data measured at the human/tool interface and (*ii*) visual information of the tool tip interacting with the tissues. The two sources of information were synchronized in time, and recorded simultaneously for off line analysis. 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.

The forces and torques 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 force/torque sensor (ATI - Mini model) which was mounted into the outer tube (proximal end) of a standard reusable 10 mm endoscopic grasper (Storz) - Fig. 1a. The sensor was capable of measuring simultaneously three components of force (F_x, F_y, F_z) and three components of torque (T_x, T_y, T_z) in the Cartesian frame (Fig.1b). The forces and torques developed at the sensor location were a result of interacting with three interfaces in the

MIS environment: (*i*) hand-tool (*ii*) grasper tool-tip/tissue, and (iii) grasper outer-tube/trocar (port) in addition to the gravity and inertial loads. The summation of applied forces and torques were transferred through the grasper structure to the surgeon's hand and vice versa. The sensor orientation was such that X and Z axes generated a plan which was parallel to the tool's internal contact surface with the tissue in closing position, and the Y and Z axes defined a plane which was perpendicular to this surface (Fig.1b).

One of the grasper's mechanical features enabled the surgeon to rotate the grasper's outer tube, using a joint located near the handle, in order to change the orientation of the tool tip relative to the grasped tissue without changing the handle orientation. The alignment between the tool tip origin relative to the sensor remained unchanged since the outer tube and the tool tip were linked mechanically. A hole in the middle of the sensor allowed the rod inside the grasper tube to transfer the handle grasping force to the tool tip.

The second force sensor was mounted on the endoscopic grasper handle. Moving this handle caused the rod, sliding inside the outer tube, to transmit grasping/spreading forces from the surgeon's hand (F_g) to the tool tip. Due to this internal mechanism, whenever a grasping force was applied on the handle the outer tube was compressed. The outer tube compression was sensed by the force/torque sensor mounted within it. A nonzero force along the Z axis (F_Z) would be developed during grasping, even if there were no external forces acting along this axis. This internal force coupling between the grasping/spreading and compression/tension along the Z axis was canceled by the processing software using a model of the grasper internal mechanism.

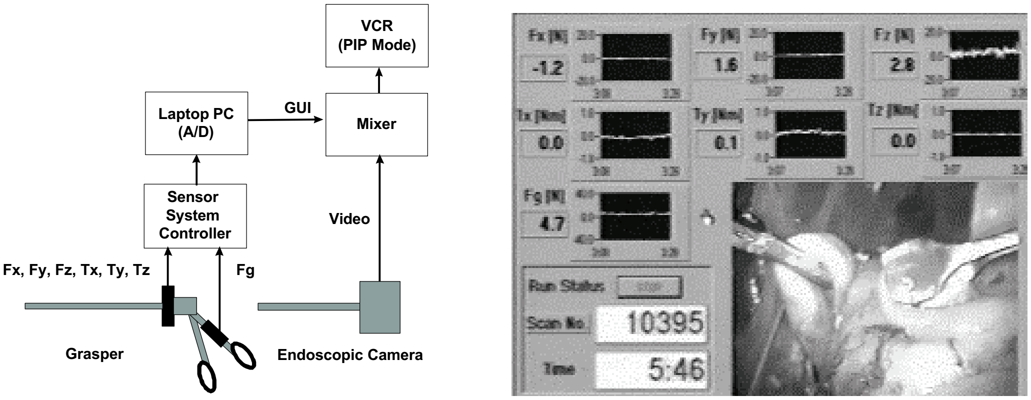


(a) (b)

Figure 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.

The seven channels force/torque data were sampled at 30 Hz using a laptop with a PCMCIA 12 bit A/D card (National Instruments - DAQCard 1200). In addition, a LabView (National Instruments) application was developed incorporating a user interface for acquiring visualizing the force/torque data in real-time (Fig. 2).

The second source of information was the visual view from the endoscopic camera monitoring the movement of the grasper while interacting with the internal organs/tissues. This visual information was integrated with the force/torque human interface using a video mixer in a picture-in-picture mode and synchronized with time. The integrated interface was recorded during the surgical operation for off-line state analysis (Fig. 2).



(a) (b)

Figure 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 user interface of force/torque information synchronized with the endoscopic view of the procedure using picture-in-picture mode.

3.2 Surgical Experiment Setup and Clinical Trails

Four surgeons (two novice surgeons - NS and two experienced surgeons - ES) performed laparoscopic Cholecystectomy and laparoscopic Nissen Fundoplication in a porcine model (pig). Each operation was divided into steps (Table 1). Although all the steps were performed in each procedure, data were recorded only when the grasper was used with the following tool tips: atraumatic grasper, curved dissector, Babcock grasper.

3.3 Data Analysis

Two types of analysis were performed on the raw data: (*i*) video state analysis (SA) encoding the type of the tool-tip/tissue interaction into states and (*ii*) vector quantization (VQ) encoding the force/torque data into clusters (signatures). Each step of the operation was further divided into 17 different discrete tool maneuvers (states) in which the endoscopic tool was interacting with the tissue (Table 2). Each identified surgical maneuver (state), had a unique force/torque pattern. For example in the laparoscopic Cholecystectomy, isolation of the cystic duct and artery involves performing repeated pushing and spreading maneuvers which in turn requires to apply 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 SA of the videotape with similar results.

Procedure	Step	Description	Tool Type	Hand	Video F/T
Laparoscopic Cholecystectomy	1	Positioning Gall Bladder	Atraumatic Grasper	L	+
	2	Exposure of Cyctic Duct	Curved Dissector	R	+
	2*	Divide of Cyctic Duct	Scissors	R	-
	3	Dissection of GallBladder Fossa	Curved Dissector	R	+
	4	Exposure of Cystic Artery	Curved Dissector	R	-
	4*	Dividing Artery	Scissors	R	-
Laparoscopic Nissen Fundoplication	1	Dissect Right Crus	Surgiwand	R	-
	2	Dissect Left Crus	Surgiwand	R	-
	3	Dissect Esophagus / Blunt	Curved Dissector	R	+
	4	Placing a Wrap Around the Esophagus	Babcock Grasper	R	+
	5	Suture Wrap / Intracorporeal Knot Tying With Needle Holder	Curved Dissector	R	+
	6	Coronal Sutures / Intracorporeal Knot Tying Endostitch	Endostitch	R	-

Table 1: Definitions of surgical procedure steps and types of the tool tip (Shaded steps performed but not recorded).

The 17 states can be divided into three types based on the number of movements performed simultaneously. The fundamental maneuvers were defined in type I. The idle state was defined as moving the tool in space without touching any internal organ, and the forces and torques developed in this state represented mainly the interaction with the trocar and the abdominal wall in addition to the gravitational and inertial forces. In the grasping and spreading states, compression and tension were being applied on the 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 and lateral retraction, the tool was placed in one position while rotating it around the X and Y axes (trocar frame). The difference between sweeping and lateral retraction was that lateral retraction was a step-like movement as opposed to sweeping, which was a continuous movement. The rest of the states in groups II and III were combinations of the fundamental states of group I.

The second type of analysis used VQ algorithm to encode the multi dimensional force/torque data ($F_x, F_y, F_z, T_x, T_y, T_z, F_g$) into discrete symbols representing clusters (signatures). First the 7D force/torque data vector was reduced to a 5D vector by calculating the magnitude of the force and torque in the XY plane (F_{xy}, T_{xy},). Then The K-means algorithm was used to cluster the data into force/torque signatures of each one of the state defined in Table 2. Each force/torque signature represented a cluster center in a 5 dimensional space.

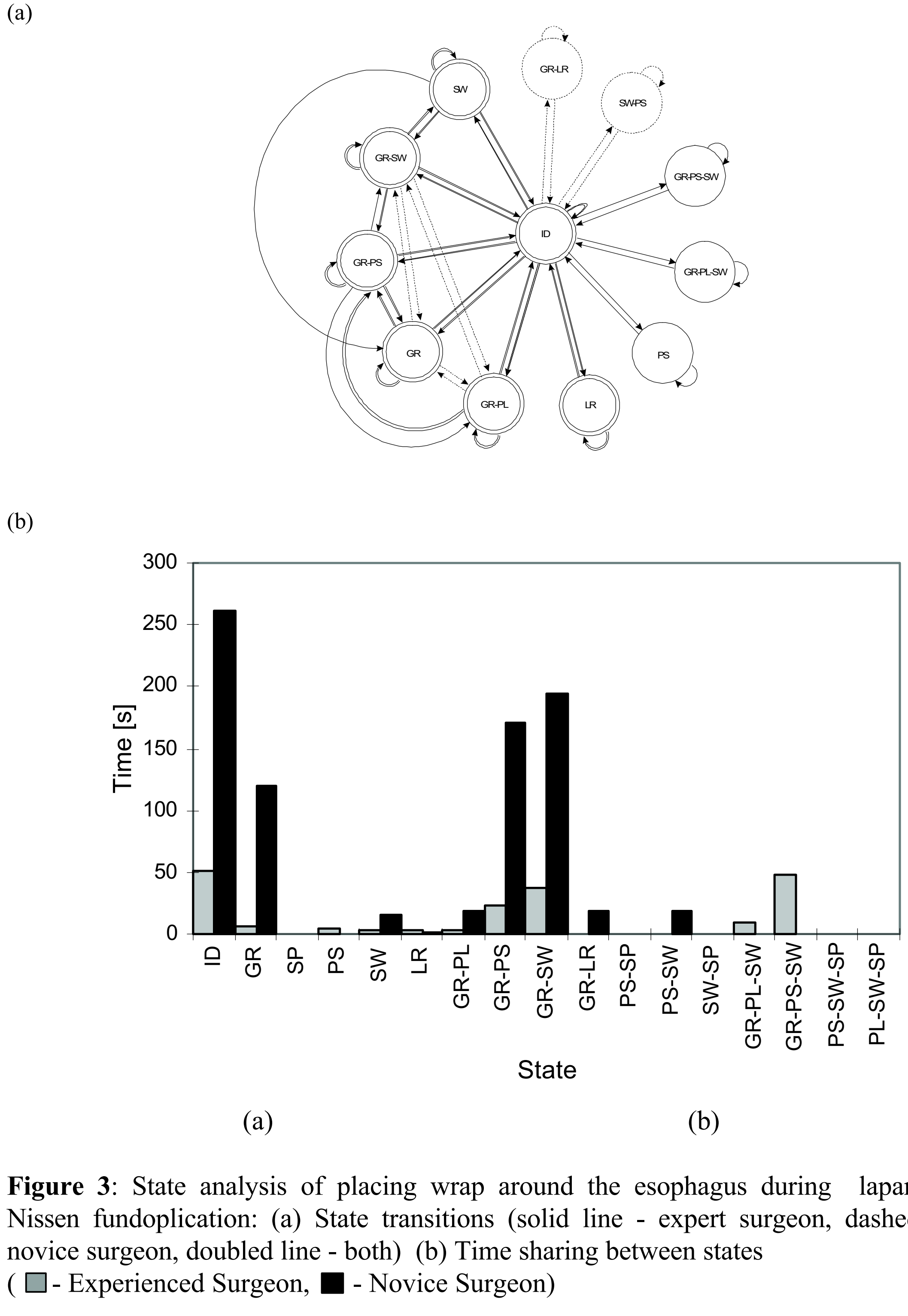
Type	State Name	State Acronym	Force / Torque						
			Fx	Fy	Fz	Tx	Ty	Tz	Fg
I	Idle	ID	*	*	*	*	*	*	*
	Grasping	GR							+
	Spreading	SP							-
	Pushing	PS			-				
	Sweeping	SW	+/-	+/-		+/-	+/-		
	Lateral Retraction	LR	+/-	+/-		+/-	+/-		
II	Grasping - Pulling	GR-PL			+				+
	Grasping - Pushing	GR-PS			-				+
	Grasping - Sweeping	GR-SW	+/-	+/-		+/-	+/-		+
	Grasping - Lateral Retraction	GR-LR	+/-	+/-		+/-	+/-		+
	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	+/-	+/-	-	+/-	+/-		-
	Pulling - Sweeping - Spreading	PL-SW-SP	+/-	+/-	+	+/-	+/-		-

Table 2: Definition of states and the corresponding directions of forces and torques applied in Cholecystectomy and Nissen fundoplication during MIS.

4. Results

A typical result of the state analysis was summarized for placing a wrap around the esophagus during laparoscopic Nissen fundoplication in Fig. 3. The state transition diagram had a shape of a star with a center point including the idle state (Fig 3a). This state was mainly used by both expert and novice surgeons to move from one operative state to the other. However the expert surgeons used the idle state only as a transition state while the novice spent significant amount of time in this state (Fig 3b). In general, it took to the novice surgeons 270% more time then the experienced surgeons to perform the same operation.

The force/torque data were plotted in a 3D space showing the loads developed at the sensor location while placing a wrap around the esophagus (laparoscopic Nissen fundoplication) - Fig. 4a. Using the state analysis and dividing each step of the operation into states, the force/torque segments for each state were lumped together. Figure 4b shows the force/torque distribution of the grasping-pulling state with respect to the normalized time spent in this state. Using the VQ algorithm the force/torque data of each state were further divided into clusters (Signatures). Figure 5 shows three typical signatures of the grasping-pulling state. The forces F_z and F_g were dominant in this signatures, whereas the rest of the force/torque values remained relatively low. This three clusters may represent the entire force/torque space of the grasping-pulling state, and the rest of the data in these state can be correlated with this three signatures. Analyzing the data of the experienced and novice surgeons showed that the forces and torques used to perform an operation was 130%-138% greater for novice surgeons



(a) (b)

Figure 3: State analysis of placing wrap around the esophagus during laparoscopic Nissen fundoplication: (a) State transitions (solid line - expert surgeon, dashed line - novice surgeon, doubled line - both) (b) Time sharing between states
(▨ - Experienced Surgeon, ■ - Novice Surgeon)

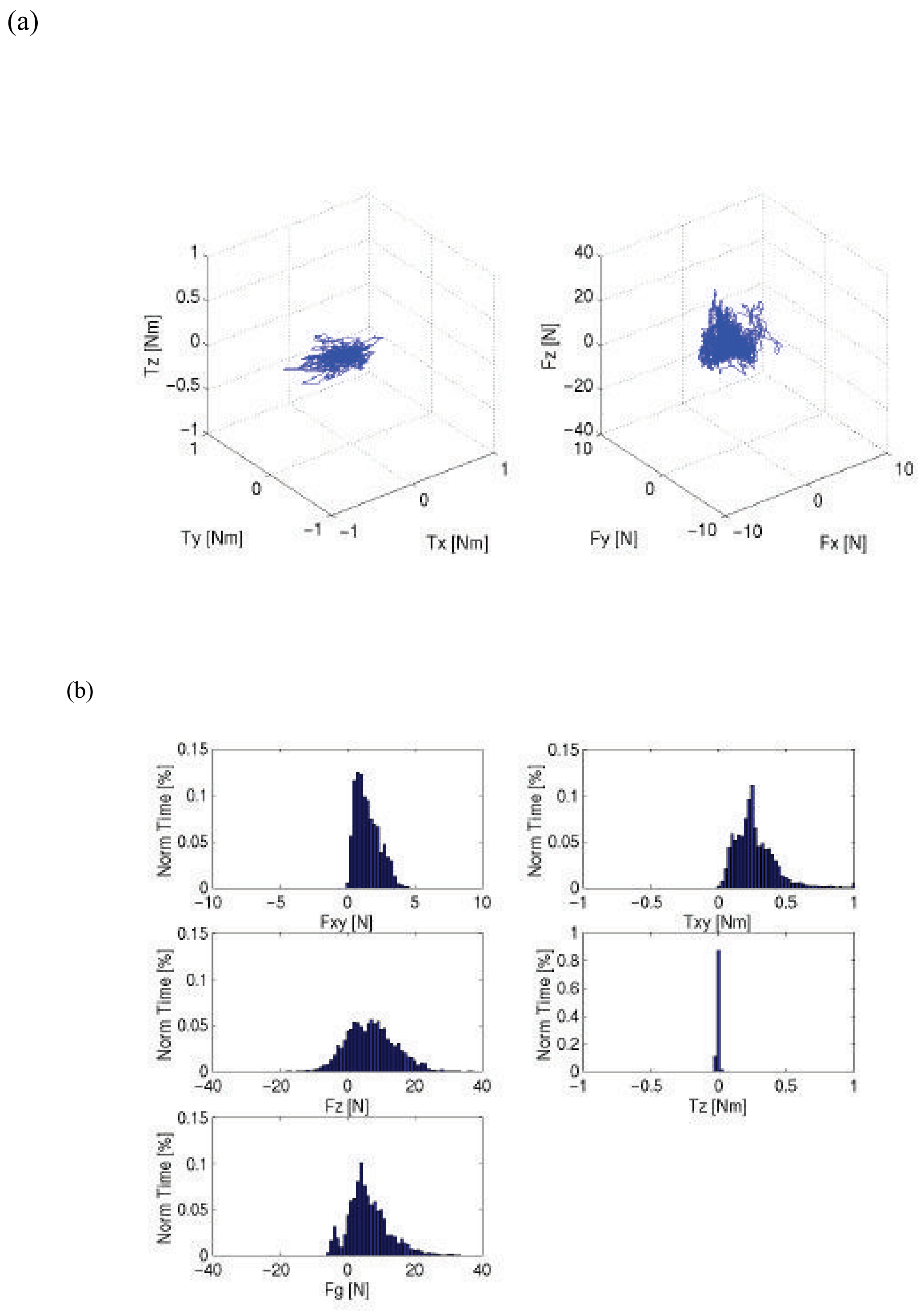


Figure 4: Force/torque data measured during placing wrap around esophagus (laparoscopic Nissen fundoplication) by an experienced surgeon: (a) Raw force/torque data, (b) Force/torque data distribution during grasping-pulling state with respect to the normalized time.

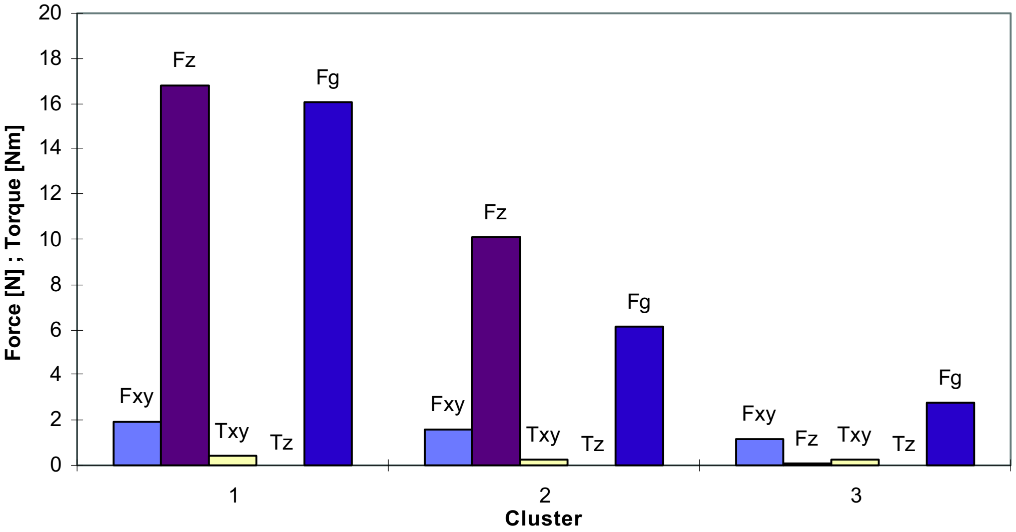


Figure 5: Force/torque signatures of the grasping-pulling state

5. Conclusions

Minimally invasive surgery is a complex task which requires a synthesis between visual and haptic information. Analyzing MIS in terms of these two sources of information is a key step towards developing objective criteria for training surgeons and evaluating the performance of a master/slave robotic system for teleoperation or a haptic device for virtual reality simulations. The state transition data and the force/torque signatures are objective criteria for evaluating skills and performance in MIS. In general, it took the expert surgeon less time while applying less forces and torques to perform a typical MIS compared to the novice surgeon. This may be a result of advanced knowledge of the anatomy, higher level of eye-hand coordination and greater experience in handling the endoscopic surgical instrument.

The approach outlined in this study could be extended by increasing the size of the database which will allow development of statistical models like the Hidden Markov Model (HMM) of surgical procedures. This information, combined with other feedback data, may be used as a basis to develop teaching techniques for optimizing tool usage in MIS. The novice surgeons could practice these skills outside of the operating room on animal models or by using realistic virtual reality simulators, until they had achieved the desired level of competence, and compare themselves to norms established by experienced surgeons.

Acknowledgments

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