Force Measurement Capability for Robotic Assisted Minimally Invasive Surgery Systems

Mohsen Moradi Dalvand, Bijan Shirinzadeh, Saeid Nahavandi, Fatemeh Karimirad, and Julian Smith

***Abstract*— An automated laparoscopic instrument capable of non-invasive measurement of tip/tissue interaction forces for direct application in robotic assisted minimally invasive surgery systems is introduced in this paper. It has the capability to measure normal grasping forces as well as lateral interaction forces without any sensor mounted on the tip jaws. Further to non-invasive actuation of the tip, the proposed instrument is also able to change the grasping direction during surgical operation. Modular design of the instrument allows conversion between surgical modalities (e.g., grasping, cutting, and dissecting). The main focus of this paper is on evaluation of the grasping force capability of the proposed instrument. The mathematical formulation of fenestrated insert is presented and its non-linear behaviour is studied. In order to measure the stiffness of soft tissues, a device was developed that is also described in this paper. Tissue characterisation experiments were conducted and results are presented and analysed here. The experimental results verify the capability of the proposed instrument in accurately measuring grasping forces and in characterising artificial tissue samples of varying stiffness.**

***Index Terms*— Robotic Assisted Minimally Invasive Surgery (RAMIS), Force Measurement, Laparoscopic Instrument, Transmission Mechanism, Strain Gages, Modularity, Actuation Mechanism.**

I. Introduction

HAVING improved the disadvantages of the traditional laparoscopic surgery, Robotic Assisted Minimally Invasive Surgery (RAMIS) has negatively affected the surgeon's ability in palpating and diagnosing soft tissues of varying stiffness during surgery [1, 2]. The lack of force feedback has motivated several researchers to explore possible methods of restoring this feature to RAMIS by making laparoscopic instruments capable of measuring tip/tissue interaction forces. Strain gauges were applied on the tip and handle of laparoscopic surgical forceps to characterise tissues [3-6]. Retrofitting of laparoscopic forceps with a commercial six-axis force/torque sensor encapsulated in the instrument shaft [7] and a force sensor on the handle of the tool [8] were studied. A two Degree Of Freedom (DOF) force sensing sleeve for 5-mm laparoscopic instruments was developed with advantages of compatibility and modularity among several types of surgical instruments [9].

Manuscript received July 18, 2013; revised August 15, 2013.

M. M. Dalvand and S. Nahavandi are with Centre for Intelligent Systems Research (CISR), Deakin University, Waurn Ponds Campus, VIC 3216, Australia (Corresponding author – phone: +61 3 5247 9233, fax: +61 3 5227 1352, email: mohsen.m.dalvand@deakin.edu.au).

B. Shirinzadeh and F. Karimirad are with Robotics and Mechatronics Research Laboratory (RMRL), Department of Mechanical & Aerospace Engineering, Monash University, Melbourne, Australia.

J. Smith is with Department of Surgery, Monash Medical Centre, Monash University, Melbourne, Australia.

A micro-machined piezoelectric tactile sensor embedded beneath silicon teeth of the grasper jaws was developed that has some disadvantages including ability to measure only dynamic forces, susceptibility to damage from shear forces, non-sterilizability, and high cost [10]. At more complex level, a distal force/torque sensor for laparoscopic instruments was developed that uses Stewart platform to locate six strain gauges for measuring forces and torques along all of its six measurement axes [11, 12]. Preliminary results on design and fabrication of a cutting tool with an integrated tri-axial force sensor to be applied in fetal surgery procedures were reported [13, 14]. A miniature uniaxial force sensor for use within a beating heart during mitral valve annuloplasty was presented [15].

Besides retrofitting conventional laparoscopic instruments, research efforts have also been conducted in developing automated laparoscopic tools with force measurement capability [16, 17]. Most of these tools incorporate the advantage of actuation mechanisms for utilising in robotic surgical systems [18, 19]. Further to the force sensing laparoscopic instruments, robotic surgical systems were proposed with force measurement capabilities including Black Falcon [20] and BlueDRAGON [21]. The possibility of using a trocar sensor for measurement of the surgical forces was also investigated in a robotic surgical system [22]. Although these research efforts were steps toward introducing force-feedback in robotic assisted surgical systems, there still exist many problems within the designs of surgical tools and their use in robotic surgery including modularity, size and force measurement issues.

In this paper, an automated modular laparoscopic instrument is introduced that provides tool/tissue interaction force measurement capability directly from the surgery site. Figure 1 shows an overview of the proposed system incorporating the introduced instrument with a robotic assisted minimally invasive surgery system [2]. The proposed instrument is presented in Figure 2 and different components of it are highlighted in this figure. The proposed instrument is incorporated with a micropositioning parallel manipulator and the RCM control algorithms has already been developed and evaluated [23-25].

The rest of the paper is organized into three sections. In the next section, the modelling and development of the proposed instrument are described that cover modularity feature, force sensing capability and modelling of tool tip. In section 3, a device developed to measure stiffness of soft tissues is described. Experimental results are also presented in this section to verify the capabilities of the proposed instrument in probing and characterising soft tissues. Concluding remarks are made in Section 4.

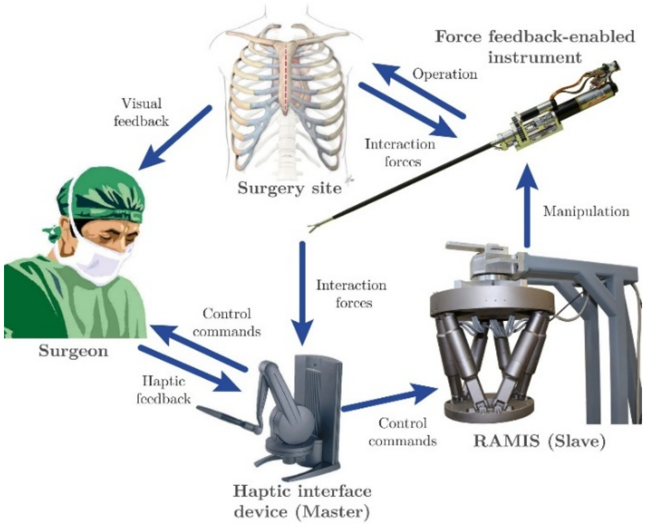

Figure 1 – Overview of the proposed surgery setup

II. Modelling And Development

A. Interchangeability Feature

Interchangeability feature of the proposed instrument enables the operator to easily and quickly change between variety of laparoscopic insert types e.g., grasping, cutting, and dissecting without loss of the force sensing capability. A stainless steel tube with 7 (mm) in diameter and 33 (cm) in length was designed in the way that it can be fitted concentrically, like a sleeve, over any 5-mm insert type manufactured by Matrix Surgical company.

The nut (Figure 2) couples the sleeve and the insert assembled to it to the base module. To minimise any potential error caused by unwanted clearance in the assembly, a part called nut-base was employed that is attached to the nut using a ball-bearing. Fastening the nut slides two supportive guides (Figure 3) incorporated to the base inside two holes of the nut-base supporting the long tube of the instrument (Figure 3). By help of this nut, insert, long tube and base module can be quickly disassembled and the insert type can be converted to the variety of insert types available. Two actuators from Maxon Motor company were employed to actuate two DOFs related to the tip direction and operation (Figure 3).

Transmission and conversion of power required to change grasping direction and to operate tip jaws were achieved by spur gears and a lead-screw mechanism (Figure 3). The size of the screw used in the lead-screw mechanism is $M6$ with 1 (mm) pitch. The mechanism to lock the insert to the lead-screw is also shown in Figure 3.

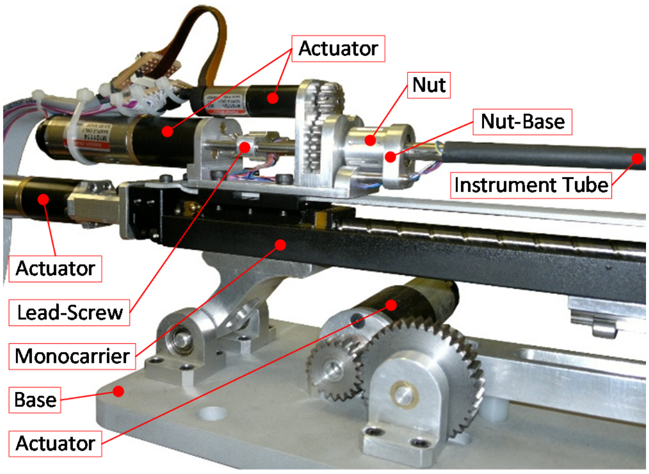

Figure 2 – The proposed instrument incorporated with a four-bar mechanism in a robotic assisted surgery system [24]

B. Force Measurement

In the proposed instrument, surface strains of the lead of the lead-screw mechanism is measured as a quantity for the normal grasping forces applied to the soft tissue at tip jaws. Two strain gages were embedded in the lead-screw mechanism (Figure 3) to measure tension and compression strains in the lead of the lead-screw representing the normal grasping forces. Calibrations of the strain gage configurations were performed using known masses.

C. Grasper Operational Mechanism

Pivotal mechanism are utilised at the tip jaws of most of the laparoscopic surgical instruments. The pivotal motion is commonly generated by linear displacement of the push rod and a mechanism to convert it to rotary displacement. In the proposed instrument the required linear movement is produced by a rotary actuator coupled with a lead-screw mechanism.

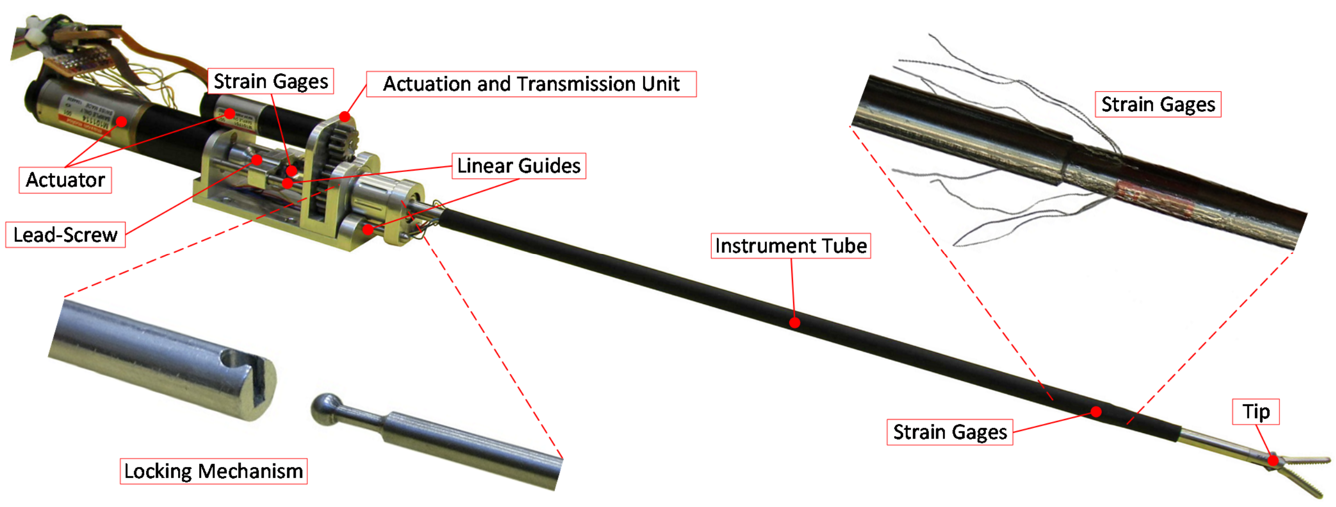

Figure 3 - Proposed force feedback-enabled minimally invasive surgery instrument

ISBN: 978-988-19252-3-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Figure 5 describes the kinematics parameters of the tip mechanism for two different states where the tip is closed and tip jaws are at an arbitrary angle θ. The nonlinear relationship between the angular position of the jaws (θ) and that of the screw at the gearbox shaft (ϕ) can be obtained as follows:

$$\theta = arcsin\left(\frac{\sqrt{[4L_1^2L_2^2 - ((D - \frac{\phi}{2\pi})^2 - L_1^2 - L_2^2)^2]}}{2L_1(D - \frac{\phi}{2\pi})}\right) - \alpha_0 \quad (1)$$

where L_1 and L_2 are the constant geometrical parameters of the tip mechanism and α_0 and D are the variables of the mechanism where the tip is at closed state (θ=0) as described in Figure 5. The nonlinear relationship between θ and ϕ for the allowable range of movements of the tip jaws is plotted in Figure 4. According to this figure, the response of the tip with relatively closed jaws to the actuator shaft displacements is faster than that of the tip with relatively opened jaws.

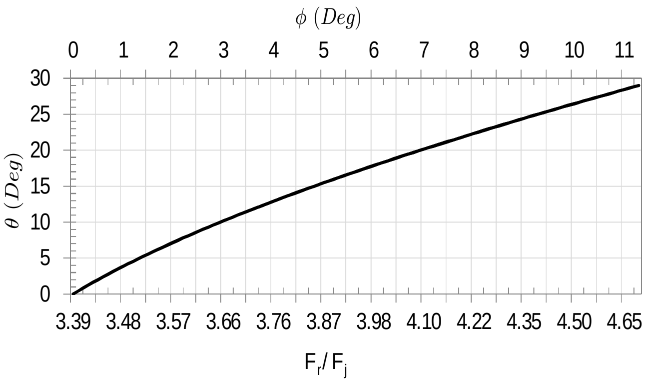

Figure 4 - Nonlinear relationships of θ with ϕ and F_r/F_j

Tension and compression forces of the push-rod marked by F_r in Figure 5 is measured using the strain gages applied to the lead-screw mechanism. The force propagation of the tip mechanism and in other words the relation between F_r and the actual forces applied to the tissue at the tip jaws (F_j) is defined as follows:

$$\frac{F_j}{F_r} = \frac{L_1 sin(\theta + \alpha_0 + arcsin(\frac{L_1 sin(\theta+\alpha_0)}{L_2}))}{2L_j cos(arcsin(\frac{L_1 sin(\theta+\alpha_0)}{L_2}))} \quad (2)$$

The ratio of the forces in the push rod and at tip jaws (F_r/F_j) with respect to jaws angular positions is also plotted in Figure 4. As this plot indicates, applying a force to the push rod generates greater force at the jaws with relatively small angular position in comparison with the force that it generates at the jaws with relatively large angular position. In other word, closing the tip jaws results in increasing the grasping force with a rate higher than that of the decrease in the angular position of the jaws.

III. Experimental Results

A. Stiffness Measurement

The Young's modulus is a measure of the stiffness of an elastic material and is a quantity used to characterize materials. An indentation experiment was conducted in this research to compute the effective Young's moduli of artificial tissue samples and study their mechanical properties relative together assuming linear elasticity. The assumption of linear elasticity relies on the applying of small indentation relative to the characteristic dimensions of the tissues. The effective elastic Young's modulus (E) corresponding to an indentation depth of δ may be calculated as follows [26]:

$$E = \frac{3F}{8d\delta} \quad (3)$$

where F is the reaction force and d is the diameter of a circular punch indenter applied to the soft tissue.

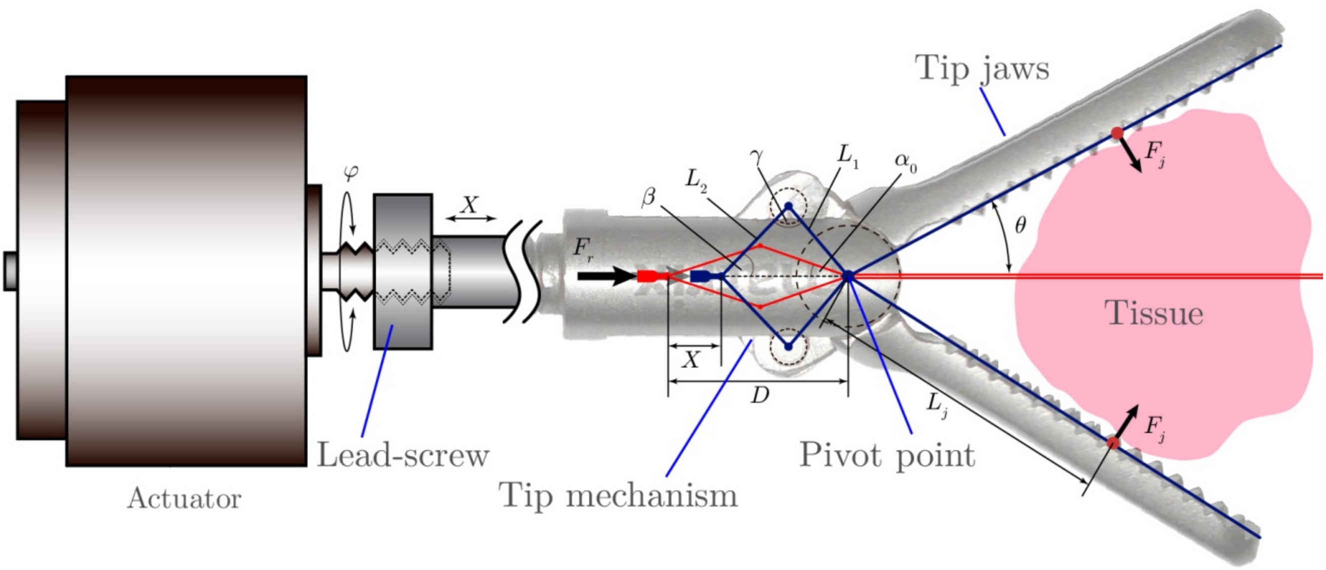

Figure 5 - Kinematics parameters of the tip mechanism for two different states of tip jaws

ISBN: 978-988-19252-3-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

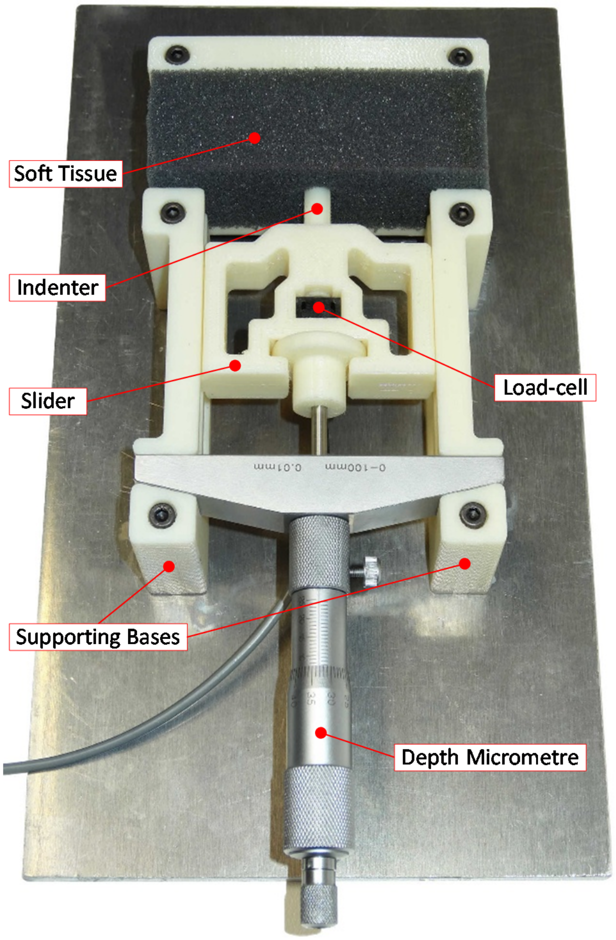

Figure 6 – The developed high-precision indentation device for stiffness measurement of soft tissue

To conduct the experiment, a high-precision instrument was developed (Figure 6) by retrofitting a micrometre with position resolution of 0.01 (mm) with a FSG-15N1A force sensor from Honeywell Sensing and Control (1985 Douglas Drive North Golden Valley, MN 55422 USA) with the force resolution of 1 (gr). The instrument was used to apply precise indentations to the tissue samples and record the force responses using a U6 data acquisition (DAQ) module from LabJack Corporation (3232 S Vance St STE 100 Lakewood, CO 80227 USA) for three cycles per tissue sample. The average values were calculated and force-displacement relationships were obtained that are presented in Figure 7.

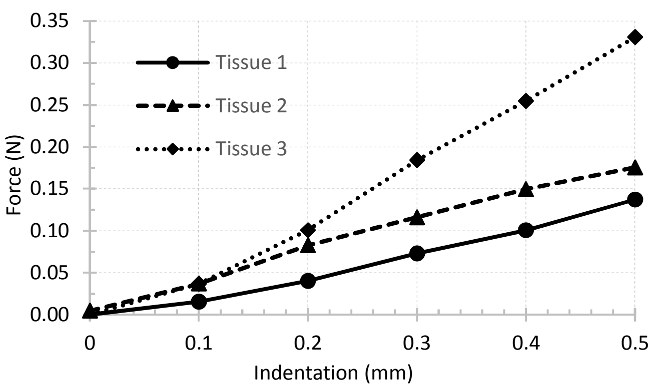

Figure 7 - Force/displacement relationships for the three selected artificial tissue samples made up of sponges

The young modulus of the three selected soft tissues (Figure 8) were calculated using Equation (3) as 10.5, 17.7, and 26.0 (kPa). These artificial tissue samples were deliberately chosen to be relatively close in terms of stiffness. They are also selected to be representative of relatively softer tissues among human soft tissues with the range of young modulus from 0.1 to 241 (kPa) [27, 28]. These selections were made in order to properly evaluate the effectiveness of the proposed instrument in characterizing soft tissues with low and relatively close young moduli. These tissue samples were also examined by the surgeon collaborator to make a realistic choice of human soft tissues in the experimental studies.

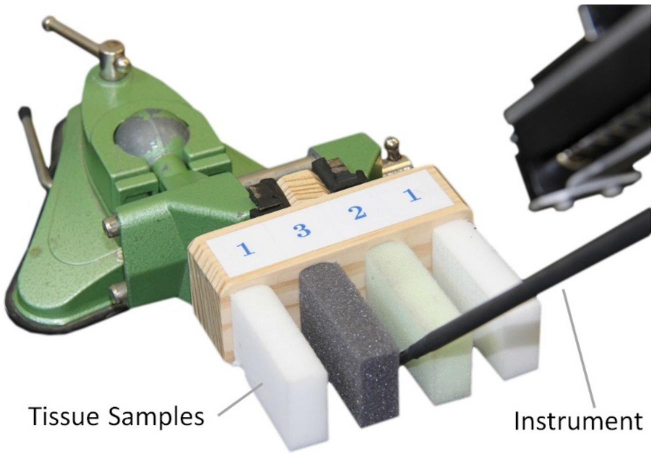

Figure 8 - Artificial tissue samples made up of sponges of varying stiffness

B. *Tissue Characterization Experiment*

This experiment was conducted to evaluate the capability of the proposed instrument in non-invasive measurement of the grasping forces for tissue samples of varying stiffness. Three artificial tissue samples made up of sponge material that are identical in thicknesses but slightly different in stiffness were chosen for this experiment. In order to verify the accuracy of the measurement methodology as well as the correctness and the effectiveness of the post-processing algorithm, even in characterizing tissues with close stiffness, the tissues were purposely selected with slight variation in stiffness (Figure 7), such that they would be hardly differentiated by direct exploration with one's fingers.

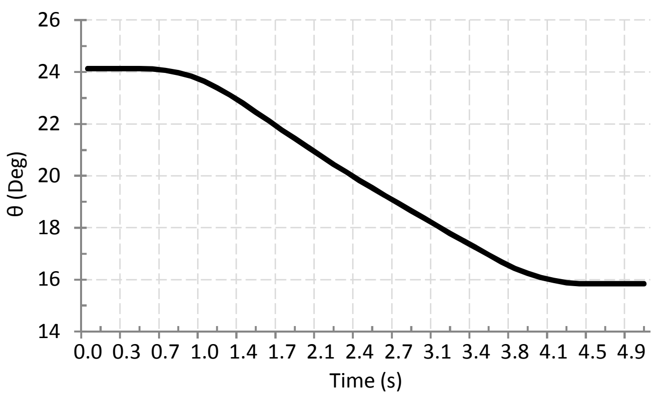

Figure 9 – Angular displacement of the tip jaws in the experiment

ISBN: 978-988-19252-3-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

In this experiment, according to the tip jaws angular displacements illustrated in Figure 9, the tip jaws were closed from 24 to 16 (deg) while the tissue samples were grasped and the applied force to the push rod were measured using the strain gages applied to the lead-screw (Figure 3). The initial positions of the tissue samples between jaws were held constant, therefore they all were incurred similar deformation but with different normal forces. The data acquired in this experiment are plotted in Figure 10. This figure shows the measured forces applied to the push rod (F_r). The normal forces applied to tissues at tip jaws calculated using Equation (2) are plotted in Figure 11. According to the Figures 9-11, the jaws started to close at the initial angular position of 24 (deg) at time 0.7 (s) and reached the final position of 16 (deg) at time 4.3 (deg).

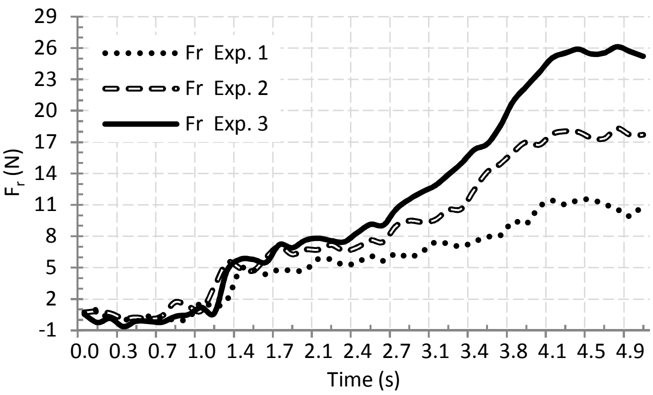

Figure 10 – Measured forces applied to the push rod (F_r) in the experiment

Compression started at time 1.2 (s) with tip jaws in angular position of 23.2 (deg) where the recorded data showed a sudden increase in grasping forces. As the jaws were closing, the grasping forces were increasing but with higher rate for harder tissue than the rate for softer tissue. Once the jaws got to the final position at time 4.3 (s), the forces remained constant to the maximum grasping forces. In this experiment, the measured peak forces applied to the push rod of the insert for three tissue samples from softer to harder are 12, 18, and 26 (N), respectively. These forces are, respectively, equivalent to 2.5, 3.8, and 5.6 (N) of the calculated normal forces at jaws directly applying to the tissue (Figure 11). As it is also observed from the Figures 10 and 11, the differences between increase rates of F_j and F_r increased as jaws were closing, got to the maximum difference at time 2.4 (s) where the jaws were at 20 (deg), and decreased to its minimum value in this experiment when the tip was at its closest state of 16 (deg). This phenomenon confirms the nonlinear relationship of F_j and F_r or the angular position of tip jaws (θ) with the angular displacement of the actuator shaft (ϕ) as it is also presented in Figure 4. As it is clear from the Figures 10 and 11, the measured forces using the proposed instrument are easily distinguishable which results in ability to characterise soft tissues of varying stiffness. Therefore, it can be concluded that the proposed laparoscopic instrument has good accuracy and performance for the grasping force measurement and is able to distinguish between tissues of varying stiffness even with relatively close young moduli.

IV. Conclusion And Future Works

An automated minimally invasive surgical instrument was introduced, the modelling and development issues were discussed, and experimental results were presented and analysed in this paper. The proposed surgery instrument has the capability of minimally invasively measuring normal tip interaction forces e.g. grasping and cutting. The instrument features non-invasive actuation of the tip and also the measurement of interaction forces without using any actuator and sensors at the jaws. The grasping direction in the proposed instrument can also be adjusted during the surgical procedure. The modularity feature of this force feedback-enabled minimally invasive instrument makes it interchangeable between various tool tips of all functionalities (e.g. cutter, grasper, and dissector) without loss of control and force measurement capability necessary to avoid tissue damage and to palpate and diagnose tissue and differentiate its stiffness during surgery. A high precision device for the measurement of young modulus of soft tissues were developed and utilised in this research. Experiments were conducted to evaluate capabilities of the proposed instrument in non-invasively measuring normal grasping forces. The result showed high accuracy and performance and verified the ability of the instrument in measuring normal grasping forces and in distinguishing between tissue samples even with slight differences in stiffness. The sterilizability of the instrument and especially the force sensing sleeve also needs improvements in future works before it can be used in surgery operating room.

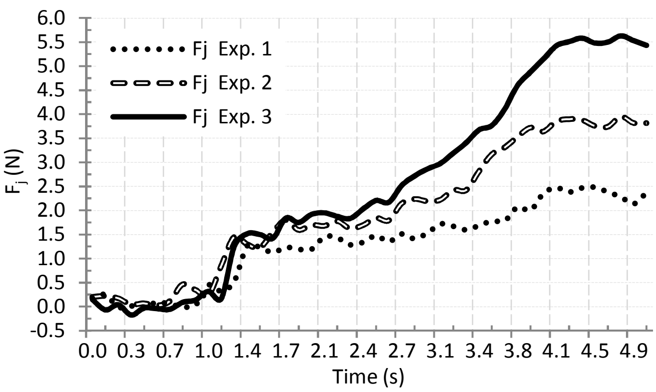

Figure 11 – Calculated forces applied to the artificial tissue samples (F_j) in the experiment

Acknowledgement

This research is funded by Australian Research Council, ARC Discovery-DP0986814, ARC LIEF-LE0668508, and ARC LIEF-LE0453629.

References

[1] A. R. Lanfranco, A. E. Castellanos, J. P. Desai, and W. C. Meyers, "Robotic surgery: a current perspective," *Annals of Surgery*, vol. 239, p. 14, 2004.

[2] M. Moradi Dalvand, B. Shirinzadeh, and J. Smith, "Effects of Realistic Force Feedback in a Robotic Assisted Minimally Invasive Surgery System," *Minimally Invasive Therapy and Allied Technologies (MITAT)*, Submitted - Revision 4, 2012.

[3] S. M. Sukthankar and N. P. Reddy, "Towards force feedback in laparoscopic surgical tools," in *Proceedings of the 16th Annual International Conference of the IEEE Engineering in Medicine and*

Biology Society, 1994, pp. 1041-1042.

[4] C. E. Reiley, T. Akinbiyi, D. Burschka, D. C. Chang, A. M. Okamura, and D. D. Yuh, "Effects of visual force feedback on robot-assisted surgical task performance," *Journal of thoracic and cardiovascular surgery,* vol. 135, pp. 196-202, 2008.

[5] M. Fakhry, F. Bello, and G. B. Hanna, "A Real-Time Compliance Mapping System Using Standard Endoscopic Surgical Forceps," *Biomedical Engineering, IEEE Transactions on,* vol. 56, pp. 1245-1253, 2009.

[6] P. Lamata, E. J. Gomez, F. L. Hernandez, A. Oltra Pastor, F. M. Sanchez-Margallo, and F. Del Pozo Guerrero, "Understanding perceptual boundaries in laparoscopic surgery," *IEEE Transactions on Biomedical Engineering,* vol. 55, pp. 866-873, 2008.

[7] P. Dubois, Q. Thommen, and A. C. Jambon, "In vivo measurement of surgical gestures," *IEEE Transactions on Biomedical Engineering,* vol. 49, pp. 49-54, 2002.

[8] J. Rosen, B. Hannaford, C. G. Richards, and M. N. Sinanan, "Markov modeling of minimally invasive surgery based on tool/tissue interaction and force/torque signatures for evaluating surgical skills," *IEEE Transactions on Biomedical Engineering,* vol. 48, pp. 579-591, 2001.

[9] S. K. Prasad, M. Kitagawa, G. S. Fischer, J. Zand, M. A. Talamini, R. H. Taylor*, et al.*, "A modular 2-DOF force-sensing instrument for laparoscopic surgery," in *Medical Image Computing And Computer-Assisted Intervention*, 2003, pp. 279-286.

[10] J. Dargahi, M. Parameswaran, and S. Payandeh, "A micromachined piezoelectric tactile sensor for an endoscopic grasper - Theory, fabrication and experiments," *Journal Of Microelectromechanical Systems,* vol. 9, pp. 329-335, 2000.

[11] U. Seibold, B. Kuebler, and G. Hirzinger, "Prototype of instrument for minimally invasive surgery with 6-axis force sensing capability," in *Proceedings of IEEE International Conference on Robotics and Automation*, 2005, p. 496.

[12] B. Kuebler, U. Seibold, and G. Hirzinger, "Development of actuated and sensor integrated forceps for minimally invasive robotic surgery," *International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 1, pp. 96-107, 2005.

[13] P. Valdastri, K. Harada, A. Menciassi, L. Beccai, C. Stefanini, M. Fujie*, et al.*, "Integration of a miniaturised triaxial force sensor in a minimally invasive surgical tool," *IEEE Transactions on Biomedical Engineering,* vol. 53, pp. 2397-400, 2006.

[14] M. Mahvash, L. M. Voo, D. Kim, K. Jeung, J. Wainer, and A. M. Okamura, "Modeling the forces of cutting with scissors," *IEEE Transactions on Biomedical Engineering,* vol. 55, pp. 848-856, 2008.

[15] M. C. Yip, S. G. Yuen, and R. D. Howe, "A Robust Uniaxial Force Sensor for Minimally Invasive Surgery," *IEEE Transactions on Biomedical Engineering,* vol. 57, pp. 1008-1011, 2010.

[16] J. Rosen, B. Hannaford, M. P. MacFarlane, and M. N. Sinanan, "Force controlled and teleoperated endoscopic grasper for minimally invasive surgery-experimental performance evaluation," *IEEE Transactions on Biomedical Engineering,* vol. 46, pp. 1212-1221, 1999.

[17] G. Tholey and J. P. Desai, "A Modular, Automated Laparoscopic Grasper with Three-Dimensional Force Measurement Capability," in *Proceedings of IEEE International Conference on Robotics and Automation*, 2007, pp. 250-255.

[18] C. R. Wagner, N. Stylopoulos, and R. D. Howe, "The role of force feedback in surgery: Analysis of blunt dissection," in *Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2002, pp. 73-79.

[19] M. MacFarlane, J. Rosen, B. Hannaford, C. Pellegrini, and M. Sinanan, "Force-feedback grasper helps restore sense of touch in minimally invasive surgery," *Journal of Gastrointestinal Surgery,* vol. 3, pp. 278-285, 1999.

[20] A. J. Madhani, G. Niemeyer, and J. K. Salisbury Jr, "The Black Falcon: a teleoperated surgical instrument for minimallyinvasive surgery," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1998, pp. 936-944.

[21] J. Rosen, J. D. Brown, L. Chang, M. N. Sinanan, and B. Hannaford, "Generalized approach for modeling minimally invasive surgery as a stochastic process using a discrete Markov model," *IEEE Transactions on Biomedical Engineering,* vol. 53, pp. 399-413, 2006.

[22] S. Shimachi, Y. Hakozaki, T. Tada, and Y. Fujiwara, "Measurement of force acting on surgical instrument for force-feedback to master robot console," in *Proceedings of the International Congress Series*, 2003, pp. 538-546.

[23] M. Moradi Dalvand and B. Shirinzadeh, "Forward kinematics analysis of offset 6-RR$\underline{C}$RR parallel manipulators," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2011.

[24] M. Moradi Dalvand and B. Shirinzadeh, "Motion control analysis of a parallel robot assisted minimally invasive surgery/microsurgery system (PRAMiSS)," *Robotics and Computer-Integrated Manufacturing,* vol. 29, pp. 318-327, 2013.

[25] M. Moradi Dalvand and B. Shirinzadeh, "Remote centre-of-motion control algorithms of 6-RRCRR parallel robot assisted surgery system (PRAMiSS)," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2012, pp. 3401-3406.

[26] S. B. Kesner and R. D. Howe, "Position control of motion compensation cardiac catheters," *Robotics, IEEE Transactions on,* vol. 27, pp. 1045-1055, 2011.

[27] S. G. Yuen, N. V. Vasilyev, P. J. del Nido, and R. D. Howe, "Robotic tissue tracking for beating heart mitral valve surgery," *Medical Image Analysis,* 2010.

ISBN: 978-988-19252-3-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)