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Mechanical Forces in Minimally Invasive Surgery: An Analysis of Surgical Experience

Analysis of mechanical forces on a porcine ureter during laparoscopic simulated training

Dominic Jones, School of Mechanical Engineering, University of Leeds

Ata Jaffer, Specialist Urology Registrar, St. James's University Hospital, Leeds

Chandra Shekhar Biyani, Consultant Urologist, St. James's University Hospital, Leeds

Peter Culmer, School of Mechanical Engineering, University of Leeds

Address for Correspondence:

Chandra Shekhar Biyani
Consultant Urologist & Hon Senior Lecturer
Department of Urology, St James's University Hospital
Leeds Teaching Hospitals NHS Trust, Beckett Street, Leeds, LS9 7TF
Telephone: 0113 206 6017
Fax: 0113 206 4920
Email: shekharbiyani@hotmail.com

Key words: laparoscopy, mechanical force, simulation, ureter

Abbreviations

MIS = Minimally Invasive Surgery

MRCS = Membership of the Royal College of Surgeons

Introduction

The concept of minimally invasive surgery (MIS) was introduced in 1901 when George Kelling performed the first laparoscopic procedure on dogs[1]. Development in technology allowed MIS to gain popularity in the 1990's whereby it posed formidable competition to existing open techniques. Since the 90's, MIS has completely revolutionized surgery[2]. One of the pitfalls of MIS however, as indeed with most new technological advances in surgery, is the accompanied learning curve.

During open operative procedures, the surgeon receives direct haptic feedback when manipulating tissues and is therefore able to regulate the amount of exerted forces, so that they are sufficient to prevent tissue slipping out of the instrument, yet not excessive to prevent tissue damage. Moreover, direct vision and three-dimensional visual cues are available; hand-eye coordination is therefore preserved. With the advent of MIS, long rigid instruments have been introduced between the surgeon's hands and the tissue, and therefore the direct feedback of mechanical forces is lost. The current instrumentation obstructs the perception of forces, velocities, and displacements of the tissues and the proprioception required for motor performance is distorted[3]. With direct haptic feedback, the trainee is able to perform laparoscopic tasks more consistently[4]. This is likely to be a result of better differentiation of tissue types with the use of direct vision as well as tactile feedback[5.] The steep learning curve required to overcome these obstacles posed by MIS has long been recognized as a potential hurdle for trainee surgeons especially given the static training models currently in place. Although virtual reality simulation has the potential to offer important advantages in the area of training for new skills and procedures, evidence on the transfer of skills from the simulated environment to the operating theatre is still limited, especially in advanced surgical procedures[6]. The direct feedback from tissue handling is diminished in MIS and therefore the discrepancy between 'safe' and potentially 'traumatic' mechanical forces applied to tissues is far more discrete as compared to traditional approaches in surgery. Given that most virtual reality simulators used for training currently lack realistic haptic feedback[7], trainees find it difficult to safely differentiate between varying forces applied to tissues.

In this study, we look to compare mechanical forces applied to ex-vivo porcine tissue through laparoscopic instruments by novice, junior and expert surgeons to assess whether those with more experience, handle tissue with a reduced, consistent level of mechanical force. If so, this would highlight the need to reinforce the importance of mechanical forces applied to tissues at an early stage of training to ensure safe handling and minimal trauma.

Materials and Methods

Thirty-four participants with different levels of experience in laparoscopy participated in the experiment. In the UK, once a student graduates from medical school, a further 2-years of foundation training is carried out to acquire the general competencies to work as a junior hospital doctor. This will involve working on wards with nurses and allied health professionals and delivering day to day medical care to in and out patients. Having completed the required foundation in the practice of hospital medicine, the next stage involves 2 years of core training either in surgery or medicine. Core surgical training lasts two years and provides training in a hospital in a range of surgical specialties and trainees are expected to take the examination to achieve membership of the Royal College of Surgeons (MRCS) or equivalent. For surgical specialty training, core trainees are invited to apply for the specialty training post through a national selection process. If successful, trainees are allocated a national training programme number and join a regional “rotation” as a Specialty Trainee (ST3 – designating the fact that is the third year of a seven-year formative training programme and finish as ST7. STs are often called registrars [resident]). The participants were divided into three groups (Novices, Intermediate and Experts) defined by their position in the medical training pathway. Novices included junior doctors who had been qualified for 1-2 years and had completed at least 4 months training in surgery, Intermediate as surgeons who were in surgical specialty training ~~(UK: Specialty Registrar, US: Resident),~~ and Experts were defined as surgeons who had completed their training (UK: Consultants, US: Attending). This did not correlate directly with specific training on MIS skills, yet was a good indication. The study was approved by the local research committee.

Instrumented Graspers

The laparoscopic graspers used in the experiment were curved dissectors (Surgical Innovations), modified to provide sensing of both grasping force and grasper face angle. This sensing module was positioned between the handle of the instrument and the shaft leading to the grasper faces (**Error! Reference source not found.**).

It contained a 200N load cell (LCM201-200N, Omega) and positioned between the existing mechanism to measure the grasp forces, and a Hall Effect sensor coupled to a moving magnet to measure the movement of the linkage, thereby measuring the grasper face angle. The sensors were calibrated across a range of values and achieved resolutions of 0.005N and 0.1°respectively. The instrumentation was housed in a custom casing fabricated by 3D printing. The full instrumentation module weighed 90g. The data was logged and recorded by a custom data acquisition software at 100Hz (Labview).

Experimental Protocol

The Instrumented Graspers were used to analyse grasping forces in a simulated surgical environment. A portable laparoscopic box trainer (Eosim) was used in conjunction with a webcam (C920 HD Pro, Logitech) to replicate the visual environment of MIS (**Error! Reference source not found.**). Porcine ureter samples were divided into ~50mm sections, and spatulated from the distal end. The samples were then affixed within the simulated environment. Participants were then asked to grasp the sample in three positions with each hand, both dominant and non-dominant. Each position was designated to a task, specifically grasping a total of 1, 5 or 10 times. Before the measurements were started, an overview was provided to the novices to explain how to perform the task.

The grasp forces and grasper face angle were recorded, with a video of each task also saved. Grasps were identified by analysing the force and position data, selecting peaks which surpassed both force and position thresholds. For each grasp, the peak force (Fmax), and mean force (Frms) were calculated, illustrated in Figure 3. using typical data for a grasping task. To eliminate bias of differing dominant hands, an Edinburgh Handedness Survey (EHS) was completed by each participant.

Results

The grasping study consisted of 34 participants, of which 8 were experts, 10 intermediates, and 16 novices completed a total of 32 grasps over the six tasks. Significant correlation was observed between Fmax and Frms (Pearson Correlation, $r = 0.97$, $p < 0.0005$). Due to this the reported results in Figure 3 only focus on Fmax.

Error! Reference source not found. shows a summary of grasps across tasks for the three skill levels. The associated grasp metric Fmax is shown in Table 1. A one-way ANOVA was conducted to compare the effect of the three different Tasks on Peak force, yielding no significant differences (F (2,1084) = 0.28, p = 0.753).

A Two-Way ANOVA was conducted to compare the effect of surgeon's experience on the Peak Grasp forces. This showed that there was a statistically significant difference with those more experienced applying consistently lower mechanical forces (F (2,1084) = 21.36, p < 0.0005). A similar test was conducted to assess the relationship between experience and handedness however this did not show a statistically significant interaction between dominant and non-dominant hands (F (1,1084) = 0.06, p = 0.806). The interaction effect (Training X Hand) was significant (F (2,1084) = 5.66, p = 0.004), therefore assessment of handedness in individual groups was performed.

In individual training groups the effect of Dominant Hand is significant in the Novice (significantly lower, F (1,510) = 6.70, p = 0.010) and Consultant (significantly higher, F(1,250) = 9.601, p < 0.020). The Intermediate group showed no significant difference between the hands (**Error! Reference source not found.**).

Discussion

The advent of endoscopic, laparoscopic, robotic, and image-guided percutaneous techniques to manage patients is only the beginning of an ever-expanding array of minimally invasive modalities available. Such modalities have reduced haptic feedback as compared to conventional open techniques[8,9] and therefore the demands placed upon surgeons in training to be able to differentiate between the subtleties of safe and excessive mechanical forces is significantly greater. There is evidence to suggest that experience is the most important factor in allowing the surgeon to develop a safer sense of mechanical forces applied to tissues[10]. This evidence was echoed by the results obtained from our study where we have shown that there are significant discrepancies in the mechanical forces applied to tissue between novice/intermediate trainees as compared to experts. Horeman et al also observed similar findings[11]. Whereas the novice/intermediate group where applying significantly higher forces onto tissue with increased variability over grasp time, the expert group showed a far greater level of force consistency with significantly reduced levels of forces applied as shown in **Error! Reference source not found.**).

In vivo, there is a direct, graded response between forces applied and tissue damage with liver and small bowel being most susceptible and ureter most robust[12]. In addition, certain laparoscopic complications can be attributed directly to tissue handling. One study analysing the errors during laparoscopic cholecystectomies showed that graspers were the most frequently involved instrument in erroneous task performance: 70 out of 189 errors (37%) in 20 procedures. Importantly, 14 out of the 70 grasping errors (20%) were due to excessive forces and all of them required corrective action[13]. A further study investigating erroneous task performance during 977 laparoscopic operations performed by 20 surgeons, graspers came third in frequency of causing complications (53%), after coagulators and dissectors. Because of the delicate arterial supply of the ureter, it is very important to handle the ureter with minimal force. Clearly, the threshold of safe mechanical pressure that one can apply is dependent on the type of tissue surface and therefore further work is required to firstly identify these thresholds and secondly to incorporate a feedback mechanism to alert the operating surgeon.

As such systems are currently not in place, surgeons find the ability to differentiate between safe and dangerous levels of tissue handling in laparoscopic surgery very challenging. It is felt by some that there is currently an insufficient training model in place for surgical trainees to develop this skill[14.] In years gone by, trainees were able to learn and develop open surgery in the operating theatre however the complexities of MIS are such that these conventional training methods cannot be replicated. Many have looked to simulation to fill this void in surgical and this has been an area which has grown in recent times[15]. Several training models have been proposed with the virtual reality simulators being very popular in surgical training[16]. These can provide basic skills training in a controlled environment free of pressure of the operation on patients. They can also offer objective performance assessment without the need for monitored human supervision and directly measure multiple aspects of a subject's psychomotor performance on specific laparoscopic skills. The major flaw with current virtual reality simulators however is that the majority lack the feel of realistic haptic feedback[17]. As discussed earlier, this is crucial in allowing trainees to develop an understanding of safe grasping forces and is therefore an area which is deficient in current training models. There clearly needs to be improvement within this area of training if future MIS surgeons are to perform safer procedures with fewer complications.

Analysis of the forces acquired with the instrumented grasping system has given us a quantitative insight into the mechanics of surgical grasping. Specifically, it has suggested a relationship between the training level of the surgeon and the forces imparted on the tissue. This demonstrates a need for further training in surgeons until a consistent low force can be applied to tissues. Whether such measures could be used as an indicator of surgeon proficiency is unclear, however it has the potential to be used to determine whether more training is needed for surgeons. Future work would characterise the tissues commonly involved in MIS to find the safe levels of force which can be applied.

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Legends to figures and table.

Figure 1- A Photo indicating the structure of the instrumentation module of the Graspers

Figure 2 - The test setup in use, showing the simulated environment and positioning of the participants.

Figure 3 - Example of typical Grasping data. Indicates the Peak Force (F_{MAX}) and the force threshold at which grasps were detected.

Figure 4 - The average grasp for each skill level (±SEM)

Figure 5 - Mean peak forces (F_{MAX}) ±95%CI for all tasks against training level

Table 1 – Mean values of F_{MAX} for each task, (Hand (No. of Grasps))

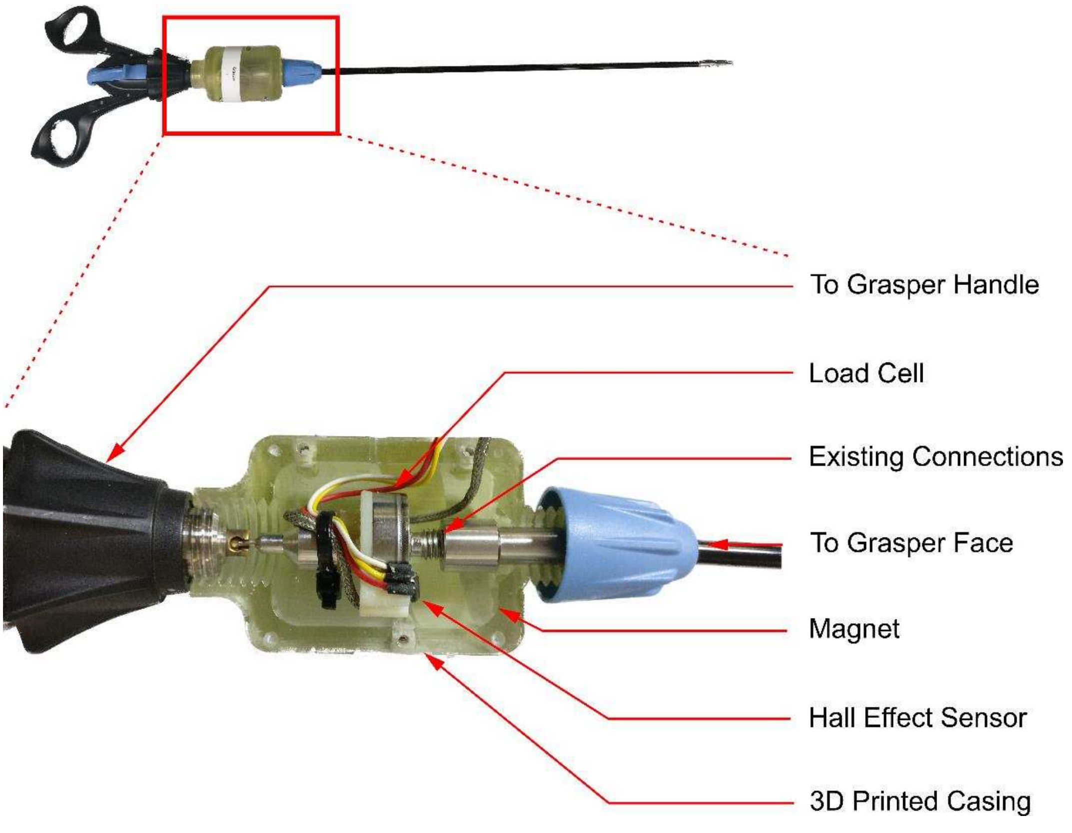

Figure 6- A Photo indicating the structure of the instrumentation module of the Graspers

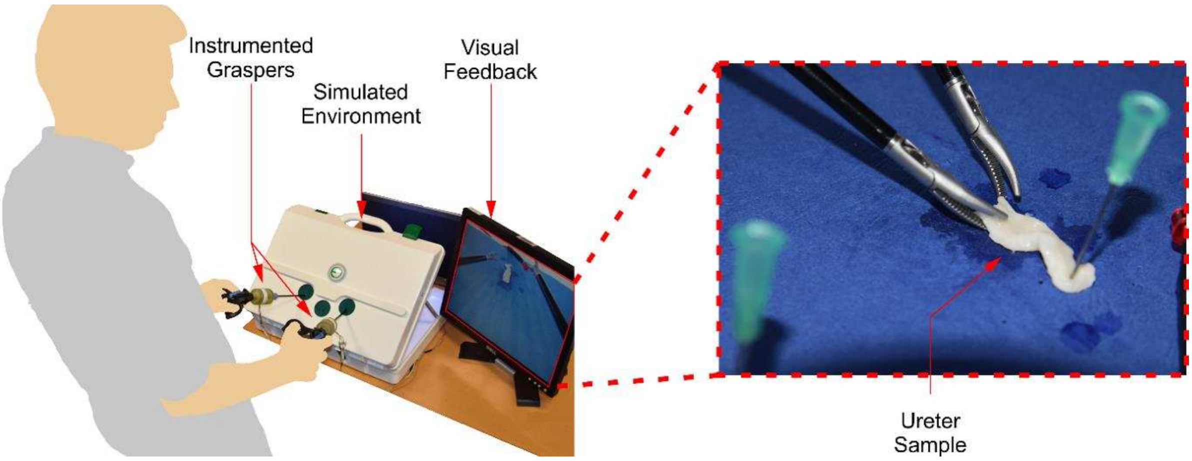

Figure 7 - The test setup in use, showing the simulated environment and positioning of the participants.

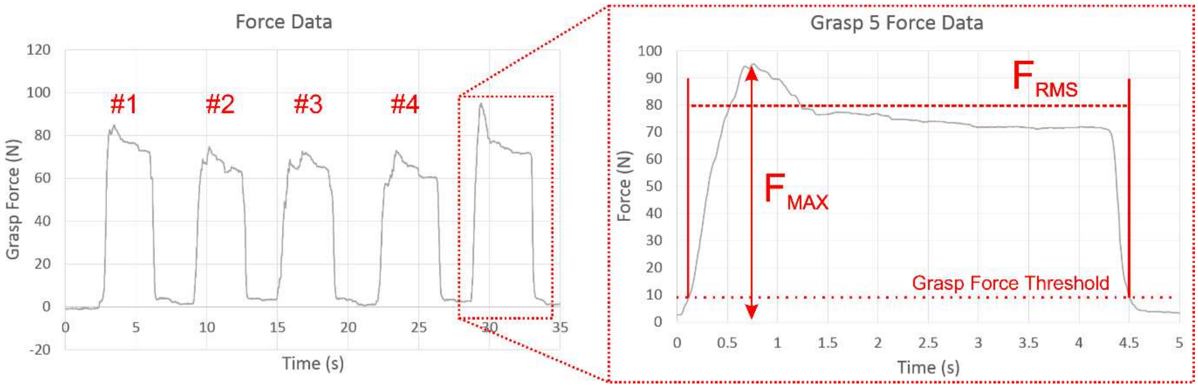

Figure 8 - Example of typical Grasping data. Indicates the Peak Force (F_{MAX}) and the force threshold at which grasps were detected.

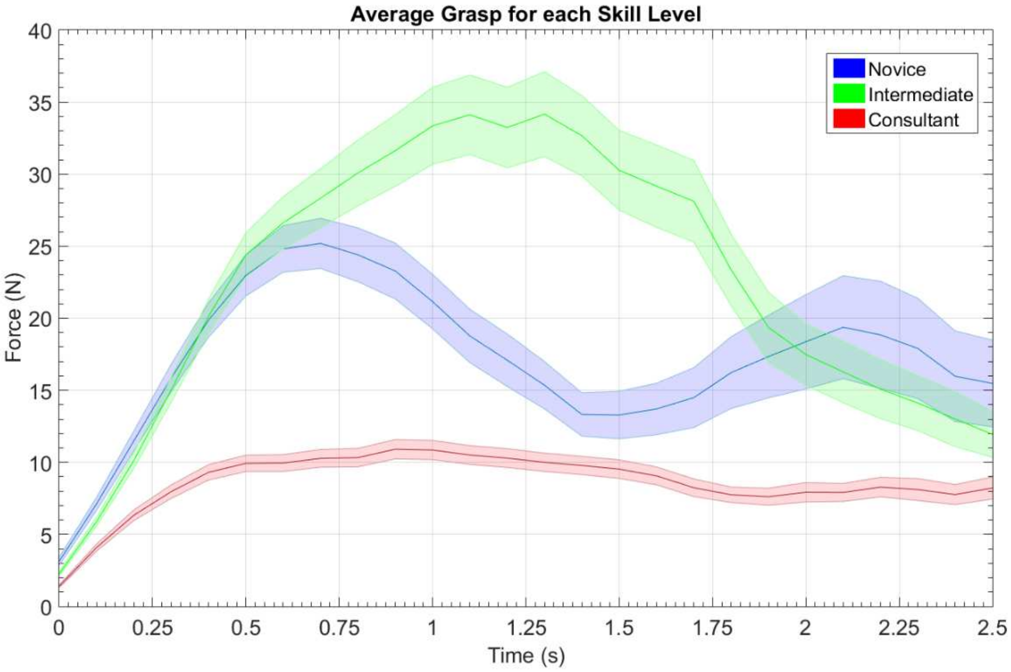

Figure 9 - The average grasp for each skill level (±SEM)

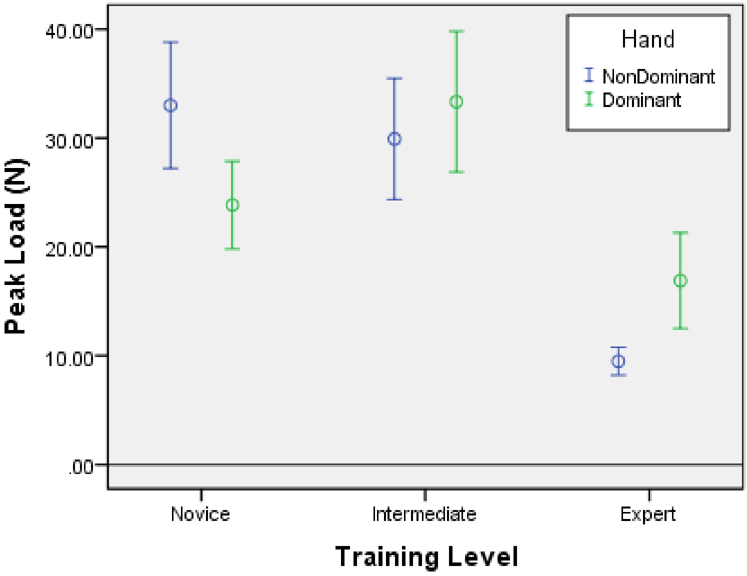

Figure 10 - Mean peak forces (F_{MAX}) ±95%CI for all tasks against training level

Table 2 – Mean values of F_{MAX} for each task, (Hand (No. of Grasps))

TASK	FMAX (MEAN±SEM)
NON-DOMINANT 1	19.69±4.53
NON-DOMINANT 5	18.16±2.09
NON-DOMINANT 10	23.24±2.29
DOMINANT 1	22.81±5.39
DOMINANT 5	24.41±2.75
DOMINANT 10	21.55±2.19