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Friction Characteristics of Trocars in Laparoscopic Surgery

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Abstract

This paper investigates the friction characteristics of the instrument/trocar interface in laparoscopic surgery for varying linear instrument velocities, trocar seal design and material, and trocar tilt. Further, the effect of applying lubrication at the instrument/trocar seal interface on friction was studied. A friction testing apparatus was designed and built to characterise the resistance force at the instrument/trocar interface as a function of the instrument's linear movement in the 12 mm trocar (at constant velocity) for different design, seal material, and angle of tilt. The resistance force depended on the trocar seal design and material properties, specifically; surface roughness, elasticity and hardness, the direction of movement and the instrument linear velocity, and varied between 0.25 and 8 N. Lubricating the shaft with silicone oil reduced the peak resistance force by 75% for all trocars and eliminated the stick-slip phenomenon evident in non-lubricated cases. The magnitude of fluctuation in resistance force depends on the trocar design and is attributed to stick-slip of the sealing mechanism, and is generally higher during retraction in comparison to insertion. Trocars that have an inlet seal made of rubber/polyurethane showed higher resistance forces during retraction. Use of a lubricant significantly reduced frictional effects. Comparisons of the investigated trocars indicate that a low friction port, providing the surgeon with improved haptic feedback, can be designed by improving the tribological properties of the trocar seal interface.

Keywords: trocar, friction, sliding speed, surface roughness, haptic feedback

1 Introduction

In open surgery, the sense of touch (haptics) is a key source of information that guides the surgeon. The manipulation of the organs and tissues are achieved via a direct contact to perceive the structure and properties of tissues, as well as force need to manipulate them.[1] The advent of laparoscopic surgery has transformed the practice of surgery, replacing a wide 'open' incision with several small incisions and specialised instruments. This has resulted in reduced trauma, shorter hospital stays, and quicker recovery for the patient. In laparoscopic surgery, surgical instruments are inserted into the body through trocars to interact with the patient's tissues. The instruments are long, placing the surgeons' hands at a distance from the tissues. This prevents the surgeon from using direct touch which results in reduced and distorted haptic feedback, and significant problems of hand-eye coordination.[2, 3]

It is widely accepted that the surgeon receives limited haptic feedback due to the current design of laparoscopic instruments.[4] The laparoscopic instrument placed inside a trocar is in contact with a series of overlapping seals that fit tightly around the instrument to maintain gas pressure within the body cavity. Friction forces generated at the instrument/trocar seal interface can contribute to errors in surgeons' haptic perception.[5] For surgeons to perceive useful force information from the surgical site during a surgical procedure, they must be able to accurately differentiate between trocar seal resistance force and tissue contact. Therefore, when the magnitude of tissue contact forces are similar to the resistance force, the surgeon may have difficulty in perceiving differences in tissue resistance.

A number of researchers have reported the resistance force at the surgical instrument/trocar seal.[6, 7, 8] Picod *et al.* found that the forces applied at the distal extremity of the instrument range from 0 to 10 N with a considerable friction force of 3 N. Dobbelsteen *et al.* reported friction variations between 0.25 and 3 N for 5 and 8 mm trocars, with maximum fluctuations of 2.5 N when the movement starts or when the direction reverses. However, none have considered the effect of sliding speed on the resistance forces in relation to the mechanical properties of the trocar seals and their design. When a laparoscopic instrument is moved through a trocar, the force that it takes to start its motion is different from the force needed to keep it in motion. The static friction force provides the stability to the instrument at any instant when the instrument is not under consideration during surgery. The force required to start instrument movement has to overcome the static frictional resistance, whereas the force required keeping the instrument in reciprocating or rotation motion has to overcome the dynamic frictional resistance. The difference between these two forces can significantly vary according to the trocar seal, design, and surgical instrument in use. This factor affects the dynamic stability of the instrument in the trocar and the fidelity with which the surgeon can feel the tissue during surgery.[8]

To address this, AirSeal® port (SurgiQuest Inc., Connecticut, USA) is marketed as a 'frictionless' trocar system using its valve-free design. It removes contact between the instrument shaft and trocar by using a high flow air bearing configuration, thus friction is reduced. However, these trocars require additional equipment to maintain the insufflation pressure and cannot be used in some cases due to the noise associated with the inherent gas leakage or if a large amount of tissue is retracted from the abdomen.[9] Consequently, it remains important to improve existing trocar seal assemblies to overcome the deficiencies outlined above.

In this paper, five commercially available 12 mm trocars are studied for their friction characteristics under dynamic conditions. The trocar seal surface roughness, modulus of elasticity and design are examined and correlated against the frictional resistance observed during laparoscopic instrument linear motion in various trocars. Further, the effect of lubrication at the interface on the resistance force was studied.

2 Materials and Methods

2.1 Laparoscopic Instrument and Trocars

Current laparoscopic instruments typically have a maximum diameter of 15 mm, but the majority of instruments are designed to pass through 5 to 12 mm cannulas. In this paper, a 10 mm diameter grasper (Surgical Innovations© Ltd., with a reusable jaw insert/tube made of polyphenylsulphide insulated stainless steel 304, having a working length of 305 mm) was selected due to its prevalence in routine laparoscopic surgery. The handle, gasket seal and knob were removed from the instrument prior to study.

The majority of trocars not only provide access to the abdominal cavity during laparoscopic surgery, but also maintain separation between the abdominal and atmospheric pressures for surgical procedures. Five brands of commercially available trocars, compatible with 10 mm instruments, were used in this study, see Figure 1. The trocars were selected for their varied design, seal material and sealing mechanism. All trocars have a top (proximal) seal for creating a gas-tight seal with the instrument shaft and a duckbill (distal) seal below the top seal for sealing the trocar cannula in the absence of an instrument.

The selection of seal material is important to the proper functioning and quality of the trocar. In general, the seal requirements are similar among different trocar designs. The surface roughness of the seal has to be low so that laparoscopic instrument insertion is smooth and the seal can hold its shape around the instrument as it moves during the surgical procedure. The sealing material must be highly durable to withstand multiple insertions and removals of the instrument during surgery. It must be elastic so that it stretches properly while maintaining a seal during use and must have the ability to relax to its original shape when instruments are removed. Furthermore, the sealing mechanisms must be tough and resistant to tearing.

2.1.1 Applied® Trocar

The 12 mm diameter Applied® trocar (Applied Medical Resources, Rancho Santa Margarita, CA, US) comprises a compression molded polyisopropene instrument (proximal) seal and a compression molded polyisopropene zero seal, see Figure 1(a). The cover is fitted on the instrument seal and the zero seal. The zero seal is generally cylindrical with the proximal end coupled to the proximal portion of the instrument seal.[10]

2.1.2 Genicon® Trocar

Figure 1(b) shows a 12 mm diameter Genicon® trocar (Genicon Inc, Florida USA) consisting of a conically shaped elastomeric material inlet valve housing extending axially from the proximal end and a proximal seal (lip seal) for sealing. The elastomeric material includes polyisoprene and a fibrous material (a high-strength and resilient synthetic polymer containing polyurethane) being impregnated with a silicon material to enhance the strength of the valve and sliding of the instruments. The valve housing has a roughened outer dimple surface to enhance gripping and rotational motion.[11]

2.1.3 Laport® Trocar

The 12 mm diameter Laport® trocar (MGB Endoskopische Geräte GmbH Berlin, Germany) incorporates a spring-loaded flap valve and an inlet silicone valve, as shown in Figure 1(c). The flap valve is a self-opening mechanism during passage of the instrument and subsequent automatic re-closure in the absence of the instrument. Sealing is achieved through an inlet silicone valve at the trapdoor.

2.1.4 Endopath® Xcel Trocar

Figure 1(d) shows a 12 mm diameter Endopath® Xcel™ trocar (Ethicon Endo-Surgery Inc, Cincinnati, Ohio, US) containing a proximal seal assembly composed of four overlapping self-adjusting elastomeric (polyisoprene) rubber seals that create a conical hole to accommodate instruments and an internal plastic seal. The cone feature of the seal assembly reduces the possibility of seal inversion upon instrument retraction and provides a natural lead-in towards the center of the seal assembly.[12]

2.1.5 SI SwingTop® Trocar

The SI SwingTop® trocar (Surgical Innovations Group Plc, Leeds, UK) has a cannula diameter of 11 mm with the removable rubber sealing cap and a swing top unit option which retains the lip seal; see Figure 1(e). The sealing cap prevents gas leakage while the instrument is inserted and moved, and a silicone valve at the proximal end of the cannula provides a seal in the absence of an instrument.

2.2 Test Rig and Instrumentation

A testing apparatus, shown in Figure 2, was designed and built to characterise the friction dynamics between the laparoscopic instrument shaft and trocar. The rig enables varying tilt angles of the instrument/trocar pair to the horizontal to emulate a laparoscopic configuration. The apparatus consists of a high precision linear motor (LCA25-100-15, SMAC Inc., USA), fixed to the vertical base to actuate a drive assembly and move the instrument axially through the trocar. The drive assembly comprises a linear guide and slider attached to an interface bracket, and provides a mechanism to move the shaft of the instrument without misalignment and eliminates the radial load to the motor's shaft. The interface bracket was mounted to the laparoscopic instrument via a 6 DoF force/torque transducer (Nano17-E, ATI Industrial Automation, USA) and to the linear motor via an elliptical hole to avoid possible misalignments. The centre of the transducer was aligned axially with the instrument shaft, and attached to the bracket and proximal end of the instrument shaft using custom-designed mounting adapters. The trocar port was mounted on the frame such that the instrument shaft remains concentric to the cannula and does not touch the side wall or the edge during its linear motion within the trocar.

The friction dynamics of the instrument produced by its axial movement through the trocar were characterised by measuring the resultant load through the force/torque transducer. The Nano 17-E has a resolution of 0.0125 N along its z axis (which was aligned with the axial movement of the instrument for this experiment), with a tested repeatability error of less than 1%. Custom software (LabVIEW™, National Instruments Inc., USA) was developed to configure, monitor, and control the linear motion and record the axial position and force at a sampling rate of 250 Hz. The linear actuator was controlled using a single-axis motor drive (LCC-11, SMAC, CA, USA). The output of the force/torque transducer was measured using a data acquisition device (USB-6212 DAQ, National Instruments, USA). Before each experiment, the system was initialised by moving the linear actuator to its predefined home position, and the force/torque transducer was zeroed by removing any bias reading. Subsequently, the instrument was driven through a series of inward and outward movements at a constant velocity with configurable motion profiles defined in the software. Tests were repeated 6 times for each condition. The inward and outward movement distance for all runs was 40 mm.

3 Results

Figure 3 shows typical force-time and displacement-time curves for a cyclic inward and outward movement of the laparoscopic instrument in the trocar. The load cell records positive values for an inward movement of the instrument and negative values for outward movement of the instrument from the trocar. In the example shown, AB represents the initial resistance force due to the elasticity of the top seal. Here, the top seal sticks to the instrument and the interfacial attraction at the interface allows the seal to extend till it reaches a maxima, as shown by point B. BC is the insertion force (F_i) recorded for combined resistance by the top seal and the valve for instrument forward movement at a constant velocity in the trocar. At point C the instrument is retracted. CD is the peak resistance force (F_p) observed instantaneously with a reversal of motion of the instrument. This peak resistance force is due to the stiction of the instrument to the seal. The seal reverses its direction with the instrument outward movement and stretches until it reaches its limit during expansion (point D). At D, the seal relaxes to attain a conformal resistance to the instrument shaft resulting in reduced resistance force (point E). A time lag exists between point D and E. EF is the end of the cycle representing the resistance force during retraction (F_o) until it reaches its original position at F.

3.1 Seal Material

Table 1 shows the surface roughness and modulus of elasticity of the seal material for various trocars and the instrument shaft used in this study. An optical white light interferometer (Veeko Wyko^{TM}, NT 3300), a non-contact type of optical profilometer having a vertical resolution of 3 nm, was used to measure the centreline average surface roughness (Ra) of the trocar seal/valve and the instrument shaft. It can be seen that the instrument shaft (Ra ~ 94.8±7 nm) is smooth in comparison to the trocar seals (Ra>200 nm). Surface roughness measurements were taken at three places at the edge of the seal/valve, the surface which is normally in contact with the instrument shaft during its linear motion within the trocar and at three positions on the instrument shaft. Measures of elasticity were taken on a 20 µm × 20 µm scanned area on the seal/valve surface with a nano-indentation instrument (Micro Materials Ltd.). Depth versus load measurements were made for each surface using a diamond nano-indenter tip applied to seal/valve surfaces at five different depths up to a maximum of 4 µm and a maximum load of 1 mN. The loading and unloading rate was 0.02 mN/s with 60 s dwell time in the applied position.

3.2 Effect of Sliding Speed

Experiments were performed to explore the effect of the instrument speed on the friction forces; F_i, F_o, and F_p. Three different sliding speeds of 2 mm/s, 5 mm/s and 20 mm/s were chosen. Here, a sliding speed of 2 mm/s and 5 mm/s represents the speed of the instrument during manipulation and ideal insertion respectively,[13] and 20 mm/s represents a simulated speed at which the instrument is pulled outwards during surgery.[14]

Figure 4 and Figure 5 show that sliding speed did have an effect on F_p at the instrument/trocar seal interface. As sliding speed increases, there is a corresponding decrease in the F_p. This is in line with the findings of Dobbelsteen *et al.*.[8] Also, the resistance force recorded for the instrument during inward and outward movements differs in magnitude at all velocities. The Applied and Laport trocars showed a low F_p during inward movement of the instrument as they have a polished surface finish (Ra<300 nm) and similar modulus of elasticity of the valves/seals, see Table 1. Endopath Xcel trocars showed intermediate F_p due to the high resistance force during retraction of the instrument even though the resistance offered during insertion of the instrument is low. This difference in resistance force was attributed to a high surface roughness of the bottom seal in comparison to the top seals. The SI SwingTop and Genicon trocars showed high resistance force due to rougher sealing cap and septum seal (Ra~500 nm), with Endopath Xcel trocar offering least resistance due to a smooth top seal laminate surface (Ra~200 nm) in contact with the instrument during their insertion into the trocar. The SI SwingTop trocar showed high frictional resistance due to large contact area and high contact pressure resulting from a tight fit at the sealing cap instrument interface. The large contact area at the instrument/seal interface occurred due to the stiffness of the seal in the SI SwingTop trocar (E>10 MPa). Compared to the SI SwingTop trocar, the Genicon trocar showed a low F_p, however, it is prone to stick-slip (stretching and slipping of the inlet seal) as shown by a large variation in force when the instrument motion reverses. A large variation in F_p is due to a stiffer proximal seal (E~6 MPa) in comparison to the bottom seal (E~3 MPa). With a change in movement direction the flexible bottom seal material deforms quickly, however the proximal seal remain in contact to follow the profile on the instrument, creating a large contact area at the instrument/trocar seal interface. The trocars with an inlet seal made of rubber/polyurethane showed high F_o. The resistance offered by these trocars significantly depends on the sliding speed of the instrument. Further, it can be observed that the Applied and Laport trocars exhibit similar resistance force during insertion and retraction of the instrument at different sliding speeds due to their comparable surface roughness, modulus of elasticity and seal materials.

3.3 Effect of Instrument/Trocar Tilt

The mechanical properties of the abdominal wall around the trocar port are not always isotropic during surgery.[7] The movements of the instrument may lead to tilting of the instrument/trocar pair and the tight fit contact at the trocar seal and instrument shaft becomes asymmetric leading to frictional disturbance between the instrument/trocar interfaces.

Figure 4 and Table 2 show the resistance force during insertion and retraction of the instrument, and peak retraction force at different sliding speeds and tilt of the instrument/trocar pair for all five trocars. The magnitude of this resistance force depends on both sliding speed and movement direction. It can be seen that the resistance force during retraction of the instrument is greater than the resistance offered during insertion of the instrument in SI SwingTop, Endopath Xcel, and Laport. During inward movement of the instrument, the top and bottom seals are in tension and move along the instrument; however on retraction of the instrument, the bottom seal may have recovered from the deformation but the top seal is still under tension leading to high resistance force. At a low instrument sliding speed of 2 mm/s and 5 mm/s, the angle of tilt of the trocar has no significant effect on the frictional resistance during insertion or retraction of the instrument. The peak retraction force for the trocars is similar in magnitude at configured angle of tilt of the trocars/instrument pair. At low sliding speed of 2 mm/s, the trocars show similar frictional resistance during retraction of the instrument, irrespective of the angle of tilt to the horizontal. Resistance force during insertion of the instrument is low (<2 N for sliding speeds of 2 mm/s and 5 mm/s) and depends on the trocar design. However, at an instrument sliding speed of 20 mm/s the trocars show large variability in the resistance force (6±3 N), with the Genicon and SI SwingTop trocars significantly affected by the inclination of the instrument/trocar pair.

3.4 Effect of Lubrication on Frictional Resistance

The main purpose for lubricating the instrument shaft was to ensure its proper sliding between the seal assemblies without having the stick-slip phenomenon. A fixed quantity (1 ml) of fluid was used to wet the instrument shaft. The instrument shaft was lubricated with water and hydrophobic volatile silicone oil (Dow Corning® 200 Silicone fluid, normally used in cosmetics).[15, 16] Water and Dow Corning 200 fluid have viscosities of 0.89mPa.s and 1 mPa.s respectively at 25°C.[17] The fluids were selected for this study since they have similar viscosities to those of the peritoneal fluid, a natural lubricant of abdominal organs.[18, 19]

Tests were conducted under dry and lubricated conditions using an Endopath Xcel port, selected as the median performing device, see Figure 6. It can be seen that water and silicone oil reduces the F_i and F_o at sliding speeds of 5 mm/s and 20 mm/s. The level of reduction in friction depends on the design of the trocar and the lubricant used. When the instrument moves in the trocar, the lubricant spreads to the contact area between the seals and the surface of the instruments shaft leading to a thin film formation at the instrument/trocar seal interface. The reduction in friction is more prominent with silicone oil in comparison to water. Silicone oil reduces friction by forming a non-greasy thin film between the sliding surfaces. Water lubrication was found to be ineffective due to its behaviour under use; the water is either squeezed out of the contact area or drains out due to poor integrity of the instrument/trocar seal interface.[8] Lubricating the instrument shaft with silicone oil reduced the peak force significantly by 75%. In addition to this, stick-slip phenomena disappeared completely.

4 Discussion

This study shows that the friction characteristics at the instrument/trocar seal interface depend on instrument sliding speed and differ significantly according to trocar design. In most cases, the friction force during insertion of the instrument is different from the resistance during retraction of the instrument. The resistance force does not vary significantly with the inclination of the instrument/trocar pair at low sliding speeds, however, it varies significantly at moderate sliding speeds of 20 mm/s. Lubricating the instrument/trocar seal interface subsequently reduces friction during insertion and retraction of the instrument from the trocar. Friction reduction is accomplished by a thin layer of lubrication at the interface. It also reduces the difference between the static and dynamic friction. Low viscosity lubricants such as water squeezed out of the contact area at lower movement velocity, and therefore no significant difference is seen in friction profiles. However we found that by adding a silicone lubricant significant reduction in F_i, F_o, and F_p can be observed.

Inward movements of the laparoscopic instrument through the trocar, results in static friction due to stiction of the instrument shaft to the seal. The resistance force during an insertion movement reaches a critical force until slip occurs at the interface. It is important that the seal material is such that the seal does not rip or tear as the seal is stretched to its limit. Beyond this point, the friction force reduces to a constant value. The exact magnitude of this reduction depends on the elasticity of the sealing mechanisms. If the seal material is stiff, the deformation and the contact area is less, stickiness is low and therefore static friction is small. Furthermore, a small slip at the interface results in a low difference between static and dynamic friction. In addition, this prevents large fluctuations in resistance force at the movement reversals.

Low friction means that the surgeons do not need to apply extra force to overcome the resistance force at the interface. A reduction in resistance force at the instrument/trocar seal interface reduces the likelihood that the seal assembly and/or cannula will be dislodged from a body during retraction of the instrument. However, it is very important that the sealing fits exactly. Too tight a fit will result in high contact pressure resulting in increased static and dynamic friction, and too loose a fit will result in gas leakage from the interface. The seal material roughness and modulus of elasticity is important in designing a low friction trocar port to allow movement of the instrument with negligible friction at the instrument/seal interface. Trocar ports with narrow and thick sealing caps generated a high amount of friction at the instrument/trocar seal. Forcing large diameter instruments through a small diameter seal significantly increases the resistance force on the instrument shaft.

5 Conclusions

Comparisons of the investigated trocars indicate that the fluctuation in resistance force is higher during instrument retraction. The magnitude of the fluctuation depends on the trocar design, seal material roughness and modulus of elasticity, and stick–slip phenomenon of the sealing mechanism in those trocars. Trocars using rubber/polyurethane seals showed high resistance force during retraction. Frictional resistance is higher during retraction in comparison to the insertion of the instrument. At movement reversals, high frictional resistance occurs due to a large contact area and high contact pressure resulting from a tight fit at the sealing cap instrument interface. Although the bottom seal recovers rapidly from the deformation the top seal remains under tension leading to high resistance force. Lubricating the instrument reduces the peak resistance force by 75% for all trocars and stick-slip phenomena disappeared completely. The choice of lubricant is also significant, silicone oil is far more effective than water in minimising friction. This study represents initial work to investigate and quantitatively document the frictional characteristics of trocars.

The wide range in frictional characteristics seen between trocars and between differing movement speeds have significant implications for the surgeon. Accounting and compensating for these factors is likely to be extremely difficult, hence it may cause the surgeon not to use direct haptic feedback as a reliable source of information. To address this, the optimal trocar would have low friction at constant speed, low variation during direction change, and consistency across movement speeds. Interestingly, we found that performance of the Endopath Xcel with lubricant is no better than the dry performance of Laport and Applied trocars. Thus, while lubrication improves performance, more significant gain could be made by optimising the instrument/trocar seal design and material tribological properties. These may be more appropriate in complex surgical environments rather than requiring lubrication to be applied and maintained.

Ultimately, this study indicates that current trocars could be optimised by improving the design and tribological properties of their seals. This will significantly improve the haptic feedback received by the surgeon and consequently improve the quality of their operative experience.

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Figure and Table Legends

Figure 1. Commercially available trocars used in the experiment

Figure 2. Experimental friction testing apparatus designed and built for the friction measurement. The entire apparatus was mounted on an adjustable frame that could be clamped to a workbench at various angle of tilt.

Figure 3. Example of typical force-time and displacement-time curves for a cyclic movement of the laparoscopic instrument in the trocar. Here, F_i and F_o are resistance forces during insertion and retraction of instrument, and F_p is the peak resistance force.

Figure 4. F_i (positive wide bars) and F_o (negative wide bars) for a linear instrument motion at different sliding speeds. The top and bottom graphs are for instrument/trocar pair's angle of tilt of 90 and 0 deg, respectively.

Figure 5. Friction dynamics of the trialled trocars at different speed with the angle of tilt of 90 deg. The force scale of each plot is adjusted for clarity. Each trace shows the mean response of 6 repeats (solid line) together with the standard deviation (shaded area).

Figure 6. Effect of lubrication on resistance force at different speeds (shown for the Endopath Xcel). Each trace shows the mean response of 6 repeats (solid line) together with the standard deviation (shaded area). The lower chart shows the effect of lubrication on F_i (positive wide bars) and F_o (negative wide bars) for the Endopath Xcel motion at different sliding speeds.

Table 1. Material, average surface roughness and modulus of elasticity values for the trocar seal/valve surfaces and a laparoscopic instrument. The laparoscopic instrument used was a stainless steel tube insulated with polyphenylsulphide (Ra = 94.8±7.0 nm) with the total diameter of 10 mm.

Table 2. Kinetic inward/outward frictions and peak resistance force at different speeds and angle of tilt

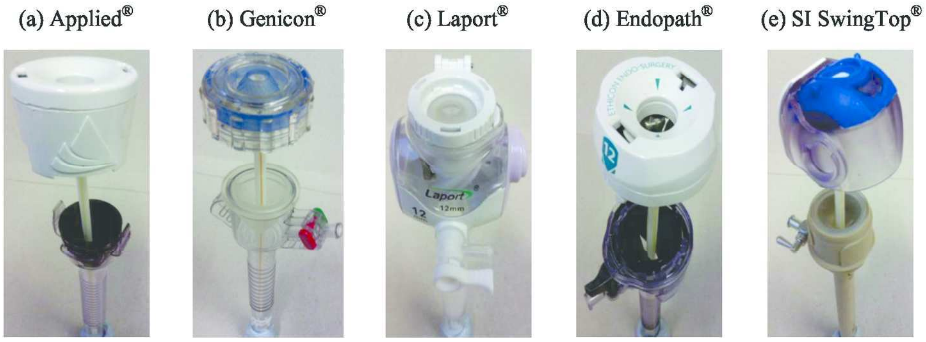
Table 1. Material, average surface roughness and modulus of elasticity values for the trocar seal/valve surfaces and a laparoscopic instrument. The laparoscopic instrument used was a stainless steel tube insulated with polyphenylsulphide (Ra = 94.8±7.0 nm) with the total diameter of 10 mm.

Trocar	Valve/Seal		Material	Surface Roughness, Ra (nm)	Modulus, E (MPa)
SI SwingTop	P:	sealing cap	Rubber	460±35	11.0±0.6
	D:	lip seal	Silicone	470±20	10.3±0.3
Genicon	P:	septum seal	silicone containing polyurethane	450±30	0.82±0.2
	D:	lip seal	Silicone	380±25	0.68±0.2
Endopath Xcel	P:	top seals	rubber with plastic laminate	200±30	6.30±0.4
	D:	bottom seal	Rubber	460±30	4.00±0.5
Laport	P:	inlet valve	Silicone	270±5.0	7.12±3.0
	D:	flap valve	Silicone	220±10	7.10±0.5
Applied	P:	zero seal	Rubber	260±35	1.38±0.1
	D:	septum seal	Rubber	240±30	0.70±0.1

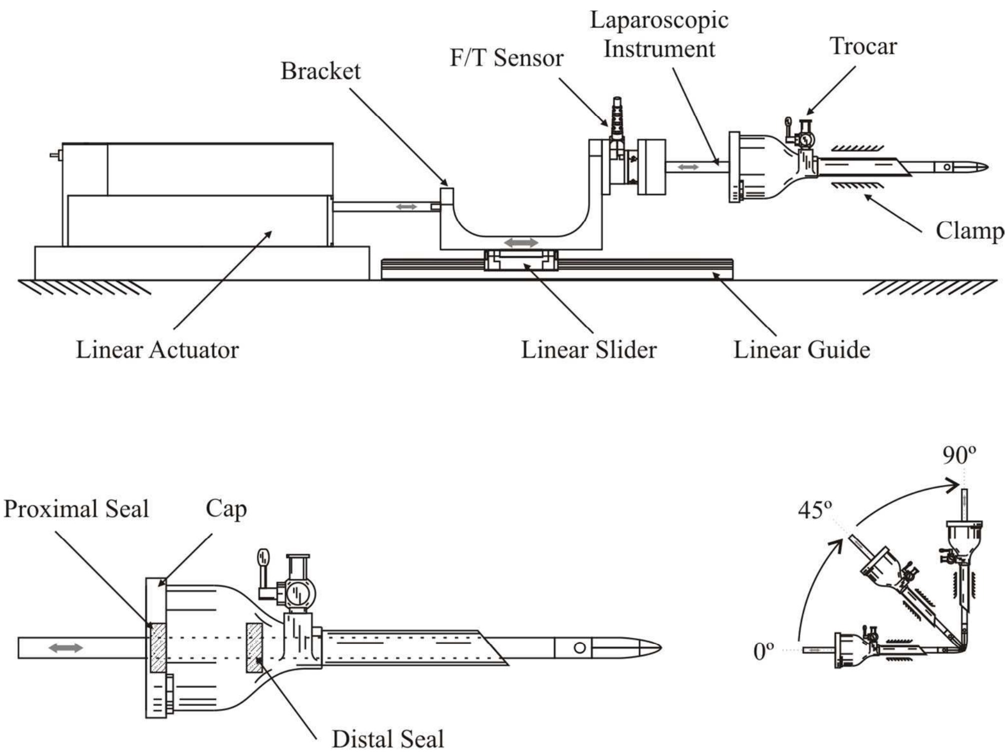
, where P and D stand for, respectively, the proximal and distal ends.

Table 2. Kinetic inward/outward frictions and peak resistance force at different speeds and angle of tilt

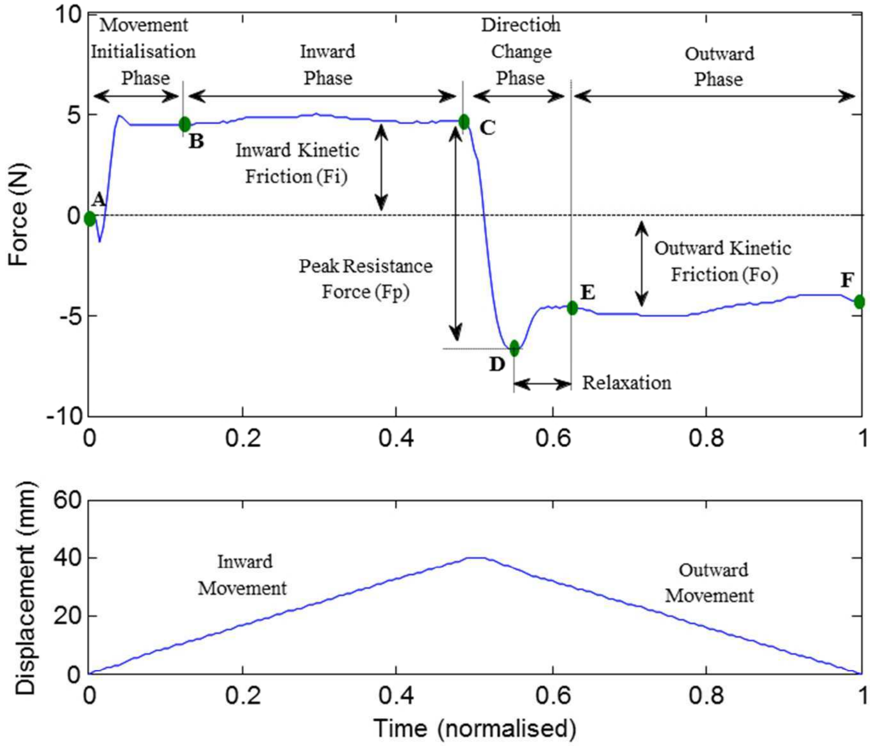
Trocar		2 mm/s		5 mm/s		20 mm/s	
		90 deg	0 deg	90 deg	0 deg	90 deg	0 deg
SI SwingTop	F_i	2.6503±0.0073	2.5008±0.0058	3.2113±0.0166	3.1367±0.0097	4.2188±0.1379	3.6037±0.0154
	F_o	-2.2405±0.0014	-2.4533±0.0061	-3.3918±0.0032	-3.5248±0.0085	-4.9154±0.0837	-5.3121±0.0573
	F_p	5.4879±0.0137	5.5772±0.0203	7.2859±0.0451	7.4344±0.0159	10.8809±0.3341	10.6170±1.2100
Genicon	F_i	2.7746±0.2009	2.2556±0.0056	3.4898±0.0050	2.8783±0.0163	3.1125±0.4909	2.4622±0.5083
	F_o	-1.8675±0.0039	-2.5367±0.0044	-2.2235±0.0033	-2.8618±0.0091	-2.4784±0.2126	-3.0832±0.0675
	F_p	4.7186±0.2184	4.8807±0.0156	5.7477±0.0056	5.7525±0.0274	6.2038±0.5265	6.2016±0.5330
Endopath Xcel	F_i	0.9104±0.0173	0.3532±0.0089	0.9252±0.0069	0.4778±0.0039	1.0023±0.0077	0.6350±0.0121
	F_o	-2.1441±0.0242	-2.7049±0.0044	-2.2139±0.0119	-3.2761±0.0201	-2.9157±0.0133	-3.4784±0.0134
	F_p	3.2710±0.0501	3.2363±0.0134	3.8320±0.0169	3.8861±0.0161	4.6564±0.0105	4.8827±0.0483
Laport	F_i	0.5606±0.0159	0.0739±0.0034	0.5867±0.0014	0.0584±0.0068	0.6791±0.0100	0.1306±0.0012
	F_o	-0.7419±0.0130	-1.0845±0.0057	-0.7775±0.0081	-1.1366±0.0012	-0.8423±0.0196	-1.1600±0.0011
	F_p	1.4517±0.0208	1.2998±0.0121	1.4988±0.0155	1.3234±0.0057	1.6525±0.0548	1.3757±0.0081
Applied	F_i	1.1637±0.0045	1.1629±0.0050	1.2086±0.0036	1.2065±0.0043	1.3230±0.0147	1.3296±0.0144
	F_o	-0.5344±0.0027	-0.5356±0.0033	-0.5261±0.0034	-0.5271±0.0034	-0.5790±0.0129	-0.5848±0.0146
	F_p	2.0254±0.095	2.0253±0.0122	2.1022±0.0057	2.1008±0.0065	2.2698±0.0190	2.2746±0.0234



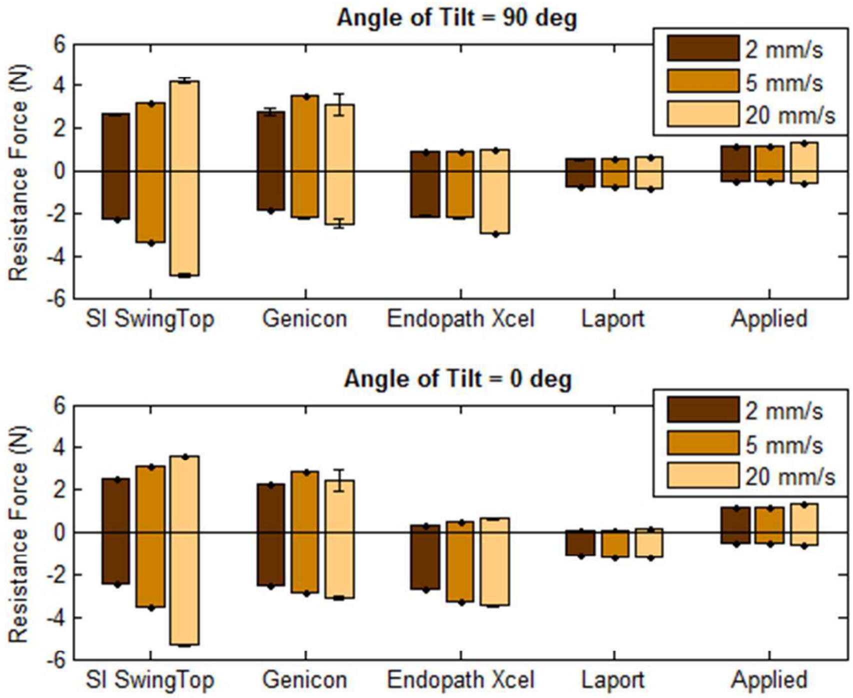
Commercially available trocars used in the experiment
156x54mm (300 x 300 DPI)



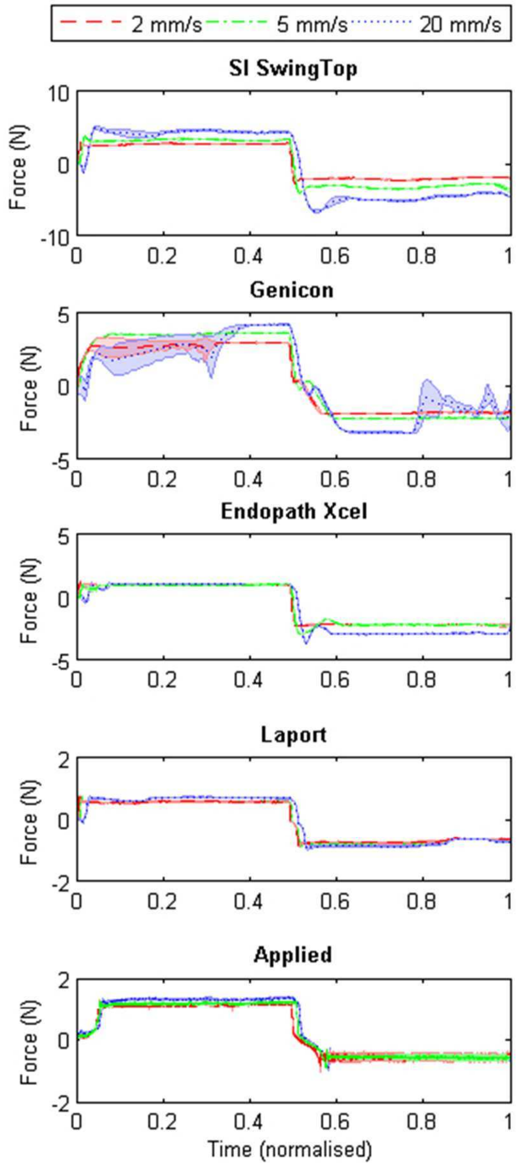
Experimental friction testing apparatus designed and built for the friction measurement. The entire apparatus was mounted on an adjustable frame that could be clamped to a workbench at various angle of tilt.
122x90mm (300 x 300 DPI)



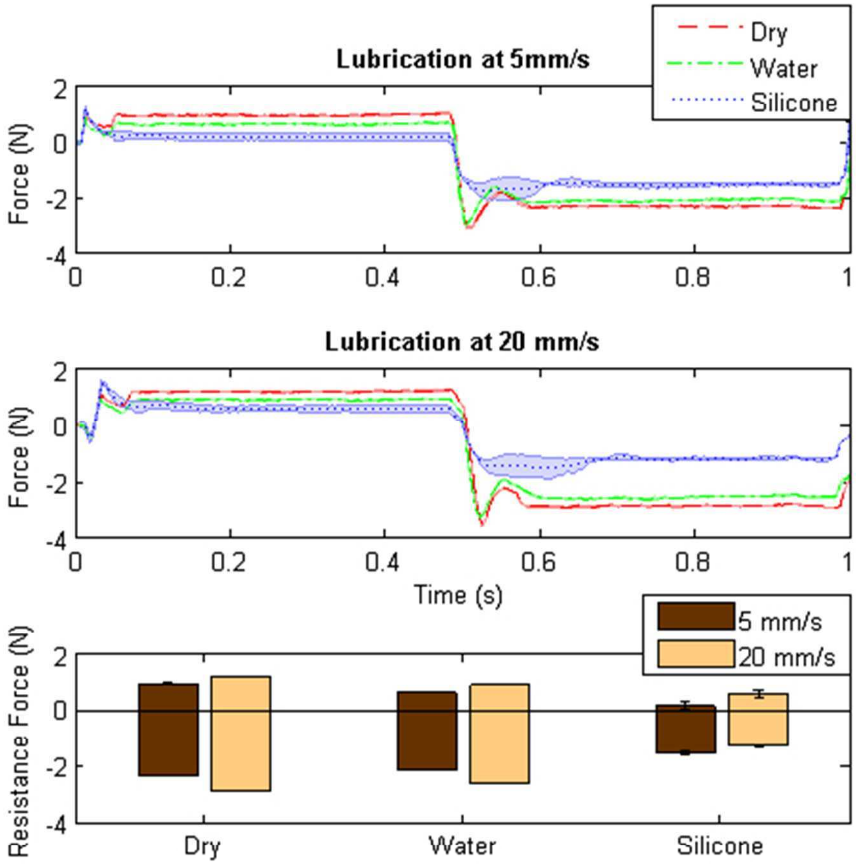
Example of typical force-time and displacement-time curves for a cyclic movement of the laparoscopic instrument in the trocar. Here, Fi and Fo are resistance forces during insertion and retraction of instrument, and Fp is the peak resistance force.
139x113mm (150 x 150 DPI)



Fi (positive wide bars) and Fo (negative wide bars) for a linear instrument motion at different sliding speeds. The top and bottom graphs are for instrument/trocar pair's angle of tilt of 90 and 0 deg, respectively.
148x113mm (96 x 96 DPI)



Friction dynamics of the trialled trocars at different speed with the angle of tilt of 90 deg. The force scale of each plot is adjusted for clarity. Each trace shows the mean response of 6 repeats (solid line) together with the standard deviation (shaded area).
92x197mm (96 x 96 DPI)



Effect of lubrication on resistance force at different speeds (shown for the Endopath Xcel). Each trace shows the mean response of 6 repeats (solid line) together with the standard deviation (shaded area). The lower chart shows the effect of lubrication on Fi (positive wide bars) and Fo (negative wide bars) for the Endopath Xcel motion at different sliding speeds.
139x132mm (96 x 96 DPI)