Output force and ratio of laparoscopic graspers: an evaluation of operating room ergonomics

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BACKGROUND: "Laparoscopist's thumb," or thenar paresthesia, can result from prolonged or excessive grip force during laparoscopy, as can more general syndromes, such as carpal tunnel syndrome. This is particularly relevant in gynecology, where laparoscopic procedures are standard. Although this method of injury is well known, there is a paucity of data to guide surgeons in selecting more efficient, ergonomic instruments.

OBJECTIVE: This study compared the ratio of applied tissue force and required surgeon input in a sample of common ratcheting laparoscopic graspers in a small-handed surgeon, to provide potential metrics applicable to surgical ergonomics and surgeon instrument choice.

STUDY DESIGN: Laparoscopic graspers with varied ratcheting mechanisms and tip shapes were evaluated. Brands included Snowden-Pencer, Covidien, Aesculap, and Ethicon. A Kocher was used as an open instrument comparison. Flexiforce A401 thin-film force sensors were used to measure applied forces. Data were collected and calibrated using an Arduino Uno microcontroller board with Arduino and MATLAB software. Single-handed, complete closure of each device's ratcheting mechanism was performed 3 times. The maximum required input force in Newtons was recorded and averaged. The average output force was measured with a bare sensor and the same sensor between 2 different thicknesses of LifeLike BioTissue.

RESULTS: The most ergonomic ratcheting grasper for a small-handed surgeon was identified by the output ratio: the highest output force relative to the required surgeon input (the most force for the least amount of effort). The Kocher required an average input force of 33.66 N, with its highest output ratio of 3.46 (112 N output). The Covidien Endo Grasp was the most ergonomic, with an output ratio of 0.96 on the bare force sensor (31.4 N output). The Snowden-Pencer Wavy grasper was the least ergonomic, with an output ratio of 0.06 when applied to the bare force sensor (5.9 N output). All graspers except for the Endo Grasp had improving output ratios as tissue thickness and subsequent grasper contact area increased. Input force above that provided by the ratcheting mechanisms did not increase output force in a clinically relevant amount for any of the instruments evaluated.

CONCLUSION: Laparoscopic graspers vary widely in their ability to provide reliable tissue force without requiring excessive input by the surgeon, and a point of diminishing returns often exists with increased surgeon input over designed ratcheting mechanisms. Output force and output ratio are potential quantitative measures of the efficiency of laparoscopic instruments. Providing users with this type of data could assist in optimizing instrument ergonomics.

Key words: carpal tunnel, grasping force, gynecology, laparoscopy, locking mechanism, surgeon's thumb

Introduction

Laparoscopic surgery has become the standard of care in gynecology. As with any demanding task, it has elicited a set of ergonomic concerns and risks of injury. Of note, 1 injury, "laparoscopist's thumb," or thenar paresthesia, has been documented since the early days of using laparoscopic instruments.[1–4] Moreover, more generalized injuries, such as carpal tunnel syndrome, have resulted from the repetitive motions of laparoscopy and continue to be reported by experienced surgeons.[5] Many gynecologists experience pain associated with laparoscopic surgery. In recent surveys, 60.0% to 75.6% of gynecologists experience some type of pain, with 60.9% experiencing specifically hand or wrist pain and 14.2% reporting frequent pain in these areas,[6,7] leading to recovery periods of up to 12 weeks for severe neurologic injuries.[1,8]

Laparoscopic surgery presents a greater risk of hand or wrist injury to surgeons than open surgery because of various factors, such as output efficiency, instrument mechanics, and effects of hand size, while manipulating laparoscopic instruments. Open instruments translate force at a higher ratio than laparoscopic instruments, which can lose 58% to 92% of their applied force.[9,10] Greater input forces are required to perform tasks during laparoscopic surgeries than open surgeries,[9–11] exposing the surgeon to a higher risk of injury even with similar operating times. The fulcrum effect of laparoscopic surgery and its limitations in movement can lead to surgeons operating in unusual and harmful positions.[12,13] These findings can be amplified in smaller-handed surgeons.[14] With complex cases and larger uteri being tackled laparoscopically, the ergonomic inefficiencies of laparoscopy are increasingly apparent.

Although ideal neutral positions have been described,[15] they are often difficult to achieve when actively manipulating the handle of a laparoscopic grasper. Much similar to open instruments, locking mechanisms play a key role in allowing the surgeon to manipulate their grasp on an instrument while maintaining its grasp on tissue. Grasper efficiency has previously been described as the ratio of input force to output force,[11] but the ratio of required force to engage locking mechanisms has yet to be studied.

Objective

Our objective was to evaluate a sample of laparoscopic instruments to determine which instrument's locking mechanism

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AJOG at a Glance

Why was this study conducted?

Laparoscopy has become the standard in gynecology, but prolonged or excessive grip force used during laparoscopy can cause injuries to surgeons. Understanding the output force and ratio of surgeon input force to output force of common instruments could help surgeons select the most appropriate instrument.

Key findings

This study tested Snowden-Pencer, Covidien, Aesculap, and Ethicon laparoscopic graspers with ratcheting mechanisms and found the Covidien Endo Grasp performed the best, with an input-to-output force ratio of 0.96. All graspers except for the Endo Grasp had improving output ratios as tissue thickness and subsequent grasper contact area increased.

What does this add to what is known?

This initial study explores the use of various metrics in describing the ergonomic aspects of laparoscopic instruments.

had the best ratio of input force to output force for a small-handed surgeon and what the expected grasping forces could be at different tissue thicknesses. The goal was to provide metrics that may help surgeons select appropriate instruments to minimize strain and apply reliable tissue force.

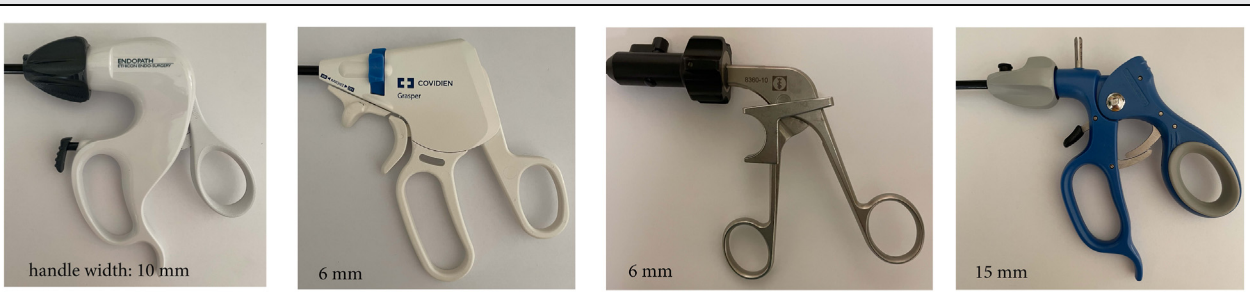
Materials and Methods

Study approval was obtained from The University of Kansas Institutional Review Board. We evaluated atraumatic laparoscopic graspers with varied ratcheting mechanisms and tip shapes: Snowden-Pencer Wavy (SP90-6366), Snowden-Pencer DeBakey (Sp90-6343), Covidien Endo Grasp (173030), Aesculap Wavy (M45711), and Ethicon Endopath (ETH5DSGH). These instruments were selected for their frequent use in our operating rooms. Traumatic graspers were not included as their functionality depends on their traumatic grip, the effects of which could not be reliably accounted for in force calculations. Handle and tip shapes are shown in Figures 1 and 2. An Aesculap Kocher was evaluated as an open instrument comparison because of its routine use on tissues requiring high grasping forces.

Tekscan A401 FlexiForce thin-film sensors were used to measure thumb force and force applied between each instrument's grasp, emulating previous evaluations of laparoscopic grasper output force.[16] A sensor was trimmed to fit the thumb region of the instrument handles. A second sensor was placed between the grasping surfaces of the instrument. The sensors were used with Tekscan FlexiForce Quickstart Boards to determine the applied forces (Tekscan, Norwood, MA). Data were collected and calibrated using an Arduino Uno microcontroller board alongside Arduino Integrated Development Environment software. Figure 3, A to E, depicts the testing setup. MATLAB software (Arduino, Partita, MA, and MathWorks, Natick, MA) was used to collect and compile data at a rate of 100 Hz. The raw voltage data were converted using MATLAB to Newtons. Before data collection, the code was calibrated using weights (0—1 kg). Output force for both the thumb (input) and tissue grasping surface (output) sensors was calculated using MATLAB.

A physician with a 6.5-glove—sized hand and experience using the ratcheting mechanisms completed 2 tasks for all the tested instruments. They were seated with a 90-degree elbow bend, adducted arm, and neutral forearm and wrist based on previously described safe positioning (Figure 3, F).[15] They performed a single-handed, complete closure of each device's ratcheting mechanism using a pinch grasp (Video 1 and Figure 4). All fingers of the hand were used to close the instruments to standardize the closure mechanics. The entire surface area of the grasper tip was

FIGURE 1
Handle shapes of tested instruments



From left to right, Ethicon Endopath, Covidien Endo Grasp, Aesculap Wavy, Snowden-Pencer Wavy, and Snowden-Pencer DeBakey (duplicate handle). The width of the thumb contact surface of each instrument is noted in millimeters in the lower left corner of each photo.

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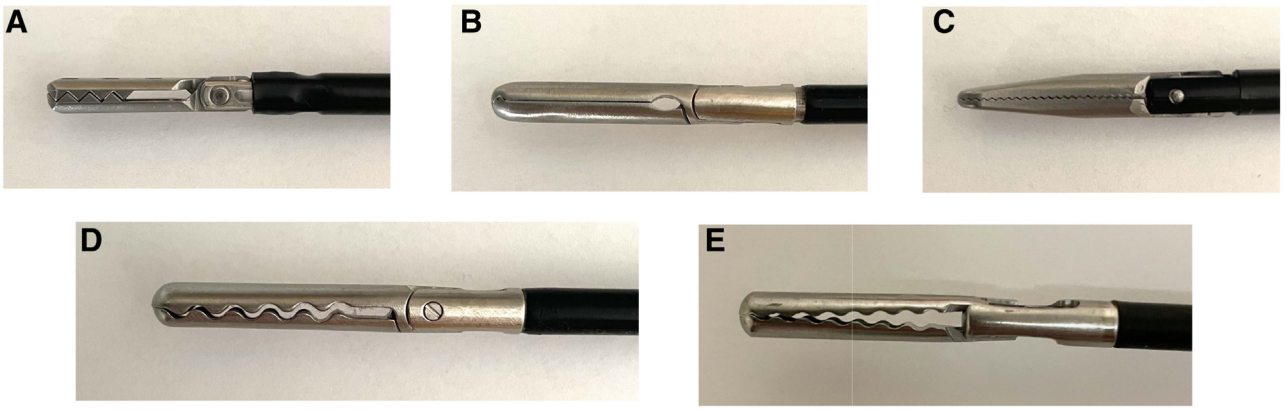
FIGURE 2
Tip shapes of tested instruments



A, Ethicon Endopath. **B,** Snowden-Pencer DeBakey. **C,** Covidien Endo Grasp. **D,** Snowden-Pencer Wavy. **E,** Aesculap Wavy.

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used. Complete closure of each instrument was performed and measured 3 times. This was repeated with the tissue sensor adjacent to a 2- mm layer of LifeLike BioTissue (number 0340) and between 2 layers of BioTissue for a total thickness of 4 mm (Figure 3, B to D). The tissue type and thickness were selected to mimic tissues commonly grasped during gynecologic laparoscopy, such as cyst walls or round ligaments. Subsequently, the participant performed the same ratcheted closure followed by 3 maximal grips on the handle (Video 1). These tasks were selected to focus on the ergonomic efficiency of the locking mechanisms and to identify whether ratcheted closure provides force comparable with the surgeon's firmest grasp.

During data collection, the participant was blinded to the real-time data to eliminate operator bias and its influence on results. Figure 5 shows representative graphs of the data collection. Data were collected until the ratcheted mechanism was completely closed. Some difficult closures required repeated effort by the user, as shown by the multiple input force peaks in Figure 5, B.

The mean input and output forces in Newtons were calculated for each task and reported for each instrument and tissue thickness. The ratio of output force to input force was calculated using the averages of the forces measured over 3 trials. The most ergonomic grasper was defined as the highest ratio of output force compared with the required input force.

The force applied at the instrument tip was measured as the average of the ratcheted force after the ratcheting mechanism was fully engaged. To examine the highest possible increase in force that could be expected when actively gripping the handle compared with the independent force of the ratchet, the ratcheted output force was subtracted from the maximum output force. Figures 5 and 6 and Table 1 describe these metrics. All statistical analyses were performed using Microsoft Excel.

Results

The Covidien Endo Grasp had the highest output ratio of 0.96. The Snowden-Pencer Wavy had the lowest output ratio of 0.06. The open instrument (Aesculap Kocher) had an output ratio as high as 3.46. Output forces across the instruments and tissue thicknesses ranged from 2.15 to 32.67 N. The Endo Grasp had the highest output force at each thickness. The input forces of all instruments can be seen in Table 2.

All instruments but the Endo Grasp had improved output ratios from bare sensor to 2 mm (Table 2). From 2- to 4-mm tissue thickness, most instruments had an improved or stable output ratio apart from the Endo Grasp. Of note, the Endopath had a consistent output ratio (0.38−0.40) but a maximum output force of only 7 N (Table 2).

When excess force was applied to the instrument handles after complete ratcheting, the difference in applied force was the largest for the Aesculap Wavy (Table 3). Maximum grip on this instrument applied excess force at an average of 3.22 N at 2-mm tissue thickness (standard deviation [SD], 1.11) and 5.11 N at the 4-mm tissue thickness (SD, 2.74). Moreover, the Endopath was able to apply some increased force at 2 and 4 mm (Table 3).

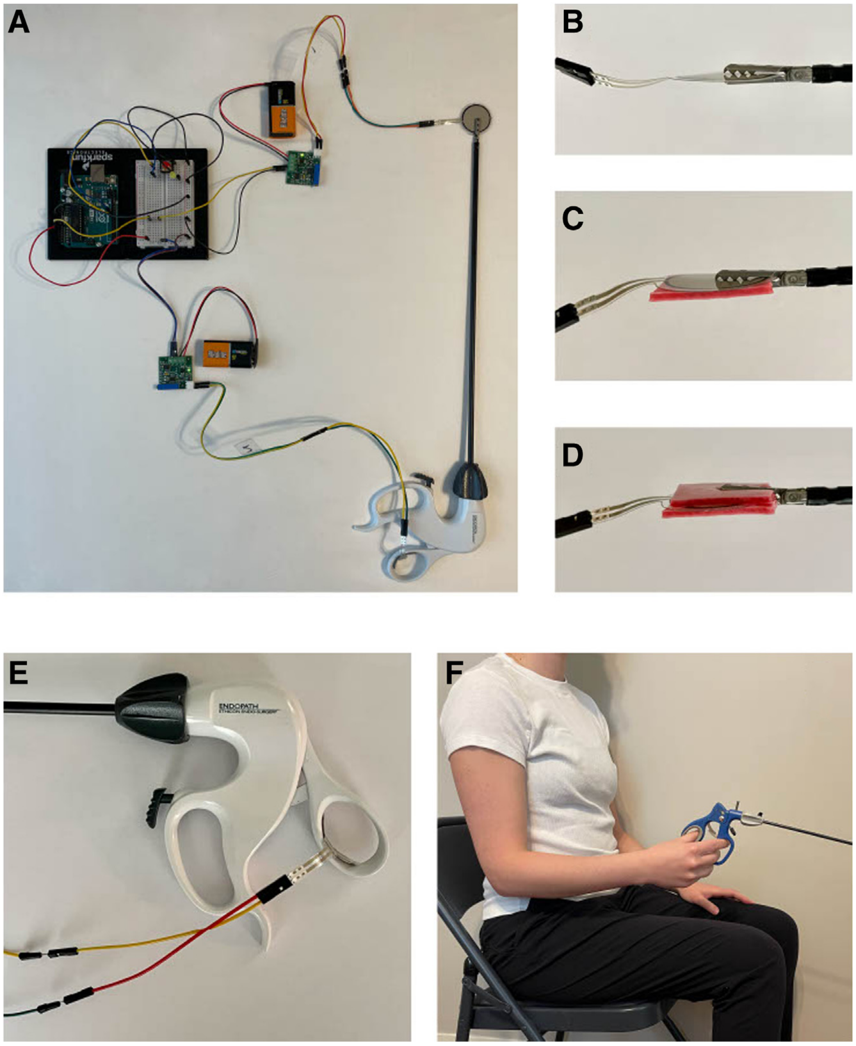
Comment

Principal findings

This research aimed to evaluate which grasper's locking mechanism had the best ratio of input force to output force as a metric of ergonomic functionality. The Covidien Endo Grasp was the ratcheting instrument with the highest output ratio for a small-handed surgeon. In addition, the Endo Grasp had the highest output force in the study setting. None of the instruments were able to achieve the force output seen in the Kocher open surgery instrument.

The noted improvement in output ratios, particularly from the bare sensor to 2-mm tissue, was likely due, in part, to

FIGURE 3
Testing setup



A, Data collection devices as they relate to the tested instruments. **B,** Location of the bare output force sensor. **C,** Output force sensor with single-tissue simulation. **D,** Output force sensor with double-tissue simulation. **E,** Location of the input force sensor. **F,** Position of the participant during testing.

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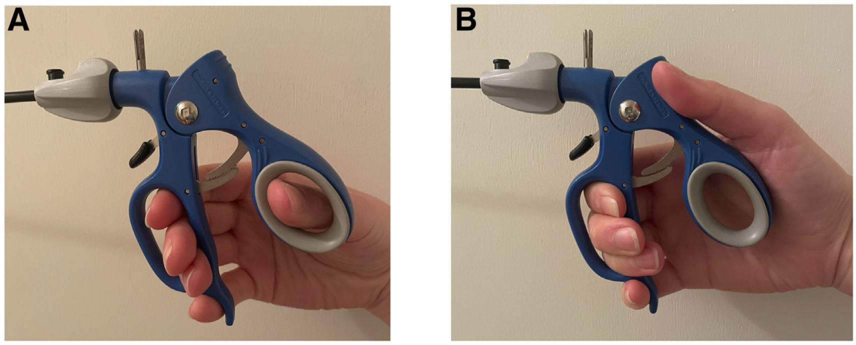
differences in tip approximation. With instruments, such as the Snowden-Pencer Wavy, the separation of interacting surfaces prevents the application of force when tissues are thin, and tissue contact would increase with increasing thickness. Conversely, the Endo Grasp's close approximation at rest allowed for the best output ratio when used on the sensor alone, with a lower ratio at increasing thicknesses.

Importantly, in the instruments we tested, we found that applying excess input force did not increase the output force a clinically relevant amount if the ratcheting mechanism was already completely engaged. Although the Aesculap Wavy and Endopath were able to apply 3 to 5 N excess force (Table 3), we believe the required maximal grip is not a sustainable expectation for the limited extra force, especially when other instruments are available, which provide similar or greater output without continued application of force.

Results in the context of what is known

Previous studies have shown that laparoscopic instruments are inefficient in force translation. Westebring-van der Putten et al[16] showed that approximately 133 N force was needed on the handle to achieve a force of 10 N at the tip of 1 laparoscopic grasper. Another study by Sjoerdsma et al[11] found the mechanical efficiency of laparoscopic instruments ranged from 8% to 42%, noting that output forces varied with different opening angles of the instruments. This concurs with our increasing output ratios with increasing tissue thickness, suggesting that this finding may be due to more factors than tip approximation as previously noted.

FIGURE 4
Depiction of pinch grasp vs palm grasp



A, Pinch grasp. **B,** Palm grasp.

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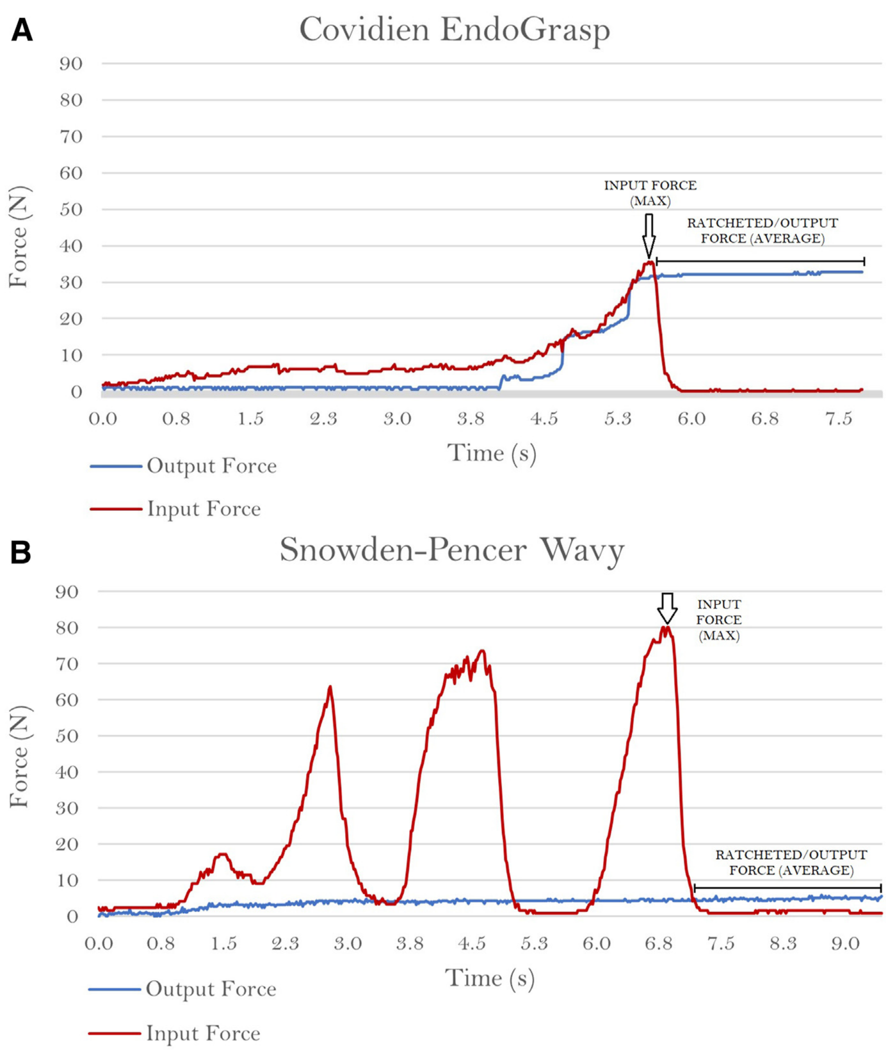
FIGURE 5
Representative graphs showing input and output forces during ratcheting



A, Covidien Endo Grasp ratcheted down onto a bare sensor. **B,** Aesculap Wavy ratcheted down onto a bare sensor requiring multiple attempts before successful closure.

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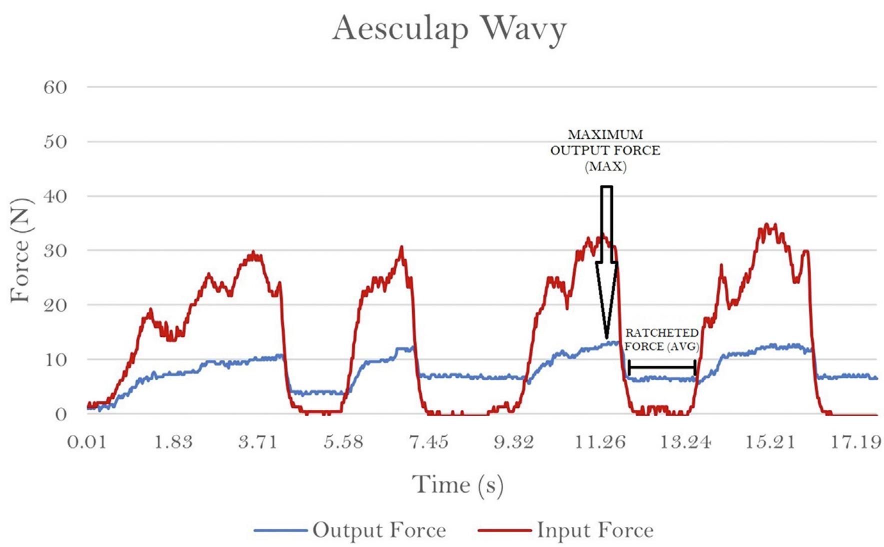
FIGURE 6
Representative graph showing excess force applied to ratcheted instrument



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We chose to study the applied forces using a pinch grasp, as most instruments used at our facility do not have spring-loaded openings and require a dexterous grip for manipulation and toggling of ratchet mechanisms. Previous studies of carpal tunnel pressure, thought to contribute to injury of the median nerve and subsequent carpal tunnel syndrome, identified significant changes in tunnel pressure with pinch forces as low as 5 to 15 N.[17,18] This suggests that many laparoscopic graspers in circulation may require unsafe amounts of force to provide the desired output, as only one of our studied instruments required <20 N for complete ratcheting. Palm grasp (Figure 4) has been shown to be more ergonomic at higher required forces[19] and may be safer for use in low output ratio instruments.

Several factors may contribute to differences in input and output forces for the instruments studied. Both disposable instruments were noted to have better output ratios and lower input forces than their reusable counterparts. These instruments weigh less than metal instruments, likely requiring less force to manipulate. Moreover, single-use instruments are not susceptible to wear, which may decrease the translation of force.

TABLE 1
Definitions of proposed metrics used to evaluate the ergonomics of ratcheted instruments

Metric	Definition
Input force	The maximum force applied to an instrument to fully engage the ratchet
Output force or ratcheted force	The force applied to the tissue after the ratchet is fully engaged, averaged during a short period of application
Output ratio	The ratio of output force to input force. A measure of efficiency, with a higher output ratio indicating a lower required surgeon input and therefore less surgeon strain for a desired effect at the tissue
Maximum grip	The user applies as much force as possible at the handle to produce as much output force as possible
Maximum output force	The highest force applied to the tissue when the user applies maximum grip
Increase in output force with maximum grip	The potential increase in force applied to the tissue when adding a maximal grip to an already ratcheted instrument. Measured as the difference between the maximum output force and the output force. Low values indicate little to no benefit to additional grip force after the ratchet is in place

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Clinical implications

Instrument fit might be the first area surgeons consider in selecting ergonomic tools. However, Franasiak et al[7] found no association between physical discomfort associated with surgery and the perceived fit of the laparoscopic instrument. Of note, 77.8% of surgeons found the instrument fit to be "just

TABLE 2
AIF and AOF (in Newtons) and output ratios of instruments while ratcheting

	Bare sensor			2-mm tissue			4-mm tissue		
Instrument	AIF (SD)	AOF (SD)	Output ratio	AIF (SD)	AOF (SD)	Output ratio	AIF (SD)	AOF (SD)	Output ratio
Aesculap Kocher (open surgery instrument)	31.85 (2.16)	60.86 (4.89)	1.91	32.67 (4.67)	112.99 (3.07)	3.46	36.48 (2.06)	121.26 (6.41)	3.32
Covidien Endo Grasp (173030)	32.67 (6.98)	31.37 (1.14)	0.96	34.84 (1.89)	30.26 (2.59)	0.87	46.28 (3.09)	24.02 (2.05)	0.52
Snowden-Pencer Wavy (SP90-6366)	82.48 (2.16)	5.30 (0.41)	0.06	57.66 (6.84)	14.23 (1.04)	0.25	83.57 (2.49)	21.47 (0.49)	0.26
Aesculap Wavy (M45711)	28.04 (0.94)	2.15 (0.38)	0.08	29.94 (1.25)	6.85 (1.88)	0.23	33.21 (0.94)	9.27 (2.17)	0.28
Snowden-Pencer DeBakey (Sp90-6343)	61.07 (4.05)	4.99 (0.72)	0.08	69.96 (8.50)	11.39 (3.12)	0.16	70.23 (3.55)	15.78 (0.39)	0.23
Ethicon Endopath (ETH5DSGH)	10.51 (0.87)	4.04 (0.46)	0.38	15.77 (2.13)	6.25 (0.21)	0.40	18.89 (0.98)	7.55 (0.63)	0.40

AIF, average input force; *AOF*, average output force; *SD*, standard deviation.

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right" for graspers. As the perceived fit of the instrument might not adequately reflect physical strain, quantitative metrics, such as output ratio, may allow surgeons to choose the most ergonomic instrument for prolonged tasks, particularly for small-handed surgeons who are more susceptible to strain.[14] Based on the trend we identified of increasing output ratio with increasing tissue thickness, matching the instrument with the tissue is also important. Instruments with higher output at the targeted tissue thickness help optimize the surgeon's input force.

Ergonomic inefficiencies have been shown regardless of grasping position.[19] A recent study by Turcotte and Kociolek[20] showed that movement and compression of the median nerve increased when combining wrist deviation with a grip similar to that applied to most laparoscopic graspers. Our data show that excess application of force does not reliably increase the force at the tissue level in the instruments we studied. Although this cannot be said for instruments not included in this study, this trend suggests that surgeons can apply these ratchets and release their hand, allowing for the neutralization of arm and wrist positioning to recommended safe angles.[15] This would theoretically decrease pressure on the thenar nerves and carpal tunnel by avoiding unnecessary grip force in unsafe positions. In instruments with known low output ratios, surgeons should have a lower threshold to convert to a stronger palmar grasp or a higher output instrument to prevent the need for pinch forces that may lead to injury.

Although the goal of this study was to characterize ergonomics in the context of situations where high tissue force is desired, one should also consider scenarios where more delicate control is required. Low-efficiency graspers have been shown to make safe grasping more difficult, causing the tissue to slip and increasing necessary manipulation to complete tasks.[16] Although low efficiency may be detrimental, a space exists for instruments with high efficiency but low output force, such as the Endopath. When grasping the bowel or other fragile tissues, a low-output instrument may prevent excessive tissue force, with higher efficiency allowing for more precision.

Research implications

The output forces in this study were measured against a negligible load with atraumatic graspers. Although operating, the weight and tension of the tissue will factor into the required input force to overcome both the locking mechanisms and the tissue factors. Our data may even overestimate real-time output ratios experienced in surgery. Additional studies of grip force while performing complex tasks may elicit more detailed information about an instrument's output ratio in surgical settings.

We selected force as a measure of ergonomic efficiency as applied forces are what allow for tissue manipulation. One can still infer potential risks of direct nerve injury secondary to the pressure applied at the thumb and thenar eminence. In rat models, pressures as low as 6.7 kPa applied directly to nerves in short intervals can lead to demyelination.[21] Moreover, lower pressures applied chronically have shown long-term deleterious effects on the peripheral nerves.[22] Here, the instruments studied frequently require approximately 30 N for closure. This may lead to pressures as high as 100 kPa, even when overestimating the contact area to be 3 cm^2 based on the handle width of approximately 1.5 cm,

TABLE 3
Difference in applied force between ratchet alone and maximum surgeon grip

Instrument	Thickness measured	Average ratcheted force, N (SD)	Average maximum force, N (SD)	Average increase in applied force with maximum grip, N (SD)
Covidien Endo Grasp (173030)	Bare sensor	31.37 (1.14)	30.54 (1.42)	−0.42 (1.42)
	2-mm tissue	30.26 (2.59)	29.4 (0)	−0.86 (2.59)
	4-mm tissue	24.02 (2.05)	24.02 (2.05)	−0.73 (1.82)
Snowden-Pencer Wavy (SP90-6366)	Bare sensor	5.30 (1.8)	7.10 (0.25)	1.80 (0.56)
	2-mm tissue	14.23 (1.04)	15.06 (0.65)	0.83 (0.82)
	4-mm tissue	21.47 (0.49)	21.02 (1.37)	−0.72 (1.52)
Aesculap Wavy (M45711)	Bare sensor	2.15 (0.38)	3.50 (0.45)	1.34 (0.25)
	2-mm tissue	6.84 (1.88)	10.10 (1.76)	3.22 (1.11)
	4-mm tissue	9.27 (2.17)	14.37 (1.2)	5.16 (2.74)
Snowden-Pencer DeBakey (Sp90-6343)	Bare sensor	4.99 (0.72)	4.97 (0.25)	−0.02 (0.79)
	2-mm tissue	11.39 (3.12)	12.07 (1.07)	0.69 (2.21)
	4-mm tissue	15.78 (0.39)	17.33 (1.37)	1.55 (0.98)
Ethicon Endopath (ETH5DSGH)	Bare sensor	4.04 (0.46)	4.83 (0.25)	0.79 (0.48)
	2-mm tissue	6.25 (0.21)	9.23 (0.25)	2.98 (0.44)
	4-mm tissue	7.55 (0.63)	11.22 (0.24)	3.67 (0.74)

N, Newtons; *SD*, standard deviation.

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the largest in our grouping of instruments. Although this pressure is not directly applied to the nerve, one can see how repetitive or prolonged use of these instruments can lead to direct nerve injury. Future studies determining the location and amplitude of pressure points at the thumb would provide additional data for the ergonomic design of laparoscopic graspers.

A systematic ergonomic assessment of laparoscopic and robotic tools should be considered to improve understanding of their mechanical efficiencies. Assessing individual components, such as which fingers or muscle groups are engaged along with hand and instrument grip congruence, can help assess how each tool behaves in individuals with different hand sizes and hand strengths. Creating these standards will help match individuals to tools, maximizing ergonomic efficiency in the operating room.

Strengths and limitations

The strength of this study is the range of laparoscopic instruments with ratcheting mechanisms that we were able to investigate and the ability to apply the concept to other instruments used in laparoscopy. Furthermore, we were able to test each instrument with various tissue thicknesses to emulate the variation surgeons interact with during surgery.

The force sensor's inability to completely bend to the shape of all grasper tips may underrepresent the full output force in thin tissues. The hardness of tissue has been shown to be inversely related to the pressure contact area, thereby decreasing the applied force.[23] Our samples had decreasing hardness as 1 tissue thickness and then 2 tissue thicknesses were placed on the sensor, which would increase the contact area and subsequent applied force. The graspers with the most notable increase in output ratio from bare to 2 mm were the wavy tip graspers, which have a notable separation at the jointed end (Figure 2), suggesting the increase in output in our study was affected by multiple factors. Additional evaluations of graspers with more pliable sensors may be useful to fully characterize their behavior in thin tissues.

In this initial study, we aimed to evaluate the inherent mechanical properties of laparoscopic instruments. We expect that the required forces for instrument closure are independent of the user, as they are a product of the instrument's design. Although the mechanical efficiency of an instrument should not change between users, the distribution of applied force and the muscle activation necessary may differ based on hand size. This limits the generalizability of the input force and output ratio data of these instruments to surgeons of similar hand sizes. Moreover, the various locations and types of locking mechanisms may alter the input force distribution, as the relative force input and orientation of the index finger changes. A specific example is the required index finger force used to close a sliding lock, which likely contributes to closing the instrument more than the index finger in an instrument with an automatic ratchet. Further studies incorporating more contact points and metrics are necessary to fully characterize the ergonomics of ratcheting laparoscopic graspers across the range of surgeon hand sizes.

Conclusions

Quantitative data regarding the expected performance and surgical ergonomics of graspers allow for more educated use. We argue that understanding the basic physics of simple instruments is crucial in performing safe laparoscopic surgery and improving surgeon longevity.

The output ratio can be used as a potential instrument characteristic when selecting ergonomic laparoscopic graspers. Not all graspers are meant to function identically, but providing ergonomic metrics, such as output ratio, will help surgeons optimize their toolkits to protect themselves. ■

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