Published in final edited form as:

Surg Endosc. 2017 August ; 31(8): 3258–3270. doi:10.1007/s00464-016-5356-1.

Tensile Strength and Failure Load of Sutures for Robotic Surgery

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Abstract

Background—Robotic surgical platforms have seen increased use amongst minimally invasive gastrointestinal surgeons¹. However, these systems still suffer from lack of haptic feedback, which results in exertion of excessive force, often leading to suture failures². This work catalogs tensile strength and failure load amongst commonly used sutures in an effort to prevent robotic surgical consoles from exceeding identified thresholds. Trials were thus conducted on common sutures varying in material type, gauge size, rate of pulling force, and method of applied force.

Methods—Polydioxane, Silk, Vicryl, and Prolene, gauges 5-0 to 1-0, were pulled till failure using a commercial mechanical testing system. 2-0 and 3-0 sutures were further tested for the effect of pullrate on failure load at rates of 50 mm/min, 200 mm/min, and 400 mm/min. 3-0 sutures were also pulled till failure using a da Vinci robotic surgical system in un-looped, looped, and at the needle body arrangements.

Results—Generally, Vicryl and PDS sutures had the highest mechanical strength (47 to 179 kN/cm²), while Silk had the lowest (40 to 106 kN/cm²). Larger diameter sutures withstand higher total force, but finer gauges consistently show higher force per unit area. The difference between material types becomes increasingly significant as the diameters decrease. Comparisons of identical suture materials and gauges show 27–50% improvement in the tensile strength over data obtained in 1985³. No significant differences were observed when sutures were pulled at different rates. Reduction of suture strength appeared to be strongly affected by the technique used to manipulate the suture.

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Disclosures.

Ahmad Abiri has nothing to disclose.

Dr. Omeed Paydar has nothing to disclose.

Anna Tao has nothing to disclose.

Megan LaRocca has nothing to disclose.

Kang Liu has nothing to disclose.

Dr. Bradley Genovese has nothing to disclose.

Dr. Robert Candler has nothing to disclose.

Dr. Warren Grundfest has nothing to disclose.

Dr. Erik Duston is on Scientific Advisory board of Titan Medical.

Conclusions—Availability of suture tensile strength and failure load data will help define software safety protocols for alerting a surgeon prior to suture failure during robotic surgery. Awareness of suture strength weakening with direct instrument manipulation may lead to development of better techniques to further reduce intraoperative suture breakage.

Keywords

robotic surgery; suture; surgical platform; force sensor; suture tensile strength; da Vinci

Introduction

Since their introduction in 1985 and first FDA approval in 2000, teleoperated robotic surgical systems have gradually gained popularity². The additional degrees of freedom and ability to scale down distractive motion have simplified many previously challenging minimally invasive operations^{3–7}. Today, Intuitive Surgical's da Vinci system is used to perform over 250,000 surgeries per year⁸. Despite obvious advantages, these systems still suffer from lack of a comprehensive haptic feedback solution. This limitation combined with the ability of the robot to generate strong forces at the tip of laparoscopic instruments have introduced a variety of issues such as tissue scaring and excessive suture breakage^{9–17}. Intraoperative suture failures can be costly as they result in surgical delays while post-operative failures could require revisions or create major complications for the patient. The growing popularity of robotic surgery as an option for gastrointestinal procedures, requiring vast amounts of intracorporeal suturing and knot tying, has resulted in a higher incidence of suture failures, occurring frequently enough to merit reference^{15,16,18,19}. There is therefore a need for the development of technologies that can provide warning prior to suture breakage or potentially even prevent breakage by introducing software barriers and virtual walls at fractions of the ultimate breaking force of the suture. In the past, attempts have been made to address intraoperative suture failure by visually estimating and then displaying the strain on the suture²⁰. However, these systems are limited by the quality of the available image because they rely on changes in the shape of specially marked sutures and visual processing to determine the strain. Other approaches such as grasper mounted shear sensors are also under investigation and can ultimately provide accurate real-time data regarding the state of the suture²¹. Despite previous research on suture tensile strength, the limited availability of more recent data on failure loads of commonly used sutures has prevented the development of warning systems that can accurately predict and prevent suture breakage before it occurs^{22–26}. More specifically, we are interested in the failure load of sutures under conditions that occur during manipulation of sutures with robotic instruments. Identification of tensile strength data for commonly used sutures is a major step to developing any kind of warning system. Additionally, availability of this data can help improve the selection of proper suture type and gauge for procedures.

In order to properly measure and characterize the suture's failure load, it is important to consider the various material properties as well as the strain conditions that occur during surgery. A suture's mechanical strength is both a fundamental material property and a function of gauge (i.e., filament diameter). In addition to the suture's mechanical characteristics, other factors can also affect the breaking force of a suture in a robotic

surgical operation. These factors include the way the suture is held, physical characteristics of the instrument holding the suture, and even the rate at which the tension is increased (the rate which the suture is pulled). The most commonly used sutures will be used to determine suture behavior under various conditions and the thresholds for suture breakage in robotic surgical operations.

Materials and Methods

In this study, we focused on evaluating Prolene, Polydioxane (PDS), Silk, and Vicryl because of their ubiquity in gastrointestinal surgeries with robotic surgical systems.

In order to evaluate the absolute tensile strength of the sutures, gauges 5-0 to 1-0 USP (United States Pharmacopeia) were studied. The cross-sectional area of the suture was calculated based on the suture gauge and used in tensile strength calculations. The sutures were pulled to failure/breakage using a high precision Tytron system (Tytron, MTS Systems Corporation, Eden Prairie, MN, USA). The mounting mechanism of the suture was designed to be similar to how a robotic instrument holds on to a suture in surgery (Fig. 1).

Sutures were held in place such that there is no slipping when sutures are pulled by the Tytron system. This was confirmed by monitoring the force-time plot and ensuring that the force constantly increased. In case of slippage, the trial was repeated. The metal pieces that hold on to the sutures were selected to be smooth and resemble a da Vinci Cadiere Forcep rather than a Micro Needle Driver (which has diamond-shaped teeth). This is to avoid reduction in breaking force caused by micro-fractures in the suture material. This initial data set is therefore meant to observe a best case scenario breaking force. The sutures were pulled at a constant rate of 50 mm/min until failure occurred (parameters from Fraunhofer et al., 1985)¹. For each suture and gauge combination, three trials were performed and the results were reported as a mean and standard deviation. The data was recorded in Newton (N) for Failure Loads kN/cm² for tensile strengths.

During a robotic procedure, the rate at which a suture is pulled can vary depending on how the surgeon operates and the type of procedure. In order to determine the effect of rate on the failure load for sutures, sutures of gauges 2-0 and 3-0 were pulled to breakage using the Tytron system. The same mounting mechanism was used as in the previous experiments. Two different gauges were selected to determine if the gauge had any significant effect on the failure load to extension rate relationship. For each sample (gauge/material combination), the suture was pulled at two different rates of 200 mm/min and 400 mm/min (this is in addition to the 50 mm/min rate tested in the previous experiment). As before, for each sample, the experiments were repeated in triplicate, and the failure load was reported in Newton (N). In order to determine whether a significant difference exists between failure loads for any one of the samples (suture/gauge combination) at different pull rates, Analysis of Variance (ANOVA) test was performed. A p-value of <0.05 was found to be statistically significant.

In a robotic surgical operation, a variety of instruments can be used to handle the sutures. These can include tools with grooves such as the Fenestrated Bipolar Forceps and the Micro-

Needle Driver or tools with smooth surfaces such as the Cadiere Forceps. The experiments performed with the Tytron system utilized a mounting mechanism that had a smooth surface. It is however possible for the suture material's structure to be weakened when held by tools that have non-smooth surfaces. In order to study how the failure load of the various samples were modified when in use by the da Vinci system, it was necessary to utilize a different failure load measuring system. This system relied on force measurements by a USSC Sutures Force Gauge (Fig. 2).

In order to ensure consistency between data recorded by the Tytron system versus the data reported by the USSC system, the initial experiments were repeated for the Vicryl suture type of gauges 5-0 to 1-0. The USSC system was modified to include mounting mechanisms similar to the original Tytron system. On both ends, the suture samples were held between two smooth metal surfaces, which were directly connected to the USSC system using 3D printed support components (Figure 3). The sutures were pulled until breakage and the data was reported in Newton (N). For each sample, experiments were performed in triplicate to produce a mean and standard deviation.

Sutures are often pulled differently during a surgical operation and using a variety of instruments. Results from previous studies show that instruments with grooves can damage a suture^{26,27}. Additionally, the way the suture is pulled can also affect the breaking force (Table 4). As the data from this study is meant to ultimately help in programming a suture-breakage warning system, it is necessary to identify the failure load under worst possible conditions. In order to determine the failure loads of the sutures when using actual robotic instruments, a da Vinci IS 1200 was used to pull sutures to breakage. Measurements were taken using the USSC system. The USSC system was mounted on a table. One end of the suture was held between two smooth metal washers (similar to previous setups) while the other end was pulled using a micro-needle driver mounted on the da Vinci. The operator of the da Vinci would use the robot arm to pull the suture to breakage. To determine variations between suture materials when placed under stress by a micro-needle driver, all four suture materials were studied, however the experiments were limited to only 3-0 gauge sutures. For each sample (material/gauge combination), three different methods were used to pull the suture: 1) Unlooped: pull suture directly parallel to the plane of the table, 2) Looped: turn grasper to wrap suture around the tip of the grasper once, then pull suture directly parallel to the table and (3) Needle: pull suture by holding on to the needle at the end of the suture. For each sample/method combination, experiments were performed in triplicate and a mean and standard deviation was reported. For statistical analysis and pair-wise comparison of sample groups, a student t test was used with $p < 0.05$ used to mark the threshold for significance (Appendix A).

Results

The failure load and tensile strength of Vicryl, PDS, Prolene and Silk when pulled using the Tytron system are reported in Table 1. The mean and standard deviation for each sample (Material/Gauge combination) was reported in both kilogram (kg) and Newtons in order to simplify comparison with existing references in literature¹. Generally, the Vicryl and PDS sutures had the highest mechanical strength (ranging from 47 to 179 kN/cm²) while Silk had

the lowest (ranging from 40 to 106 kN/cm²) ($p < 0.05$). As expected, sutures with larger diameters can withstand higher loads ($p < 0.05$) however tensile strength and gauge appear to be indirectly related. In other words, sutures with finer gauges actually appear to be able to withstand a higher force-per-unit-area (Table 1). This is an interesting observation considering that tensile strength is a material property and independent of the cross-sectional area of the suture. Direct comparison of this data to previous literature shows that there is a 27–50% improvement in the tensile strength over data obtained in 1985¹.

The failure loads (N) of PDS, Silk, Vicryl and Prolene 2-0 and 3-0 sutures were recorded when pulled at different rates using the Tytron system (Table 2). For all materials, small variations exist between the failure loads at different rates (Fig. 4). For most cases however, these variations were not statistically significant (Appendix A Table 3), at least not within the range of rates that occur under robotic surgical conditions ($p > 0.05$).

The failure loads of Vicryl sutures, gauges 5-0 to 0 USP were also reported (Table 3) using the USSC system to identify variability between data recorded by the Tytron system vs. data recorded using the USSC set-up. Treating the high precision Tytron system as the true failure load, the USSC system reported data with errors ranging from 2.45% – 7.67%.

The failure loads of PDS, Prolene, Vicryl, and Silk 3-0 gauge sutures were also reported when pulled using a micro-needle driver instrument on a da Vinci robotic surgical system (Table 4). In general, it was observed that pulling the suture thread with the micro-needle driver directly parallel to the plane of the table resulted in a lower failure load (Table 4), ranging between 45–62% of the original failure load recorded by the Tytron system (Table 1). Alternatively, if the suture was wrapped around the micro-needle driver's tip before pulling, then it consistently showed the ability to withstand higher loads. It is worth mentioning that due to high variability in failure loads of PDS and Prolene when pulled under this condition, statistical significance was not observed (Appendix A Table 4). However, the presence of a trend seems to indicate that a higher number of samples would help in more clearly observing this difference (Table 4). In both cases, the sutures failed closest to (or directly at) the point of contact with the micro-needle grasper. There was some variability between suture materials when pulled using the suture needle (holding on to the needle instead of the suture thread). Only Vicryl appeared to be able to withstand higher loads compared to the un-looped condition. The other three materials all showed that holding on to the needle instead of the suture thread results in the worst failure load values. In all of these cases, the suture failed at the swaged end (i.e. connection point) with the needle.

Discussion

The availability of tensile strength and failure load data is meant to ultimately guide the programming of a warning system for robotic surgical procedures. Such a warning system would detect forces at the grasper tip using mounted force sensors and trigger a warning to the surgeon as the forces approach the failure load of the suture being used, ultimately preventing suture breakage.

The data collected using the Tytron system assumed that the suture is held in place by two smooth surface metal plates. While this mounting mechanism is similar to the way sutures are held by robotic graspers, it does not precisely mirror the conditions that occur during surgery. Under normal surgical conditions, the suture is held on one end by a robotic grasper, which could either have smooth surfaces (as in our setup) or have teeth (e.g. Micro-Needle Driver). The differences in failure loads between Table 1 and Table 4 help in observing how these variations can change the failure load of the suture. Despite this fact, initial testing of sutures using a high precision force measurement system was necessary to establish a best-case scenario suture failure load as well as identify patterns when using different materials and gauges.

The initial data clearly showed that Vicryl & PDS demonstrate the highest tensile strength as opposed to Silk, which is consistently weaker than the other materials (Table 1). Perhaps the most interesting observation is the increasing tensile strength as diameter decreases. That is, sutures with smaller diameters are actually able to withstand higher force per unit area. While existing literature¹ also shows variations between the tensile strength of different gauges, no consistent pattern was previously observed. Normally, one would expect tensile strength data to be a function of material properties and remain relatively consistent for different gauges (of same materials) under the same test conditions. However, the current observation may indicate a potential difference in the manufacturing process of different sutures. Another possibility is that the way a suture is pressed between two metal plates (e.g. da Vinci grasper) creates micro fractures in the material¹⁵. In this case, one can imagine that the formation and rate of growth of these fractures may be reduced for sutures with smaller diameters. The initial data collected using the Tytron system (Table 1) is based on the assumption that the sutures are pulled at 50 mm/min, a relatively low rate that may not necessarily reflect the rate at which a surgeon pulls on a suture. Variations in the failure load are expected when the rate at which a suture is pulled is changed. This is due to the fact that crack propagation in the material can vary and therefore (may) cause the suture to break more quickly. In fact, one would expect that pulling the suture at a faster rate should increase the failure load because the amount of time available for the micro fractures to grow at any constant force is reduced relative to the amount of time needed to reach higher loads. The data we collected from pulling the sutures at significantly higher rates does not indicate a pattern that supports this hypothesis. That is, at least within the range of suture pulling rates that is commonly practiced in robotic surgery, it is not possible to conclude that higher rates correspond to higher failure loads. It is still worth mentioning that there is some variability in the failure loads, which must be taken into consideration when developing a suture warning system. Such a system must therefore be designed to provide feedback at a fraction of the suture's failure load in order to effectively reduce breakage during actual surgical operations.

In addition to the effect of pull-rate on failure loads, another important factor that affects the suture failure load is the characteristics of the robotic instrument holding on to the suture. The micro-needle driver is often used for manipulating sutures with the da Vinci surgical system. Existing literature has previously investigated structural changes in the suture when manipulated by robotic instruments that contain teeth on the surface of the tip. These studies have shown that such structural changes can lead to reductions in failure load. The data

collected by pulling the sutures with a micro-needle driver using a da Vinci surgical robot clearly supports this²⁷. The fact that the suture consistently breaks close to the edge of the micro-needle driver (< 5mm away from the edge) supports previous observations in the literature and this hypothesis²⁷.

In addition to providing data for programming a robotic surgery warning system, the failure load and tensile strength data can also guide the selection and usage of sutures during robotic surgical operations. More importantly, the reduction of failure load when utilizing da Vinci instruments indicates that the way sutures are manipulated during surgery can have a significant effect on intraoperative and postoperative suture failures. We observed that in most cases, sutures were able to withstand higher loads when they were wrapped around the micro-needle grasper before being pulled. This fact, and the observation that sutures always broke at the point of contact of the suture thread and the grasper, further supports our previous assertion that the teeth on the tip of the micro-needle driver may be the primary reason for the reduction in suture strength. Of course, a more complete comparison of suture failure loads placed under tension with various robotic forceps is necessary to validate this hypothesis. Additionally, for three of the four materials tested, pulling the suture by holding on to the needle resulted in the lowest failure load values (Table 4). Considering the variations between material properties of the sutures and the way the sutures are connected to the needle, this variability is expected. Regardless, it is clear that wrapping the suture around the micro-needle driver before pulling, proved to be the most effective method and resulted in the smallest reduction of suture strength from previous Tytron testing. This approach reduces the forces in the direction perpendicular to the grooves in the grasper tip, therefore preventing the suture from easily tearing. While this technique may not be possible in traditional laparoscopic surgery, the additional degrees of freedom in robotic surgical systems make this approach feasible.

Overall, the availability of tensile strength and failure load data for commonly used sutures not only guides the programming of suture-breakage warning systems, but also provides awareness of the behavior of sutures when being held by robotic tools. The observation that failure load is strongly dependent on the technique used to pull the suture, can have a major impact on how surgeons manipulate sutures during robotic surgery. Thus, the data shown may help reduce intraoperative and post-operative failures by guiding the selection of sutures and restricting manipulations known to cause suture weakening during gastrointestinal robotic procedures.

Acknowledgments

This research was partially supported by the National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health under award number R01EB019473-01. We thank our colleagues who provided insight and expertise that greatly assisted the research.

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Appendix A

Appendix Table 2

Statistical Analysis of Table 1 Failure Load Data using T-Test

Group	Vicryl 0	Vicryl 20	Vicryl 30	Vicryl 40	Vicryl 50	Silk 0	Silk 20	Silk 30	Silk 40	Silk 50	PDS 0	PDS 20	PDS 30	PDS 40	PDS 50	Pro 0	Pro 20	Pro 30	Pro 40	Pro 50
Vicryl 0	1.0000	0.0268	0.0049	0.0004	0.0005	0.0035	0.0065	0.0013	0.0023	0.0020	0.6152	0.0013	0.0030	0.0005	0.0011	0.0189	0.0015	0.0039	0.0025	0.0020
Vicryl 20	0.0268	1.0000	0.0005	0.0037	0.0009	0.0419	0.0003	0.0006	0.0000	0.0000	0.0388	0.0158	0.0054	0.0023	0.0003	0.0114	0.0159	0.0000	0.0000	0.0000
Vicryl 30	0.0049	0.0005	1.0000	0.0178	0.0010	0.0182	0.0176	0.0004	0.0002	0.0003	0.0097	0.2401	0.1089	0.0072	0.0001	0.0001	0.1693	0.0011	0.0000	0.0000
Vicryl 40	0.0004	0.0037	0.0178	1.0000	0.0168	0.0010	0.0120	0.0977	0.0287	0.0119	0.0019	0.0054	0.0048	0.4049	0.0142	0.0035	0.0043	0.1417	0.1222	0.0166
Vicryl 50	0.0005	0.0009	0.0010	0.0168	1.0000	0.0002	0.0011	0.0495	0.5638	0.0305	0.0022	0.0009	0.0002	0.0253	0.3592	0.0005	0.0007	0.0055	0.0490	0.0974
Silk 0	0.0035	0.0419	0.0182	0.0010	0.0002	1.0000	0.0430	0.0007	0.0025	0.0019	0.0105	0.0532	0.0306	0.0005	0.0005	0.0825	0.0647	0.0073	0.0025	0.0017
Silk 20	0.0005	0.0003	0.0176	0.0120	0.0011	0.0430	1.0000	0.0004	0.0000	0.0001	0.0119	0.9377	0.9893	0.0056	0.0001	0.0000	0.7058	0.0001	0.0000	0.0000
Silk 30	0.0013	0.0006	0.0004	0.0977	0.0495	0.0007	0.0004	1.0000	0.0244	0.0061	0.0036	0.0031	0.0003	0.2365	0.0083	0.0002	0.0024	0.0051	0.7781	0.0072
Silk 40	0.0023	0.0000	0.0002	0.0287	0.5638	0.0025	0.0000	0.0244	1.0000	0.0002	0.0043	0.0054	0.0017	0.0341	0.4767	0.0000	0.0047	0.0000	0.0019	0.0047
Silk 50	0.0020	0.0000	0.0003	0.0119	0.0305	0.0019	0.0001	0.0061	0.0002	1.0000	0.0056	0.0037	0.0013	0.0118	0.0218	0.0000	0.0053	0.0001	0.0010	0.0064
PDS 0	0.6152	0.0388	0.0097	0.0019	0.0022	0.0105	0.0119	0.0036	0.0043	0.0036	1.0000	0.0048	0.0083	0.0022	0.0030	0.0296	0.0054	0.0073	0.0049	0.0038
PDS 20	0.0013	0.0158	0.2401	0.0054	0.0009	0.0532	0.9377	0.0031	0.0054	0.0037	0.0048	1.0000	0.9494	0.0028	0.0018	0.0204	0.8210	0.0294	0.0073	0.0038
PDS 30	0.0030	0.0054	0.1089	0.0048	0.0002	0.0306	0.9893	0.0003	0.0017	0.0013	0.0083	0.9494	1.0000	0.0015	0.0001	0.0049	0.7368	0.0083	0.0013	0.0009
PDS 40	0.0005	0.0023	0.0072	0.4049	0.0253	0.0005	0.0056	0.2365	0.0341	0.0118	0.0022	0.0028	0.0015	1.0000	0.0153	0.0019	0.0022	0.0480	0.2738	0.0171
PDS 50	0.0011	0.0003	0.0001	0.0142	0.3592	0.0005	0.0001	0.0083	0.4767	0.0218	0.0030	0.0018	0.0001	0.0153	1.0000	0.0001	0.0014	0.0008	0.0060	0.1278
Pro 0	0.0189	0.0114	0.0001	0.0035	0.0005	0.0825	0.0000	0.0002	0.0000	0.0000	0.0296	0.0204	0.0049	0.0019	0.0001	1.0000	0.0208	0.0000	0.0000	0.0000
Pro 20	0.0015	0.0159	0.1693	0.0043	0.0007	0.0647	0.7058	0.0024	0.0047	0.0033	0.0054	0.8210	0.7368	0.0022	0.0014	0.0208	1.0000	0.0238	0.0061	0.0033
Pro 30	0.0039	0.0000	0.0011	0.1417	0.0055	0.0073	0.0001	0.0051	0.0000	0.0001	0.0073	0.0294	0.0083	0.0480	0.0008	0.0000	0.0238	1.0000	0.0001	0.0000
Pro 40	0.0025	0.0000	0.0000	0.1222	0.0490	0.0025	0.0000	0.7781	0.0019	0.0010	0.0049	0.0073	0.0013	0.2738	0.0060	0.0000	0.0061	0.0001	1.0000	0.0002
Pro 50	0.0020	0.0000	0.0000	0.0166	0.0974	0.0017	0.0000	0.0072	0.0047	0.0064	0.0038	0.0038	0.0009	0.0171	0.1278	0.0000	0.0033	0.0000	0.0002	1.0000

Appendix Table 2

Statistical Analysis of Table 1 Tensile Strength Data using T-Test

Group	Vicryl 0	Vicryl 20	Vicryl 30	Vicryl 40	Vicryl 50	Silk 0	Silk 20	Silk 30	Silk 40	Silk 50	PDS 0	PDS 20	PDS 30	PDS 40	PDS 50	Pro 0	Pro 20	Pro 30	Pro 40	Pro 50
Vicryl 0	1.0000	0.3025	0.0005	0.0128	0.0101	0.0035	0.0225	0.2653	0.0139	0.0008	0.6152	0.0129	0.0004	0.0123	0.0045	0.0189	0.0148	0.0074	0.0002	0.0001
Vicryl 20	0.3025	1.0000	0.0016	0.0196	0.0126	0.0032	0.0003	0.0885	0.0050	0.0003	0.7879	0.0158	0.0049	0.0212	0.0074	0.0000	0.0159	0.0025	0.0027	0.0019
Vicryl 30	0.0005	0.0016	1.0000	0.0946	0.0238	0.0000	0.0002	0.0004	0.0005	0.0117	0.0030	0.0001	0.1089	0.1806	0.0151	0.0005	0.0001	0.0011	0.2294	0.0022
Vicryl 40	0.0128	0.0196	0.0946	1.0000	0.0289	0.0087	0.0117	0.0107	0.0287	0.1957	0.0107	0.0085	0.1692	0.4049	0.0290	0.0112	0.0089	0.0346	0.1222	0.1299
Vicryl 50	0.0101	0.0126	0.0238	0.0289	1.0000	0.0082	0.0095	0.0093	0.0151	0.0305	0.0091	0.0082	0.0254	0.0192	0.3592	0.0093	0.0084	0.0165	0.0250	0.0974
Silk 0	0.0035	0.0032	0.0000	0.0087	0.0082	1.0000	0.0308	0.0087	0.0001	0.0000	0.0105	0.0701	0.0004	0.0079	0.0041	0.0825	0.0489	0.0001	0.0000	0.0003
Silk 20	0.0225	0.0003	0.0002	0.0117	0.0095	0.0308	1.0000	0.0531	0.0001	0.0000	0.0359	0.9377	0.0020	0.0115	0.0053	0.0347	0.7058	0.0000	0.0007	0.0011
Silk 30	0.2653	0.0885	0.0004	0.0107	0.0093	0.0087	0.0531	1.0000	0.0084	0.0008	0.1883	0.0463	0.0003	0.0099	0.0040	0.0384	0.0560	0.0051	0.0002	0.0001
Silk 40	0.0139	0.0050	0.0005	0.0287	0.0151	0.0001	0.0001	0.0084	1.0000	0.0000	0.0511	0.0020	0.0057	0.0341	0.0090	0.0003	0.0018	0.0293	0.0019	0.0015
Silk 50	0.0008	0.0003	0.0117	0.1957	0.0305	0.0000	0.0000	0.0008	0.0000	1.0000	0.0033	0.0003	0.7554	0.5151	0.0218	0.0000	0.0002	0.0000	0.1186	0.0064
PDS 0	0.6152	0.7879	0.0030	0.0107	0.0091	0.0105	0.0359	0.1883	0.0511	0.0033	1.0000	0.0204	0.0007	0.0101	0.0033	0.0296	0.0236	0.0275	0.0012	0.0001
PDS 20	0.0129	0.0158	0.0001	0.0085	0.0082	0.0701	0.9377	0.0463	0.0020	0.0003	0.0204	1.0000	0.0002	0.0076	0.0056	0.3935	0.8210	0.0014	0.0001	0.0001
PDS 30	0.0004	0.0049	0.1089	0.1692	0.0254	0.0004	0.0020	0.0003	0.0057	0.7554	0.0007	0.0002	1.0000	0.4575	0.0142	0.0022	0.0002	0.0083	0.3460	0.0014
PDS 40	0.0123	0.0212	0.1806	0.4049	0.0192	0.0079	0.0115	0.0099	0.0341	0.5151	0.0101	0.0076	0.4575	1.0000	0.0117	0.0110	0.0080	0.0434	0.2738	0.0356
PDS 50	0.0045	0.0074	0.0151	0.0290	0.3592	0.0041	0.0053	0.0040	0.0090	0.0218	0.0033	0.0036	0.0142	0.0117	1.0000	0.0052	0.0038	0.0099	0.0153	0.1278
Pro 0	0.0189	0.0000	0.0005	0.0112	0.0093	0.0825	0.0347	0.0384	0.0003	0.0000	0.0296	0.3935	0.0022	0.0110	0.0052	1.0000	0.2780	0.0002	0.0010	0.0012
Pro 20	0.0148	0.0159	0.0001	0.0089	0.0084	0.0489	0.7058	0.0560	0.0018	0.0002	0.0236	0.8210	0.0002	0.0080	0.0038	0.2780	1.0000	0.0012	0.0001	0.0001
Pro 30	0.0074	0.0025	0.0011	0.0346	0.0165	0.0001	0.0000	0.0051	0.0293	0.0000	0.0275	0.0014	0.0083	0.0434	0.0099	0.0002	0.0012	1.0000	0.0031	0.0018
Pro 40	0.0002	0.0027	0.2254	0.1222	0.0250	0.0000	0.0007	0.0002	0.0019	0.1186	0.0012	0.0001	0.3460	0.2738	0.0153	0.0010	0.0001	0.0031	1.0000	0.0015
Pro 50	0.0001	0.0019	0.0022	0.1299	0.0974	0.0003	0.0011	0.0001	0.0015	0.0064	0.0001	0.0001	0.0014	0.0356	0.1278	0.0012	0.0001	0.0018	0.0015	1.0000

Statistical Analysis of Table 2 Data using T-Test

Group	PDS 20 -50	PDS 20 -200	PDS 30 -400	PDS 30 -50	PDS 30 -200	SIL 20 -50	SIL 20 -200	SIL 30 -400	SIL 30 -50	SIL 30 -200	SIL 30 -400	Veryl 20 -50	Veryl 20 -200	Veryl 30 -400	Veryl 30 -50	Veryl 30 -200	Proline 20 -400	Proline 20 -200	Proline 20 -50	Proline 30 -400		
PDS 20 -50	1.0000	0.8338	0.1798	0.9494	0.1990	0.1239	0.9377	0.8631	0.3200	0.0031	0.0048	0.0047	0.0158	0.0229	0.0114	0.2401	0.8678	0.8023	0.8210	0.0155	0.0096	0.0311
PDS 20 -200	0.8338	1.0000	0.0486	0.6856	0.0986	0.0310	0.5538	0.9398	0.3270	0.0057	0.0019	0.0029	0.0013	0.0205	0.0328	0.9878	0.4636	0.4434	0.8435	0.0009	0.0115	0.0027
PDS 20 -400	0.1798	0.0486	1.0000	0.0576	0.0276	0.0071	0.0174	0.5382	0.8359	0.0001	0.0041	0.0031	0.0035	0.0023	0.0397	0.0025	0.2856	0.0223	0.2712	0.0003	0.0077	0.0007
PDS 30 -50	0.9494	0.6856	0.0576	1.0000	0.1445	0.0265	0.9893	0.8312	0.2546	0.0003	0.0044	0.0016	0.0054	0.0043	0.0147	0.1089	0.8061	0.7867	0.7368	0.0023	0.0099	0.0089
PDS 30 -200	0.0986	0.0276	0.1445	0.0265	1.0000	0.7433	0.1433	0.3588	0.0030	0.0111	0.0083	0.0072	0.0073	0.0055	0.0918	0.1938	0.5717	0.1720	0.0569	0.0305	0.0267	0.0593
PDS 30 -400	0.1239	0.0310	0.0071	0.0565	0.7433	1.0000	0.0521	0.3902	0.0469	0.0008	0.0131	0.0063	0.0034	0.0020	0.0069	0.3484	0.1352	0.0601	0.0228	0.0162	0.0329	0.0378
SIL 20 -50	0.9377	0.5538	0.0174	0.9893	0.1433	0.0021	1.0000	0.8247	0.2487	0.0004	0.0113	0.0083	0.0072	0.0073	0.0918	0.1938	0.5819	0.7134	0.7058	0.0021	0.0195	0.0001
SIL 20 -200	0.8631	0.9398	0.5382	0.8312	0.3588	0.3902	0.8247	1.0000	0.6215	0.0391	0.0467	0.0708	0.1238	0.0649	0.0524	0.4231	0.9511	0.7586	0.8591	0.0892	0.0532	0.1097
SIL 20 -400	0.3200	0.3270	0.8359	0.2546	0.0618	0.0469	0.2487	0.6215	1.0000	0.0034	0.0033	0.0039	0.0329	0.0649	0.0278	0.0893	0.4263	0.2089	0.4962	0.5857	0.0054	0.0231
SIL 30 -50	0.0001	0.0001	0.0001	0.0003	0.0030	0.0008	0.0004	0.0301	1.0000	0.1232	0.0537	0.0066	0.0001	0.0022	0.0004	0.0056	0.0144	0.0001	0.0024	0.0030	0.0054	0.0049
SIL 30 -200	0.0048	0.0087	0.0041	0.0044	0.0111	0.0131	0.0113	0.0391	0.0033	0.1232	0.8534	0.0036	0.0029	0.0010	0.0163	0.0065	0.0199	0.0066	0.0038	0.0027	0.1431	0.1078
SIL 30 -400	0.0017	0.0019	0.0013	0.0016	0.0083	0.0063	0.0054	0.0467	0.0039	0.0537	0.8534	1.0000	0.0021	0.0011	0.0076	0.0077	0.0244	0.0023	0.0035	0.1093	0.5511	0.0765
Veryl 20 -50	0.0158	0.0029	0.0035	0.0054	0.0072	0.0034	0.0003	0.0708	0.0329	0.0006	0.0036	0.0021	1.0000	0.0126	0.9152	0.0005	0.0234	0.0027	0.0089	0.0010	0.0050	0.0000
Veryl 20 -200	0.0029	0.0013	0.0023	0.0043	0.0073	0.0020	0.0001	0.1228	0.0649	0.0001	0.0029	0.0011	0.0126	1.0000	0.2798	0.0001	0.0378	0.0011	0.0256	0.0002	0.0046	0.0000
Veryl 20 -400	0.0114	0.0205	0.0397	0.0147	0.0055	0.0069	0.0242	0.0524	0.0278	0.0022	0.0010	0.0016	0.0126	0.2798	1.0000	0.0154	0.0142	0.0169	0.0197	0.0046	0.0012	0.0090
Veryl 30 -50	0.2401	0.0238	0.0025	0.1089	0.0918	0.3484	0.0176	0.4231	0.0893	0.0004	0.0163	0.0076	0.0005	0.0001	0.0154	1.0000	0.2423	0.0876	0.693	0.0040	0.0315	0.0013
Veryl 30 -200	0.8678	0.9878	0.2856	0.8061	0.1938	0.1352	0.7881	0.9511	0.4263	0.0056	0.0065	0.0077	0.0234	0.0378	0.0442	0.2423	1.0000	0.6828	0.9899	0.0233	0.0113	0.0397
Veryl 30 -400	0.3933	0.4690	0.1610	0.5909	0.2717	0.4247	0.5819	0.9899	0.2082	0.0144	0.0199	0.0244	0.0244	0.0367	0.0110	0.7027	0.5232	0.3665	0.6735	0.0852	0.0336	0.0921
Proline 20 -50	0.8210	0.9435	0.2278	0.7368	0.1407	0.8855	0.7058	0.9891	0.4962	0.0024	0.0038	0.0035	0.0159	0.0236	0.0131	0.1693	0.9699	0.5940	1.0000	0.0115	0.0077	0.0251
Proline 20 -200	0.0023	0.4434	0.0223	0.7867	0.1720	0.0601	0.7134	0.7586	0.2089	0.0001	0.0066	0.0023	0.0027	0.0011	0.0169	0.0876	0.6828	1.0000	0.2188	0.0013	0.0138	0.0041
Proline 20 -400	0.9930	0.4636	0.2712	0.3327	0.0569	0.0238	0.2697	0.8389	0.5857	0.0003	0.0027	0.0011	0.0089	0.0105	0.0197	0.0464	0.6633	0.2188	1.0000	0.0020	0.0009	0.0082
Proline 30 -50	0.0155	0.0009	0.0003	0.0023	0.0005	0.0162	0.0021	0.8992	0.0121	0.0000	0.1431	0.1093	0.0010	0.0002	0.0046	0.0040	0.0233	0.0013	0.0015	1.0000	0.4325	0.4305
Proline 30 -200	0.0096	0.0115	0.0077	0.0099	0.0267	0.0329	0.0195	0.0532	0.0054	0.0654	0.4897	0.5511	0.0050	0.0046	0.0012	0.0315	0.0113	0.0138	0.0059	0.4325	1.0000	0.2785
Proline 30 -400	0.0311	0.0027	0.0007	0.0089	0.0593	0.0378	0.0001	0.1097	0.0251	0.0049	0.078	0.0767	0.0000	0.0000	0.0090	0.0013	0.0397	0.0041	0.0082	0.4305	0.2785	1.0000

Appendix Table 4

Statistical Analysis of Table 4 Data using T-Test

Group	Silk UnLooped	Silk Looped	Silk Needle	PDS UnLooped	PCS Looped	PDS Needle	Vieryl UnLooped	Vieryl Looped	Vieryl Needle	Prolene UnLooped	Prolene Looped	Prolene Needle
Silk Unlooped	1.0000	0.0001	0.0450	0.0011	0.0392	0.1392	0.0007	0.0085	0.1284	0.0637	0.1215	0.2302
Silk Looped	0.0001	1.0000	0.0054	0.0269	0.1898	0.2112	0.0017	0.1495	0.5284	0.0567	0.5076	0.1239
Silk Needle	0.0450	0.0054	1.0000	0.0010	0.0113	0.0184	0.0128	0.0008	0.0270	0.0058	0.0241	0.0270
PDS Unlooped	0.0011	0.0269	0.0010	1.0000	0.5332	0.0579	0.0046	0.6513	0.1616	0.0082	0.1495	0.0377
PDS Looped	0.0392	0.1898	0.0113	0.5332	1.0000	0.0666	0.0813	0.4314	0.1229	0.0610	0.1180	0.0462
PDS Needle	0.1392	0.2112	0.0184	0.0579	0.0666	1.0000	0.9245	0.0665	0.6390	0.7971	0.6383	0.6525
Vieryl Unlooped	0.0007	0.0017	0.0128	0.0046	0.0813	0.9245	1.0000	0.0281	0.5419	0.7517	0.5352	0.6208
Vieryl looped	0.0085	0.1495	0.0008	0.6513	0.4314	0.0665	0.0281	1.0000	0.2023	0.0151	0.1878	0.0387
Vieryl Needle	0.1284	0.5284	0.0270	0.1616	0.1229	0.6390	0.5419	0.2023	1.0000	0.4773	0.9924	0.4063
Prolene Unlooped	0.0637	0.0567	0.0058	0.0082	0.0610	0.7971	0.7517	0.0151	0.4773	1.0000	0.4700	0.7731
Prolene Looped	0.1215	0.5076	0.0241	0.1495	0.1180	0.6383	0.5352	0.1878	0.9924	0.4700	1.0000	0.4006
Prolene Needle	0.2302	0.1239	0.0270	0.0377	0.0462	0.6525	0.6208	0.0387	0.4063	0.7731	0.4006	1.0000

Figure 1.

(a) CAD depiction of robotic forceps (b) Robotic forceps holding on to a suture, collapsing the cylindrical structure of the suture (c) Mounting bracket for holding on to a suture using MTS Tytron (d) Suture held in place such that it mimics surgical forceps (e) Suture being pulled by MTS system

Figure 2.
USSC Suture Force Gauge

Figure 3.
USSC force gauge modified using 3D printed components

Figure 4. Failure load of PDS, Prolene, Silk and Vicryl, gauges 2-0 & 3-0, when pulled at different rates using Tytron system

Table 1

Suture failure load and tensile strength measure using Tytron system, reported for sutures of gauges 0 to 5-0 of PDS, Silk, Vicryl and Prolene. Values are reported as Mean (std. dev.)

Material	Gauge	Failure Load (kg)	Failure Load (N)	Tensile Strength (kg/cm ²)	Tensile Strength (kN/cm ²)
Polydioxane (PDS)	0	6.18 (0.55)	60.61 (5.39)	6423 (573)	62.990 (5.619)
	2-0	3.40 (0.27)	33.34 (2.65)	4811 (383)	47.181 (3.756)
	3-0	3.39 (0.16)	33.25 (1.57)	10786 (524)	105.778 (5.138)
	4-0	2.03 (0.22)	19.91 (2.16)	11472 (1267)	112.505 (12.425)
	5-0	1.3 (0.12)	12.75 (1.18)	16588 (1514)	162.678 (14.847)
Silk	0	3.79 (0.24)	37.17 (2.35)	4126 (247)	40.463 (2.422)
	2-0	3.39 (0.07)	33.25 (0.69)	4791 (93)	46.985 (0.912)
	3-0	1.81 (0.13)	17.75 (1.27)	5759 (425)	56.478 (4.167)
	4-0	1.36 (0.03)	13.34 (0.29)	7712 (162)	75.631 (1.588)
	5-0	0.86 (0.01)	8.43 (0.10)	10897 (159)	106.866 (1.559)
Vicryl (Braided)	0	5.97 (0.39)	58.55 (3.82)	6200 (409)	60.803 (4.011)
	2-0	4.61 (0.02)	45.21 (0.20)	6525 (30)	63.990 (0.294)
	3-0	3.15 (0.08)	30.89 (0.78)	10015 (258)	98.217 (2.530)
	4-0	2.21 (0.26)	21.67 (2.55)	12519 (1474)	122.773 (14.455)
	5-0	1.43 (0.18)	14.02 (1.77)	18268 (2302)	179.154 (22.575)
Prolene	0	4.40 (0.05)	42.94 (0.52)	4573 (55)	44.669 (0.541)
	2-0	3.45 (0.26)	33.73 (2.54)	4885 (368)	47.724 (3.597)
	3-0	2.51 (0.11)	24.53 (1.06)	7993 (344)	78.078 (3.360)
	4-0	1.84 (0.06)	17.93 (0.62)	10387 (359)	101.469 (3.512)
	5-0	1.14 (0.05)	11.14 (0.47)	14515 (610)	141.795 (5.966)

Table 2

Comparison of failure loads at different rates for sutures of gauges 2-0 and 3-0 of PDS, Silk, Vicryl and Prolene. Values are reported as Mean (std. dev.)

Material	Gauge	Failure Load (N) 50 mm/min	Failure Load (N) 200 mm/min	Failure Load (N) 400 mm/min
Polydioxane (PDS)	2-0	33.34 (2.65)	33.61 (1.21)	36.21 (1.04)
	3-0	33.25 (1.57)	29.75 (2.91)	29.54 (1.67)
Silk	2-0	33.25 (0.69)	33.88 (5.45)	35.84 (2.99)
	3-0	17.75 (1.27)	21.21 (2.56)	21.58 (1.96)
Vicryl (Braided)	2-0	45.21 (0.20)	41.92 (0.73)	44.82 (3.44)
	3-0	30.89 (0.78)	33.64 (3.10)	31.69 (3.71)
Prolene	2-0	33.73 (2.54)	32.76 (1.24)	34.63 (1.79)
	3-0	24.53 (1.06)	22.87 (2.78)	25.23 (0.48)

Table 3

Comparison of mean failure loads of Vicryl, recorded with USSC Suture force gauge vs. when recorded with Tytron System

	Failure Load (Kg) Tytron	Std. Dev. Tytron	Failure Load (Kg) USSC	Std. Dev USSC	% Error
0	5.97	0.39	6.07	0.61	2.45%
2-0	4.61	0.02	4.29	0.21	6.73%
3-0	3.15	0.08	2.92	0.04	7.00%
4-0	2.21	0.26	2.04	0.15	7.67%
5-0	1.43	0.18	1.37	0.19	4.78%

Table 4

Comparison of failure loads (N), recorded using USSC force gauge, when suture is pulled by (a) holding on to the suture thread and pulling (b) holding on to the suture thread, wrapping/looping the suture thread around the grasper tip and then pulling (c) pulling the suture by holding on to the needle at the end of the suture

Material	Suture Thread - Unlooped	Suture Thread - Looped	Suture Needle
PDS 3-0	20.46 (1.18)	22.46 (4.58)	14.06 (3.15)
Prolene 3-0	13.47 (1.84)	15.53 (3.88)	12.81 (3.11)
Vicryl 3-0	13.86 (0.49)	19.81 (1.95)	15.56 (4.03)
Silk 3-0	9.77 (0.54)	17.33 (0.60)	4.87 (2.03)