Axial twisting within an ending loop of a continuous suture pattern affects the biomechanical properties of knots of certain suture sizes and types

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Abstract

Objective: To determine whether axial twisting within an ending loop of a continuous suture pattern negatively impacts security and maximum load to failure of suture knots.

Samples: 525 knots (15 samples each of seven different suture types/sizes tested in five knot twist configurations each)

Procedures: Each suture type and size were used to create a starting square knot and each of the following ending square knot configurations: 0 twists, 1 twist, 4 twists, and 10 twists. Each suture was tested to maximum failure using an Instron Universal Testing Machine with a 100 kg load cell at a speed of 100 mm/min. Each suture and knot was evaluated for mode of failure using gross evaluation of the knots and video footage recorded during testing.

Results: Maximum load to failure was decreased in knots tied within ending loops containing more twists for some types and sizes of suture. All knots with 4-twists made using 0-PDO, 1 PDO, and 2-0 Nylon were more likely to fail at the knot than knots without twists. All knots containing 10 twists, except 3-0 Monoderm, were more likely to fail at the knot than knots without twists.

Clinical Relevance: This study shows that for select suture types and sizes, increasing the number of twists present within the ending loop weakens the knot. Ideally the ending loop should be unraveled prior to tying the knot.

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Min – minute

PDO – polydioxanone

PDS – polydioxanone

GI – gastrointestinal

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Dedication

I would like to dedicate this thesis to my parents, Len and Ginny Whyte, who have always believed in me and pushed me to be the best version of myself. Their continuous support has allowed me to go further than I ever thought I would.

Chapter 1 – Types of Sutures, Knots, and Their Characteristics: A Literature Review

Suture types and their properties and characteristics

Surgical suture can be split into 2 major groups: absorbable and nonabsorbable. Absorbable sutures can be broadly defined as sutures that lose tensile strength within 60-90 days in living mammalian tissue. Within these two groups, suture can be further characterized as natural or synthetic. Natural sutures materials are those that are produced by or come from living things. Synthetic sutures have been manufactured. There are two major mechanisms of suture absorption: enzymatic and hydrolytic. Enzymatic absorption occurs in natural sutures, such as catgut and collagen-based materials. These are absorbed through enzymatic actions of cellular proteases and collagenases. Hydrolytic absorption occurs with synthetic sutures. Hydrolysis occurs by random main-chain excision of ester linkages. The absorption process can be rapid, moderate, or slow depending on the suture material and the environment surrounding the tissue.[1] The goal of a nonabsorbable suture is to never lose tensile strength, regardless of time or other factors. All nonabsorbable suture material, except stainless steel and polypropylene, will lose some tensile strength overtime and in some cases, can completely deteriorate within mammalian tissue.[2,3]

Suture can be further classified according to a variety of properties, all of which must be considered when choosing a suture type and size for a given surgery, as not all suture types are appropriate for all tissues. These specific characteristics include, but are not limited to, elasticity, plasticity, relative knot security, memory, handling, and tensile strength.[1,3]

Elasticity, or elastic deformation, is the degree to which a suture will deform under stress or load and return to its original form when the load is removed.[1] This is an important function when closing tissues where a large amount of edema is expected to form, for example, in closure of the linea alba. One study found that PDS and Maxon allow for significant elongation prior to breakage, in both knotted and unknotted suture strands, which is desirable for tissues expected to greatly expand with edema during the healing process.[4]

Plasticity, or plastic deformation, is the opposite of elasticity. It is defined as the permanent distortion that occurs when materials are subject to forces that exceed the yield strength of the material.[5] Sutures with high plasticity, like elastic sutures, do not tend to cut through tissue edges as the wound swells, however plasticity is typically an undesirable trait because once the load is removed, the deformed shape is maintained.[2] Plasticity has been shown to be decreased in monofilament sutures and certain nonabsorbable sutures (Nylon), meaning the sutures undergo very little to no deformation when a load is applied.[6,7]

A knot is formed by 2 consecutive throws. Throws are made by crossing suture ends and wrapping one strand around the other. Knot security is the ability of the knot to resist slippage and breakage as a load is applied. This is a critical factor in maintaining the integrity of a tied suture because the knot is always the weakest link in any suture.[8] Knot security has been demonstrated to be a function of knot configuration, which includes the number of throws used to make a knot, the type of knot performed, as well as the size and type of suture material.[9,10] It has been repeatedly documented that tying too few throws can result in knot failure with specific materials and knot configurations.[8,11–13] There is confounding evidence on the appropriate amount of throws recommended to form a secure knot. A 2011 study found that the most secure square knots were tied with 5 throws, but when adding a 6th throw there was no biomechanical advantage.[12] When tying a surgeon's or square knot, a 2016 study found that less than 4 throws would result in knot failure and if more than 5 throws were added, there was no additional contribution to knot security. When sliding knots were performed, 5 throws were required for a secure knot.[8] An additional study tested the knot security of three-throw sliding knots and two-throw surgeons and square knots and found that the performance of these knots was poor and should not be used clinically.[13] Various knot configurations have been tested for knot security and no consensus on the ideal knot configuration has been achieved. [8,14]

Memory is the ability of suture to return to its original shape after deformation. Sutures with greater memory are not pliable (increased stiffness) and have poorer handling characteristics and poor knot security.[15] Monofilament sutures tend to have more memory than multifilament.

Handling is determined by three different properties, elasticity, plasticity, and memory.[16] Ideally, suture material should handle easily and comfortably. Silk is considered the gold standard when comparing handleability of other suture materials due to is excellent handling and ease of knot tying. Sutures with better handling characteristics are recommended for ligating blood vessels or performing continuous suture patterns.[2]

Tensile strength, as defined by the US pharmacopeia (USP), states that it is the weight necessary to break a suture divided by the cross-sectional area of the suture. This relationship between the weight needed to break the suture and the diameter of the suture is not linear.[2] Tensile strength can further be described as the stress at which deformation or rupture occurs. Tensile strength of an unknotted suture tends to be higher than that of knotted sutures. Previous reports have shown that knotted suture material reduced the maximum tensile strength by 39% for braided suture and 24% for Nylon suture.[17] Tensile strength can be decreased due to handling of suture, including grasping with forceps, inadvertent knot formation along suture strand,[18] and increased axial twisting.[19] When considering tensile strength for closure of certain tissues, the ideal suture should retain its strength for a time sufficient to give support through complete healing.[20]

Suture can also be further classified based on its structure: monofilament or multifilament. Monofilament sutures are those that are made of a single strand of material. They tend to have decreased tissue drag and less tissue reactivity than multifilament sutures.[3] However, they can also have increased memory and decreased knot security. Multifilament sutures are composed of multiple strands of suture that are either twisted or braided together. Multifilament sutures tend to have better strength and pliability than monofilament sutures, but have higher tissue drag and friction which can lead to bunching of tissue and increased tissue trauma.[1] Multifilament sutures also have an increased risk of bacterial colonization due to the increased surface area located between the strands.[1]

Absorbable suture types and specific characteristics

Absorbable suture materials are defined as materials that lose most of its tensile strength within 60-90 days of implantation.[21] They can be synthetic polymers or of biologic origin.

Catgut is an organic, multifilament, suture composed of purified connective tissue (primarily collagen) derived from either bovine or ovine intestine and is absorbed by the action of macrophages through phagocytosis and enzymatic digestion.[22,23] There are two forms: plain or chromic. Chromic gut undergoes an additional curing or tanning process with chromium trioxide salts during production in order to delay the absorption process, increase tensile strength, and decrease tissue reactivity. This type of suture generally tends to be weaker, have high tissue reaction, and the absorption can be extremely variable depending on environmental conditions, such as the presence of infection or exposure to proteolytic enzymes. Because it is organic, the enzymatic degradation it undergoes can be rapid, particularly when used in gastric or intestinal surgery due to the exposure to proteolytic enzymes. This type of suture is fully absorbed in 60-90 days, however it only maintains tensile strength for 7-10 days.[24] Therefore, this suture should only be used in tissues where rapid healing time is expected and should not be used in species that are prone to developing adhesions.

Absorbable synthetic sutures are composed of monomers or polymers. The specific material affects strength, flexibility, and speed with which the suture is absorbed.[25] Rapidly absorbable synthetic sutures include polyglycolic acid (Dexon®), polyglactin 910 (Vicryl™), poliglecaprone 25 (Monocryl™), and polyglytone 6211 (Caprosyn™). Slowly absorbed synthetic sutures include polydioxanone (PDS™), polyglyconate (Maxon™), and glycomer 631 (Biosyn™).

Polydioxanone is a monofilament absorbable suture composed of polymerized p-dioxanone.[24] It has prolonged absorption with 50% loss of strength in 5-6 weeks. Initial tensile strength for polydioxanone is greater than chronic gut, polyglycolic acid, or polyglactin 910, but it has the poorest knot security of the synthetic absorbable sutures.[26] Polydioxanone should be selected if prolonged support of healing tissue is desired.[21]

Poliglecaprone 25 is a monofilament absorbable suture composed of segmented blocks of copolymers of e-caprolactone and glycolide that contribute to favorable handling characteristics.[27] Additionally, the suture contains segments of polyglycolide that contribute to tensile strength, making it one of the strongest absorbable sutures, however its tensile strength rapidly weakens after implantation. Only 20-30% of initial tensile strength is maintained after 14 days and complete absorption occurs between 90-100 days.

Polyglactin 910 is a multifilament suture composed of a copolymer of lactic acid and glycolic acid that is coated with calcium stearate, in order to decrease tissue drag, and a second copolymer of glycolide and lactide. It is a braided suture, which results in superior handling characteristics but also increases tissue drag.[24] Tensile strength falls to approximately 75% in 2 weeks , 50% at 3 weeks, with complete absorption at 60 days.[22,24,28] This suture is designed for rapidly healing tissues where long term support is not required.

Polyglyconate is a monofilament suture composed of copolymers of glycolide and trimethelyene carbonate. Tensile strength falls to approximately 80% at 1 week, 75% at 2 weeks, 50% at 4 weeks, and 25% at 6 weeks, with complete absorption at 180 days.[21]

Glycomer 631 is a monofilament suture composed of synthetic polyesters with segments of glycolide and dioxanone alternating with segments of trimethelyene carbonate and dioxanone.

It retains 75% of its tensile strength at 2 weeks and 40% at 3 weeks, with complete absorption occurring between 90-110 days.[3]

Polyglycolic acid is a braided suture composed of the homopolymer of glycolic acid and coated with polycaprolate, which is a copolymer of glycolide and e-caprolactone. It is a rapidly absorbable suture and loses tensile strength shortly after implantation. At 14 days, polyglycolic acid only has 20% of its initial tensile strength and it is completely absorbed in 60 days.[2]

Polyglytone 6211 is a monofilament absorbable suture composed of synthetic polyester of glycolide, caprolactone, trimethylene carbonate, and lactide.[29] It provides short term tensile strength and rapid absorption. Upon implantation, 70-80% of tensile strength is lost at 10 days and it is completely absorbed within 60 days.[30]

Non-absorbable suture types and specific characteristics

Nonabsorbable suture materials undergo very little degradation following implantation. These sutures are used where extended wound support is required or in areas where suture removal is expected, such as skin closure and when reactivity is undesirable. They are composed of organic or synthetic fibers. Organic fibers tend induce an inflammatory response; therefore many surgeons prefer synthetic nonabsorbable sutures. Commonly used nonabsorbable sutures include silk, nylon, polyester, and polypropylene.

Silk is the most commonly used organic nonabsorbable suture material.[21–23] It is braided and has excellent handling properties and knot security. It does, however, lose tensile strength after an extended period of implantation. It is considered nonabsorbable because of the length of time it remains in the tissues after implantation. There is a loss of 30% of tensile strength at 14 days and 50% at one year. Time for complete absorption is greater than 2 years.[28]

Nylon is a synthetic nonabsorbable suture that can be found in both monofilament and multifilament (braided) forms.[21,22,24,28] Nylon has a high level of elasticity but undergoes little to no plastic deformation before breakage.[7] Monofilament nylon has a relatively high stiffness. It has moderate handling characteristics and knot security and induces minimal tissue response. Monofilament nylon loses 30% of its tensile strength after 2 years while braided nylon loses 75-100% of its tensile strength at 6 months.

Polypropylene is a synthetic monofilament nonabsorbable suture material composed of stereo-isomers of polypropylene.[21] Polypropylene has the greatest strength of the synthetic nonabsorbable sutures and has no appreciable loss of tensile strength after implantation.[21] It has minimal tissue drag and a very smooth surface, which can lead to slipping and poor knot security.[24] It also has poor handling characteristics, high memory, and a high plasticity.[2]

Polyester is a nonabsorbable, multifilament suture formed by condensation polymerization of polyester.[2] It comes in coated and uncoated forms. The uncoated forms have a high degree of tissue drag, which is improved when the suture is coated. This suture was developed to induce minimal tissue reactivity while maintaining the good handling properties of braided multifilament sutures. Although they do produce less tissue reactivity than other multifilament sutures, it does not compare to the inert properties of monofilament sutures. Polyesters have poor knot security, especially when coated, but they are quite strong.[2]

Polybutester is a monofilament absorbable suture composed of polybutylene and polytethramethylene.[2] It was designed to combine the advantages of polypropylene and polyester, It has greater strength, less stiffness, and lower tissue drag than both polypropylene and nylon. It also has favorable handling characteristics and knot security with minimal tissue reactivity. This suture is very elastic and can stretch up to 50% of its original length under low loads.[2]

Tissue characteristics and healing

The ideal suture material provides high tensile strength for an appropriate time while allowing the tissue it is holding to heal. It should also have good knot security, resist infection, and cause no inflammatory, immunogenic, or carcinogenic reactions.[7] A surgeon must be aware of all the variability of suture materials to make an appropriate decision upon closure or ligation of any tissue or vessel, respectively. It is also important for the surgeon to have a thorough understanding of the characteristics of the tissue being handled.

Different tissue types heal at various rates, and it is very important to understand these differences to ensure adequate support while tissues are healing. The varying rates of healing equate to varying amounts of time in which the suture is required to support a specific tissue while it heals. For example, the bladder heals very quickly, regaining normal tensile strength within 14-21 days.[28] When closing tissue that is expected to heal quickly, a moderately- or rapidly-absorbable suture can be selected (poliglecaprone, glycomer 631, polyglycolic acid, and polyglactin 910.). Tissues like the gastrointestinal (GI) tract also heal at a rapid rate, regaining 75% of strength of the stomach at 21 days, almost full strength in 10-17 days for small intestine, and up to 30 days for large intestine.[31,32] However, the maturation phase of healing of the gastrointestinal tract occurs between 10-180 days after surgery.[31,32] Additionally, sutures placed within the GI tract are exposed to gastrointestinal enzymes and bacteria, therefore it is important to use a suture with a longer duration in tissue, such as polydioxanone, poliglecaprone, glycomer 631, or polyglyconate. Healing times for fascia are significantly longer than those for the GI or urinary tracts. This means much longer support from suture materials is needed. As an example, 20 days after surgery the body wall has only regained 20% of its original tensile strength.[22] Additionally, when these tissues heal, significant swelling and edema is expected.[4] Sutures such as PDS or Maxon should be used for fascial incisions. Tissues such as tendons can take up to a year to achieve maximum strength and require long-term support with orthopedic implants or external coaptation in addition to suture implantation.[33] They are considered bradytrophic tissues, which means that the healing process can take several months, depending on the location.[34] Tendons regain 56% of their normal tensile strength at 6 months and are only at 75% of normal at 1 year post-repair.[1] Tissues that take an extended time to heal should be repaired with sutures that have high tensile strength and slower absorption, such as PDS or Maxon. Additionally, when repairing tendons specifically, gap formation of the tendon ends must be avoided, therefore, sutures with high plasticity should be avoided (Prolene).[6]

Factors affecting suture characteristics and strength

In any wound, whether surgically created or not, considerations should be made as to exactly what tissues are being sutured, their individual strengths during healing, as well as the environment to which the tissue and suture might be exposed to during the healing process in order to select suture material that will provide enough support to facilitate healing with minimal effects on absorption time or tensile strength.

One important factor to consider when choosing a suture is the pH that surrounds the tissues and suture during healing because pH can affect the retention of strength of suture materials. The pH of gastric fluid can be as low as 0.9 to 1.5, while pancreatic secretions in the duodenum range from 7.5 to 8.1.[35] Urine pH ranges from 4.5 to 8.0.[36] However, under pathologic conditions, the pH of body fluids can change. For instance, urinary tract infections can raise or lower the pH of urine, depending on the bacterial species that is present. [37] More acidic or alkaline pH was shown to increase the speed of degradation of naturally absorbable sutures, such as catgut, but only alkaline pH will accelerate the degradation of synthetic absorbable sutures, such as polyglycolic acid.[38] Nonabsorbable sutures are minimally affected by pH.

It has also been shown that handling by the surgeon can lead to decreased tensile strength of the suture strand. Several factors have been evaluated, including axial twisting, abrasions, kinks and knots, tugging, inadvertent knot formation, and grasping of the suture with forceps.[18] Based on a study performed by Dobrin[18] using 5-0 and 6-0 Polypropylene suture, the only factors that negatively affected the strength of the suture was inadvertent knotting of the suture and grasping of the suture strand with forceps. A later study found that when larger gauge (1 and 0) polypropylene, polydioxanone, polyglactin 910, and nylon were axially twisted 10, 15, and 20 times, there was a decrease in tensile strength of suture up to 10%, 21%, and 47%, respectively, for each suture type.[19] This study also showed that when twisting PDS, the elastic properties of the suture changed; the suture became stiffer as more twists were applied, leading to a decrease in the elongation of the suture prior to failure.[19]

Types of knots

It is important not only for the surgeon to understand the underlying characteristics of suture, but also to know the characteristics of different knot types, particularly when tied with different types and sizes (gauges) of suture. Knot strength is dependent on both the knot configuration and the type and gauge of suture material.

A throw is a specific step or layer used to create a knot. A knot is composed of greater than or equal to two consecutive throws.[39] It is often stated that the knot is the weakest point of a suture strand.[40] This is thought to be due to the shear stresses that exist at the point between the loop and the first throw of the knot.[14,41] The knot has been shown to influence mechanical performance of the suture and lowers the ultimate failure strength by up to 50%.[42] The knot also leads to an increase in suture material within the tissues.

Surgical knots can be divided into two main groups: flat knots and sliding knots. A flat knot means that the material making up the knot (such as suture or rope) sit very flatly along one another, leading to a symmetrical and flat knot. A flat knot is created when both ends of the suture are equally rotated around one another and cinched with equal tension to yield a symmetrical knot. There are three types of knot configurations that can be considered flat: square, surgeon's and granny knots. A square knot, which is considered the gold standard for surgical procedures because they have been proven to be reliably secure when tied appropriately.[43,44]Square knots are formed by a single overhand throw with a reversed overhand throw on top. These knots have regularly alternating throws (clockwise, counterclockwise, etc). A surgeon's knot is a simple modification of the square knot that adds an extra twist in the first throw forming a double overhand knot.[14,44] A granny knot differs from the square knot in that the overhand throw on top of the initial throw is not reversed. So when tying these knots, continually repetitive throws are performed (clockwise, clockwise, etc.).[44] Sliding knots, also known as hitched knots, are formed when one end of the suture is rotated and cinched down around the other end, which remains taut. Keeping one end of the suture strand taut prevents loosening of the throw during tying.[44] Historically, sliding knots are inferior to square knots, however recent literature has shown that this may not be true. Sliding knots re routinely used in surgery, potentially more commonly than square knots, depending on the location and type of surgery being performed. Arthroscopic, gynecologic, or intrapelvic surgeries tend to require sliding knots as the deep-seated locations of these surgeries make it difficult to tie square knots. Certain sliding knots have been recently discovered to be comparable in security to square knots, however this depends on the size and type of the suture, as well as the number of throws placed.[13,44] There are many different sliding knot configurations that are beyond the scope of this thesis. The square knot will be the primary focus moving forward.

What is knot security and how do knots fail?

Modes of failure of sutures include suture rupture, tissue rupture, and knot failure. Although suture rupture, which is defined as breakage of the suture away from the knot, can partly be avoided by the surgeon with careful handling of the suture strands, it still may occur even with perfect technique, as patient compliance is a major contributor. Tissue rupture occurs when the suture pulls through the tissue that has been apposed. The mechanisms by which this happens include decreased health or necrosis of the tissue that has been sutured or high tension in the area of the wound/incision.[2,45] Additionally, poor suture choice can lead to increased tissue rupture.[45] Knot failure by slippage is the most controllable failure mode. Knot failure can be prevented by appropriate choice of suture material, size, and knot configuration, as well as the number of throws performed within that knot.[46] Knot security has been directly related to the surgeon's technique, and to the number of throws included in a knot. Too few throws lead to increased slippage and failure by untying of the knot.[14,47,48] Suture fracture, on the other hand, occurs secondary to the choice of suture material or size.[46]

The ability to tie secure knots is an essential skill for any practitioner performing surgery or closing wounds. Secure knots ensure hemostasis, integrity of anastomoses, secure and appropriate apposition of wounds, and security of interventional devices.[43] A secure knot may be the difference between life and death, but can also decrease morbidity for the patients and cost for the clients. However, with the ability to tie a secure knot, a surgeon must also understand the different suture characteristics and know the ideal number of throws needed to create a secure knot, which has proved to be a difficult task as a consensus has never been met on how many throws constitutes a secure knot. Various studies have been performed, but typically lack variability in suture size and knot configuration.[4,12–14,25,47]

Knot security is dependent on several factors, including surgeon experience, knot configuration which encompasses the type of knot performed, as well as the type and size of the suture material, and the number or throws placed. Knot security is also dependent on friction and the location of the knot.

Surgeon experience has been shown to influence the security of the knot. A study found the 73% of experienced surgeons were able to tie a secure knot compared to 59% of 4th year students.[25] Additionally, with experience comes the knowledge of knowing the appropriate suture material and size to use in different tissues, as well as gentle tissue and suture handling.

The type of knot tied can decrease the security of the knot. Square knots are considered the gold standard; however surgeon's knots may be preferred by some as they are theoretically more stable than square knots due to initial the double overhand throw. A study comparing surgeon's and square knots found that a surgeon's knot offered very little advantage over a square knot. Both knot configurations had similar tension at failure or likelihood of slippage and unraveling.[14] Regardless, either of these knot types will provide a secure knot when tied appropriately. A granny knot, however, can be remarkably unstable. Because the overhand throw is not reversed, these suture strands are not locked together and the knot has a much higher tendency to slip.[49] Creating a granny knot instead of a square knot can be very easy to do, especially for a novice surgeon. This can be avoided by ensuring that each throw is reversed over the previous throw.

Surgeons should aim to tie the most secure knot using the least amount of those in order to keep the knot size to a minimum, therefore leaving as little foreign material within the patient as possible. In practice, most surgeons use anecdotal information to choose the number of throws, which varies between surgeons and training programs, but is not based on complete scientific data. Studies have been performed using various suture materials and sizes, however the results are conflicting, showing ranges between 3-5 throws being adequate, depending on the type and gauge of suture being used.[10,13,39,50–55] One study found that there was no statistically significant difference regarding the likelihood of untying between knots with 5 and 6 throws. This study concluded that 5 throws generate the maximum amount of strength necessary to protect against untying of multiple monofilament and multifilament suture types, however only one suture size was evaluated.[14] Studies comparing different types and sizes of suture found that when using silk, adding greater than three did not improve security.[11] However, when using suture such as Monocryl or Vicryl, 5 throws improved knot security[11] unless smaller suture sizes were used. When smaller gauge sutures used, most had adequate knot security with 3 throws.[46] When using surgeon's or square knots, typically 4 throws is sufficient, but 5 will improve knot security. Whenever using a sliding knot, 5 throws should be performed for optimal security.[8] All studies tend to agree that when adding more than 5 throws, regardless of suture type or size, there is no significant advantage, just increased suture material left behind.[8,11–13,46]

The type of suture also plays a role in the security of a knot. Monofilament sutures are more slippery than multifilament sutures and contain more memory within the strands. These characteristics may lead to an increased risk of knot slippage due to the inability to tie an optimal knot.

Arguably the most important factor influencing knot security is friction. Friction between the suture strands is ensured by achieving significant contact between the strands within the knot. When tying knots, it is important that equal and opposite lengths of suture are entwined to ensure the maximal amount of contact, and therefore friction, between the suture strands is obtained. If this occurs, the knots will be reliably stable.[43,56]

The location of the knot has been shown to play a significant role in knot security. A study comparing the security of three different knot locations found that simple interrupted knots and knots at the start of a continuous pattern had no significant difference in security, however knots at the end of a continuous pattern failed and untied more often than the other two knot locations.[25] This is due to the fact that the ending loop is formed using a loop from the continuous pattern that is then tied to the free strand of the suture. The loop makes the knot bulkier and more difficult to tighten, which makes the knot more likely to unravel.[25]

Knot testing

Currently, there is no standard of testing for suture material or knot security. There are many different investigators that are providing valuable insight into their specific research objectives, however when put together, the variety of the testing conditions, tensile strength measurement procedures, and suture sizes provide confusion for a surgeon looking for a simple answer on which knot is superior. There are many variables that can be seen in studies on suture material and knot security. These include the suture type and size as well as knot type, testing suture that is soaked in solution or left dry, single distraction testing or cyclic testing, and the distraction speed.[57]

Sutures that have been soaked in solution can have a different coefficient of friction from sutures that are not soaked.[46,57] Theoretically, sutures that have been soaked should be more consistent with in vivo use.

Single distraction testing involves a single test that pulls a suture apart until we get breakage of the suture or failure of the knot.[39] Cyclic testing is thought to be more clinically applicable, as it puts the suture through the loading and unloading it would experience after being placed in mammalian tissue.[58] However, this testing is more difficult to perform and there are no known values of tension for all different tissue types for distraction speed and force. Therefore, single distraction speeds are more commonly utilized and allows for more comparison between studies, as this distraction type is more commonly used.

Distraction speed can also be vastly different between studies. It is generally recorded in millimeters per minute (mm/min). Researchers can choose speeds as slow as 5 mm/min or as fast as 120 mm/min. There is conflicting information on whether distraction speed influences the mode of failure for certain knot configurations. Some studies state that the speed does not affect mode of failure,[59,60] while others do.[61]

Since there is no standardization for testing suture material or knots, it is hard for researchers to come to an agreement on what testing construct is best and what knot configuration is best. Unfortunately, due to the numerous different variables there are for testing, standardized testing for suture material may never occur. However, with each study being performed, very valuable insight is gained into appropriate and inappropriate ways to tie suture material, as well as what may weaken suture material and/or knots.

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Chapter 2 - Axial twisting within an ending loop effects the biomechanical properties of knots of certain suture sizes and types

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“Axial twisting within an ending loop effects the biomechanical properties of knots of certain suture sizes and types”

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Author Contributions:

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Abstract

Objective: To determine whether axial twisting within an ending loop negatively impacts maximum load to failure and failure mode of suture knots.

Samples: 525 knots (15 samples each of seven different suture types/sizes tested in five knot twist configurations each)

Procedures: Each suture type (polydioxanone [PDO], Monoderm [polyglecaprone 25], and Nylon) and size (1, 0, 2-0, 3-0) were used to create a starting square knot and each of the following ending square knot configurations: 0 twists, 1 twist, 4 twists, and 10 twists. Each suture was tested to failure using a universal testing machine (Instron) with a 100 kg load cell at a speed of 100 mm/min. Each suture and knot was evaluated for mode of failure using gross evaluation of the knots and video footage recorded during testing. Maximum load at failure (p-value set at 0.005) and failure mode (p-value set at 0.003) were recorded for each group.

Results: Maximum load at failure was decreased in knots tied within ending loops containing more twists for some types and sizes of suture. With 4-twists, 0-PDO, 1 PDO, and 2-0 Nylon were more likely to fail at the knot than knots with 0 twists. All sutures containing 10 twists, except 3-0 Monoderm, were more likely to fail at the knot than knots with 0 twists.

Clinical Relevance: When performing a continuous pattern, the number of twists within the ending loop may not increase the risk of failure at the knot, however it can decrease the maximum load to failure at a knot, particularly as the suture size increases.

Introduction

Monofilament absorbable and non-absorbable sutures are used to close various types of tissues inside and outside the body. There are various benefits of monofilament suture over braided sutures, including less tissue drag, lower risk of infection, and lower knot tie down resistance. [1,2] However, they have a relatively higher bending stiffness and memory, leading to difficulty forming a stable knot.[2,3,4]

Normal passage of suture and movement of a surgeon's wrist while suturing can lead to axial twisting longitudinally along the suture strand.[5] Depending on the number of twists that occur, this can result in decreased tensile strength of suture.[5,6] A prior study determined that a 4- to 5-cm strand of 6-0 polypropylene suture can be axially twisted up to 4 times without losing tensile strength,[5] however when twisted 10 times or greater, as shown in a separate study using gauge 1 polydioxanone, polypropylene, or nylon suture, significant decreases in tensile strength can occur.[6] Based on these findings, it's possible that twisting within an ending loop when tying off a continuous pattern could also affect the maximum load at failure and failure mode of various suture types and sizes.

Numerous studies have been performed to determine knot security of different suture types and sizes under various conditions and knot configurations.[7–9] These studies have shown that in various sized sutures and knot configurations, maximum load at failure and knot security depend on suture material, tying technique, number of throws, and the location of the knot (starting knot vs. ending knot), but was not dependent on size or the type of knot tied (surgeon's vs. square).[7–9] To the best of the author's knowledge, no study has been performed to test the security of monofilament suture ending square knot where the ending loop has been twisted. The objective of this study is to determine the maximum load at failure and failure mode of ending square knots created from commonly used monofilament suture types and sizes when the ending loop has been twisted on itself and to compare these results with starting square knots and ending square knots without twists. Our hypothesis was that maximum load at failure for knots with twists would be less than for those with no twists, but that failure mode would not differ.

Materials and Methods

Three suture types were provided by TruStitch Surgical Specialties Corporation and were chosen for this study because they are commonly used to close the body wall (2-0, 0, 1 polydioxanone [PDO]), the subcutaneous and dermal tissues (3-0 PDO, 2-0 and 3-0 (poliglecaprone 25 [Monoderm]), and the skin (2-0 and 3-0 Nylon) in small animal patients. For each suture type and size, 15 knots were created for each of 5 different knot variations: 1) starting square knots 2) ending square knots with 0 twists within the ending loop, 3) ending square knots with 1 twist, 4) ending square knots with 4 twists, and 5) ending square knots with 10 twists **(Figure 1).**

All knots were created by a single individual (MAW) using a 3.175-cm-diameter, 30-cm-long PVC pipe with each end embedded into the center of a block of floral craft foam. The suture pattern was started by tying a 4-throw starting square knot, which was left on the apparatus. The suture was then wrapped around the testing apparatus twice, and a 5-throw ending square knot was performed by tying the free suture end to the second loop of the suture, as described by Upchurch et al.[10] When twists were applied to the ending square knot, after the suture was wrapped around the apparatus, the loop was grasped by hand and tied (zero twists), or manually twisted once, 4 times, or 10 times. When tying the knot, the ending loop was firmly grasped with the surgeon's non-dominant hand (a finger secured within the loop) to maintain the twists while the needle drivers were wrapped once with the free end of the suture and then the knot was tied in a standard fashion. Each knot was performed using instrument ties without the use of a tension gauge. The suture was removed from the apparatus and the suture connecting the two knots was cut and tags were measured and cut to 3-mm, as previously recommended.[11] Each of the ending knots as well as the first 15 starting knots tied for each suture were saved for testing.

Knot testing was performed using a universal testing machine (Instron Corp, Instron, Norwood, MA, USA) with a 100 kg load cell. The universal testing machine was connected to a computer equipped with standard software that recorded all data as each test was performed.[12] The machine contained a single motor unit that supplied vertical displacement in a direction away from the stationary unit, as well as two horizontal, metal rods, measuring 4-cm-long and 1-cm in diameter, with one attached to both the motor and to the stationary unit. The beams started at 3-cm apart and the suture samples were looped around each rod (**Figure 2**). The motor pulled the horizontal rods in opposite directions at a rate of 100 mm/min until failure of the sample occurred, as previously described.[10] The maximum load at failure, defined as the force required for the suture to fail, was recorded and the mode of failure was recorded for each suture size and knot type. A video camera (Sony FDR-AX33, Sony, Tokyo, Japan) was used to record each test and to allow evaluation of each knot prior to testing.

Following testing, all sutures were evaluated using video footage and gross evaluation of the suture and knot to determine where the suture had failed. Suture failure was classified into four categories: 1) unraveling of the knot, 2) failure/breakage of the knot, 3) knot intact, suture breakage occurring 1-mm from knot, 4) knot intact, suture breakage occurring >2-mm from knot.

Statistical Analysis

All statistical analysis was performed using standard software.[13] Maximum load at failure was recorded for each suture and knot type. To test for normality, a Kolmogorov-Smirnov test was performed. None of the variables were normally distributed. A Kruskal-Wallis test was performed to analyze variables (significance set at $p<0.05$). For significant variables, Dunn post-hoc analysis was performed. Bonferroni correction was performed, and significance value set to $p<0.005$. To assess failure mode for each different suture and knot type, a chi-squared test was performed. For significant variables, a post-hoc analysis was conducted by assessing adjusted residuals. Significance was set at $p<0.003$ with Bonferroni correction. Sutures were assessed first within their distinct suture type and size, then later compared to other sutures of the same size and knot type within the dataset.

Results

Overall, there is no clear trend between any suture type, size, or number of twists and maximum load. Sutures tied with PDO tended to have a lower maximum load at failure when tied with more twists, however this was not a consistent finding. Monoderm and Nylon had no clear trends in maximum load at failure based on the number of twists present. The average maximum load at failure (N) for each suture size and knot configuration are listed in **Table 1**. Within each data set, if no significant difference was noted in the maximum load at failure the results were not discussed.

Within the PDO groups **(Figure 3)**, 3-0 PDO had a significantly lower maximum load at failure in the 4-twist group compared to the starting group ($p<0.001$), the 0-twist group ($p<0.001$), and the 1-twist group ($p<0.001$). The maximum load at failure for the 10-twist group was significantly lower when compared to the starting group ($p=0.003$) and 0-twist group ($p=0.001$. For 2-0 PDO, maximum load at failure was significantly lower in the 10-twist group when compared to the starting ($p<0.001$), the 0-twist ($p=0.002$), and 1-twist ($p=0.003$) groups. With 0 PDO, maximum load at failure was significantly lower in the 1-twist ($p<0.001$), 4-twist ($p=0.004$), and 10-twist ($p=0.001$) groups compared to the 0-twist group. Within 1 PDO, maximum load at failure was significantly lower in the 4-twist group compared to the 1-twist group ($p=0.005$). There were no other significant differences in maximum load at failure between knot types.

For 3-0 Monoderm **(Figure 4A)**, maximum load at failure was significantly lower in the 4-twist group, when compared to the starting ($p=0.004$), 0-twist ($p<0.001$), and 1-twist groups ($p<0.001$). For 2-0 Monoderm, maximum load at failure was not significantly different between any group.

In the 3-0 Nylon group **(Figure 4B)**, maximum load at failure was significantly lower in the 0-twist ($p<0.001$), 1-twist ($p<0.001$), 4-twist ($p=0.001$), and the 10-twist ($p<0.001$) groups, when compared to starting group. For 2-0 Nylon, maximum load at failure was significantly lower in the starting group when compared to the 0-twist ($p<0.001$), 1-twist ($p<0.001$), 4-twists ($p<0.001$), or 10-twists ($p<0.001$).

When all suture types and sizes were compared to each other, there was no significant difference in maximum load at failure ($p=0.411$). However, when all 3-0 sutures were compared, there was a significant difference in maximum load at failure between the number of twists ($p<0.001$). The maximum load at failure was lower for four twists and ten twists when compared to the starting group ($p<0.01$). When all 2-0 sutures were compared, no significant difference existed in maximum load at failure.

Regardless of suture type or size, failure of the starting knot always occurred by breakage 1-mm from the knot. Knots with 0 twists, regardless of type or size, failed most commonly by breakage >2-mm from the knot, except for 2-0 Nylon, which failed more commonly by breakage at the knot (8/15, 53%). Knots with 1 twist, regardless of size or type, were more likely to fail by breakage >2-mm from the knot. Knots tied with 4 or 10 twists did not have a consistent failure pattern. For knots with 4 twists, 0 PDO (10/15, 67%), 1 PDO (12/15, 80%), and 2-0 Nylon (9/15, 60%) were more likely to fail by breakage at the knot (**Table 2**). The remaining knots with 4 twists were more likely to fail >2-mm from the knot. Knots with 10 twists were more likely to fail by breakage at the knot, except 3-0 Monoderm, which more commonly failed by breakage >2-mm from the knot (10/15, 67%). All failure modes and percentages are depicted in **Table 2**.

Discussion

The purpose of this study was to determine whether axial twisting within the ending loop of a simulated continuous pattern would decrease maximum load at failure. There are no clear trends within the dataset, however it suggests that maximum load at failure is decreased when more twists are added to a loop when compared to knots without twists, particularly in larger suture. The first part of our hypothesis was that the load at failure would be less for sutures with more twists. Based on our data, we partially accept this hypothesis. The second part of our hypothesis was that mode of failure would not be different between knot configurations and we reject this hypothesis. The primary mode of failure of starting knots or knots with 0 or 1 twist within the knot was breakage of the suture away from the knot, regardless of size. However, the primary mode of failure occurred at the knot more commonly for larger suture sizes containing 4 or 10 twists within the ending loop.

Previous literature reports that axial twisting of suture during normal wrist motion of the surgeon can lead to weakening of the suture strand.[5] Twisting up to 4 times was not thought to weaken a suture strand, however twisting up to 10 times was shown to decrease tensile strength of suture.[5,6,11] By the natural motion of the surgeon's wrist while suturing, the suture can start to form curls or can twist on itself, and these may result in twisting of the loop of the ending square knot of a continuous suture strand. In some cases, the suture loop is not unwound, and the twisted suture is tied into the ending knot. We suspect that the decrease in maximum load at failure of the suture knots containing more twists could be due to the axial twisting of the ending loop, leading to compromise of the suture stand, similar to that seen in prior studies.[5,6]

Research devoted to understanding various knot configurations is lacking. A study comparing square and surgeons knots with sliding knots showed that the former had superior knot security.[14] When performing the current study, it was thought that because of the twists within the ending loop, the ending square knot would not be as secure as a standard starting knot or a knot without any twists in the ending loop due to the inability of the knot to lay down on itself appropriately. As it may be possible that the twisting within the loop decreases the contact between the suture strands and thus friction the within the knot itself. Our data showed that increased twisting of the ending loop may lead to a higher likelihood of unraveling of the knot or failure at the knot during testing, particularly for larger suture sizes. The data in this report found that only 0 PDO, 1 PDO, and 2-0 Monoderm with 10-twists were more likely to fail at the knot, while the remaining suture and knot types were more likely to have a comparable maximum load at failure and breakage of the suture strand. The sutures more likely to fail at the knot when more twists are applied had a larger gauge and because monofilament, synthetic suture tends to have more memory than multifilament sutures, this may lead to decreased ability to tighten down the knot securely,[15,16] leading to increased likelihood of failure at the knot. Thus, when twists are added, this may further decrease knot security due to the inability of tightening the knot appropriately. Suture with a smaller bore, although twisted, still has relatively strong knot security, as it is easier to tighten the knot appropriately. Because Nylon is a nonabsorbable monofilament, it will undergo very little to no plastic deformation before failure.[17] This likely contributed to the decreased failure at the knot as the suture will not undergo deformation within the knot, as may happen with monofilament absorbable sutures.

A major limitation of this study was difficulty in mimicking the axial twisting of suture, as would occur during surgery. Therefore, although our data may suggest that increased number of twists within the ending loop of larger suture will decrease maximum load at failure and increase the likelihood of failure at the knot, it is assumed that a suture that has been axially twisted is weaker than suture that has not been twisted. Because the current study was simply focused on axial twisting within an ending loop, we cannot comment on the effect of axial twisting on the strength of suture. Therefore, ending loops that are unraveled may still be weaker than those without any twisting. An additional limitation may be the removal of the suture and knot from the PVC pipe prior to testing, as the movements necessary to remove the suture from the pipe may make the knot more prone to slippage.[18] Cyclic testing was not considered in this study as single distraction tests are more commonly performed and selection of testing protocol for this study was based on prior studies.[5,6,10,16] However, cyclic loading may be a more accurate way of testing suture and should be considered for future studies. Lastly, a tension gauge was not used when tying sutures, so sutures were not tied with the exact same tension applied to more closely reflect what occurs in a clinical setting.

In conclusion, when finishing a continuous pattern, the number of twists within the ending loop may not increase the risk of failure at the knot, however it can decrease the maximum load to failure at a knot, particularly as the suture size increases. Therefore, care should be taken not to twist suture when handling.

Tables

Table 1: Evaluation of average maximum load to failure (N) for each suture size and knot configuration.

Suture	Twists	Average maximum load at failure (N)	Standard deviation (±N)
1 PDO	0	118	13.9
	1	123	7.8
	4	116	4.5
	10	113	19.9
0 PDO	0	93	3.9
	1	78	24.5
	4	87	5.4
	10	87	5.8
2-0 PDO	0	71	7.3
	1	70	4.5
	4	67	9.5
	10	63	3.9
3-0 PDO	0	51	4.4
	1	49	4.3
	4	43	1.9
	10	45	2.9
2-0 Monoderm	0	90	9.9
	1	93	8.1
	4	87	7.1
	10	84	6.6
3-0 Monoderm	0	61	4.5
	1	60	4.1
	4	52	6.0
	10	57	5.1
2-0 Nylon	0	58	4.1
	1	57	7.2
	4	58	2.6
	10	60	2.3
3-0 Nylon	0	40	5.2
	1	36	3.4
	4	40	2.2
	10	38	3.5

Table 2: Evaluation of failure mode and percent of failure within each group (%) and average maximum load at failure (N) for each suture size and knot configuration.

Suture	Twists	Failure mode and % failure at knot; suture (<1-mm); suture (>2-mm)	Average maximum load at failure (N)
1 PDO	0	5/15 (33%); 0/15; 10/15 (67%)	118
	1	4/15 (27%); 2/15 (13%); 9/15 (60%)	123
	4	12/15 (80%); 0/15; 3/15 (20%)	116
	10	12/15 (80%); 0/15; 3/15 (20%)	113
0 PDO	0	1/15 (7%); 0/15; 14/15 (93%)	93
	1	3/15 (20%); 0/15; 12/15 (80%)	78
	4	10/15 (67%); 0/15; 5/15 (33%)	87
	10	15/15 (100%); 0/15; 0/15	87
2-0 PDO	0	5/15 (33%); 3/15 (20%); 7/15 (47%)	71
	1	3/15 (30%); 0/15; 12/15 (80%)	70
	4	3/15 (20%); 8/15 (53%); 4/15 (27%)	67
	10	8/15 (53%); 0/15; 7/15 (47%)	63
3-0 PDO	0	4/15 (27%); 0/15; 11/15 (73%)	51
	1	5/15 (33%); 0/15; 10/15 (67%)	49
	4	2/15 (13%); 0/15; 13/15 (87%)	43
	10	8/15 (53%); 0/15: 7/15 (47%)	45
2-0 Monoderm	0	2/15 (13%); 0/15; 13/15 (87%)	90
	1	4/15 (27%); 1/15 (7%); 10/15 (67%)	93
	4	1/15 (7%); 0/15; 14/15 (93%)	87
	10	6/15 (40%); 0/15; 9/15 (60%)	84
3-0 Monoderm	0	1/15 (7%); 0/15; 14/15 (93%)	61
	1	4/15 (27%); 0/15; 11/15 (73%)	60
	4	5/15 (33%); 0/15; 10/15 (67%)	52

	10	6/15 (40%); 0/15; 9/15 (60%)	57
2-0 Nylon	0	8/15 (53%); 0/15; 7/15 (47%)	58
	1	6/15 (40%); 0/15; 9/15 (60%)	57
	4	9/15 (60%); 0/15; 6/15 (40%)	58
	10	9/15 (60%); 0/15; 6/15 (40%)	60
3-0 Nylon	0	6/15 (40%); 3/15 (20%); 6/15 (40%)	40
	1	4/15 (27%); 0/15; 11/15 (73%)	36
	4	4/15 (27%); 3/15 (20%); 8/15 (53%)	40
	10	8/15 (53%); 0/15; 7/15 (47%)	38

Figures

Figure 1: Illustration of how sutures were tied around PVC pipe: A) Ending loop with no twists prior to being tied. B). Ending loop with single twist. C) Ending loop with 4 twists. D) the final product for each knot conformation.

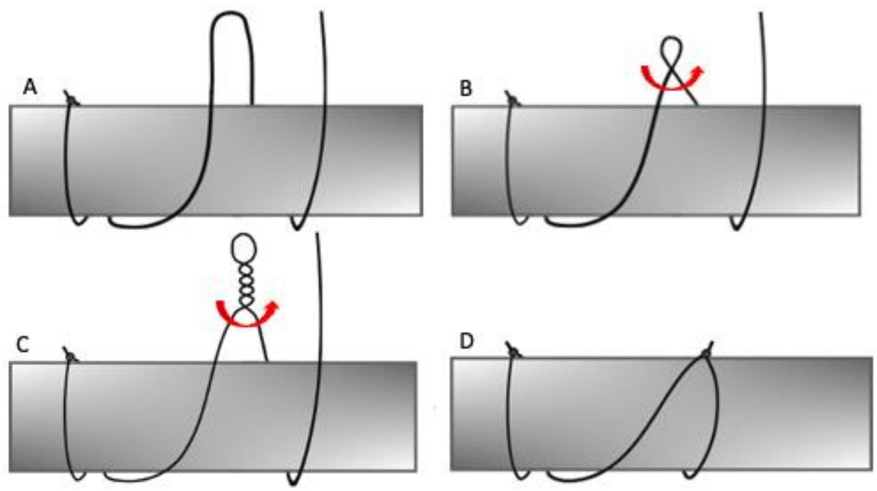


Figure 2: The Instron with the suture loop wrapped around the mobile beam (top) and the stationary beam (bottom) just prior to distraction.

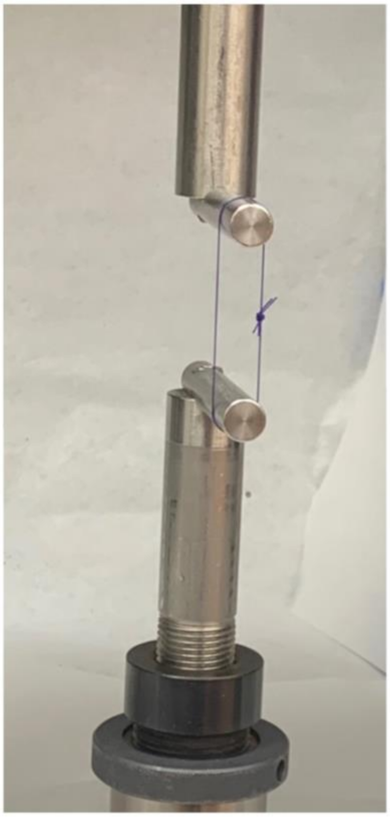


Figure 3: Comparison of maximum load at failure of all PDO sizes for each knot type: Within each suture size, columns with different superscripts have significantly different maximum load.

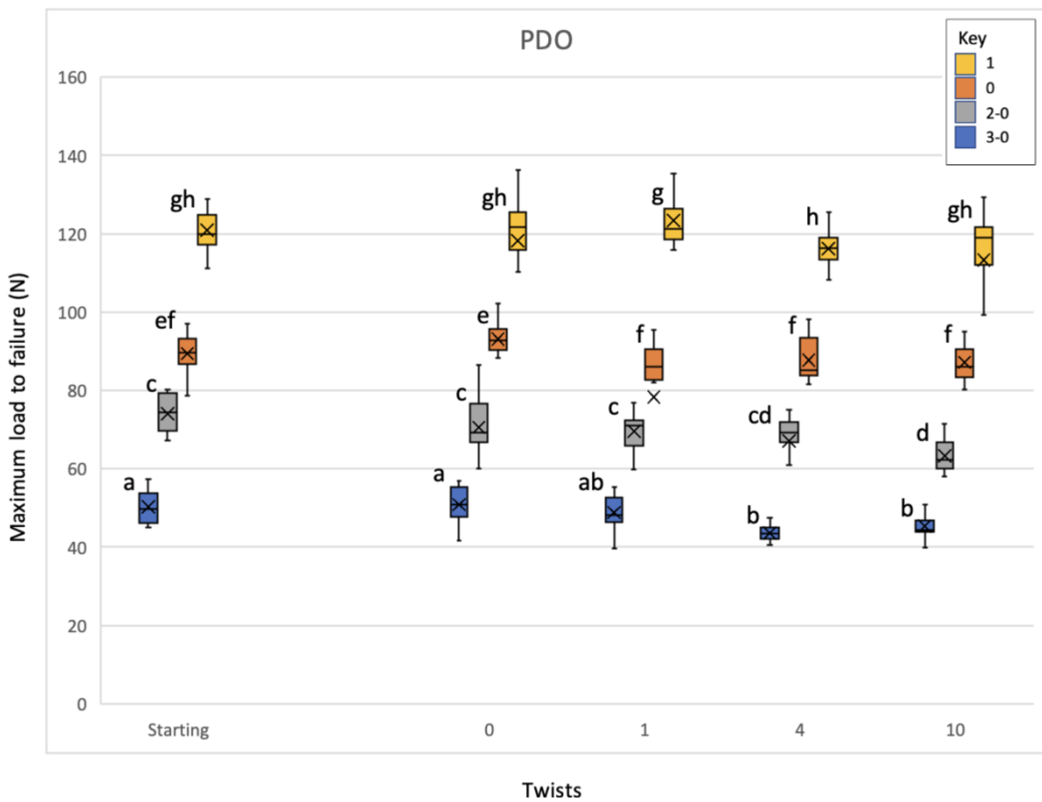
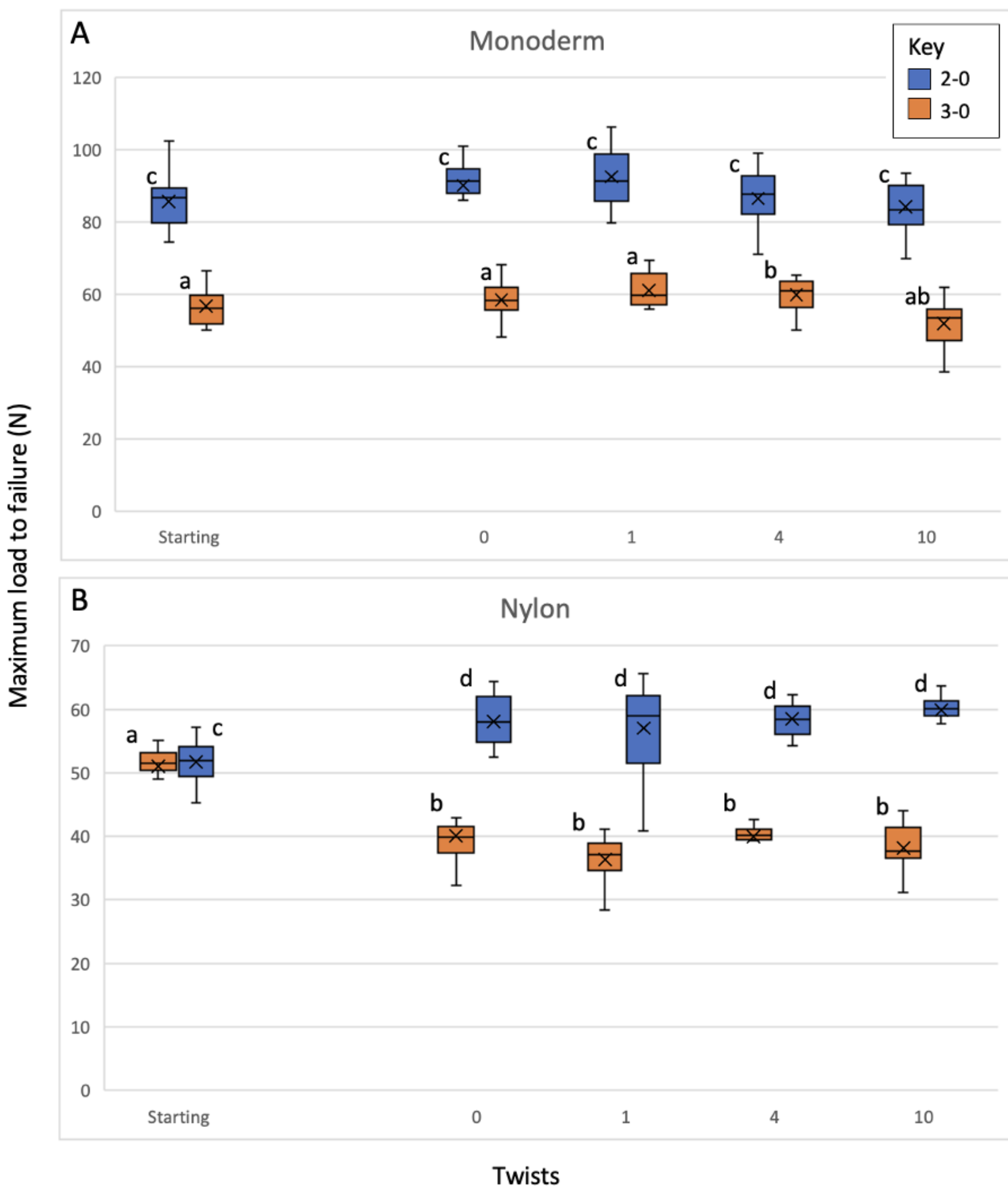


Figure 4: A) Comparison of maximum load at failure of all Monoderm sizes for each knot type. Within each suture size, columns with different superscripts have significantly different maximum load. B) Comparison of maximum load at failure of all Nylon sizes for each knot type. Within each suture size, columns with different superscripts have significantly different maximum load.



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