Umut Akgun
Mustafa Karahan
Pietro S. Randelli
João Espregueira-Mendes
Editors

Knots in Orthopedic Surgery

Open and Arthroscopic Techniques

European Society of Sports Traumatology, Knee Surgery & Arthroscopy

ESSKA

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Any success I have had is thanks to my beloved Yasemin, Zeynep and Ali.

U.A.

Preface by Umut Akgun

Knots were being used since the beginning of human life. Mankind used different types of knots to survive in nature. In those years, many knots were described for constructing, fishing, climbing, and sailing. Perfection in tying knots saved many lives on the mountains and the sea. As an irreplaceable tool of civilization, it was also used in surgery.

Knot tying is an essential step in almost every orthopedic procedure. Knots are needed for a wide spectrum of procedures from a simple skin closure to a complex shoulder arthroscopy. Some textbooks cover few aspects of knots according to their scope. The aim of this book is to provide a complete source for orthopedic surgeons about knot tying from basic science to clinical practice.

Knot tying starts with correct selection of the material. In the first step, readers will learn the materials used in sutures and their biomechanical properties. The second step will be the essential biomechanics of knot tying and the failure modes. After completion of basics, readers will find a technical chapter including many open and arthroscopic knots. All knots are described in detail by a step-by-step manner including their clinical aspects, tips, and tricks. Readers can also find current literature regarding knots and suture materials.

We would like to thank the ESSKA Board and all the authors who made a great effort to bring this project to life. Let's tie some knots....

Umut Akgun
Istanbul, Turkey

Yasemin, Zeynep, Ali and Duman

Preface by Mustafa Karahan

Orthopedic sports surgery consists of various complex skills which would take years to acquire. Throwing a safe and secure knot is the most basic skill which could have a high cost if failed. Therefore, learning to throw an efficient knot early in residency is fundamental to having a successful surgical training. This book puts the basic science of surgical knots into spotlight, and through a variety of chapters, it effectively discloses the full technique behind open and arthroscopic knots.

Istanbul, Turkey — Mustafa Karahan

Preface by Pietro S. Randelli

Dear colleagues and readers,

Since long time ago, all surgeons approaching open or arthroscopic techniques had to face with knots.

The knot represents most of the time the conclusion of a successful procedure and even more one of the most delicate passages of surgical technique.

Thus, all of us recognize the importance of dominating this matter in order to treat in the best way our patients. I remember several overseas flights with a rope between my hands training about knots.

The sources to be updated and trained about knots are scarce, not clear, and incomplete. For this reason, when Prof. Karahan and Dr. Umut Akgun had the idea to write this book, I was honored to be included among the editors and to contribute to its concept and contents.

The book is divided into several parts. An initial basic science part is necessary to choose the right material for each surgery and to understand mechanical and biological properties of those materials. Then the open and arthroscopic techniques to manage knots are well described and finally a literature review is concluding the book.

The full Esska board is grateful to Prof. Karahan, Dr. Akgun, and Prof. Espregueira Mendes for this book and we hope you'll enjoy it.

Warm regards,

San Donato Milanese, Italy — Pietro S. Randelli

Preface by João Espregueira-Mendes

Education should lead the way to proficiency and take doctors to superior standards of medical care, contributing, therefore, to better outcomes for patients. This book is an asset for the noble mission of medical education and the advance of techniques within this particular and important field.

The readers will profit from it. Certainly, it will add substantial knowledge and leverage the acquisition of skills to achieve a more safe and effective intervention with the patients. The contents of this book are the result of a group of leading and skillful professionals that constantly seek for improvements within scientific research, clinical practice, and education. This drive for daily achievements and knowledge share is a warranty that, in the present and future, higher expectancies from society on medical performance are to be met.

I am grateful to all the contributors who carried into this book so much of hard work, talent, and commitment. It is very clear that the most important and inspiring compliment will be conveyed from all those who go a step further in their standard of care by getting acquainted with the content of the book.

Sincere congratulations to all.

Porto, Portugal

João Espregueira-Mendes

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Part I

Basic Sciences

1 Terminology

Simon Donell

When we hold back out of laziness, that is when we tie ourselves into knots of boredom
*(*Walter Annenberg *1908–2002, American Publisher)*

Knots are integral to orthopedics, not only as part of the repair of tissues but also as a component of traction equipment. A **stitch** or **suture** is a loop of thread or yarn resulting from the passing of a needle. In surgery its function is to hold or bind tissues together. For the suture to maintain its function, it is secured by a knot. The word "knot" has a number of meanings in the English language. It can be:

1. Fastening made by looping a piece of string, rope, etc. on itself and tightening it
2. Tangled mass in something
3. Knob, protuberance, or node in a stem, branch, or root
4. Unpleasant feeling of tightness or tension in a part of the body
5. Small tightly packed group of people
6. Unit of speed equivalent to one nautical mile per hour
7. Small, relatively short-billed sandpiper (bird)

The verb "to knot" can mean "to fasten with a knot," "to make something tangled," or "to cause a muscle to become tense and hard." A **surgical knot** clearly is a fastening made by a loop, although a suture can become tangled!

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1.1 History

It is not possible to weave cloth without a knowledge of knots. Knots are needed to make nets or sail a boat and for ancient man to build a house. In early times they were used for counting and by the Inca for record making and as a memory aid. They therefore predate history. Our knowledge of knots and the terms used come from sailing. A fishing net is a series of knots, and there are many types of knots and uses for them. Surgeons only need to know a few knots aimed at binding tissues together or sealing off hollow tubes.

Eyed needles for suturing have been found in archaeological sites dating from around 30,000 BC, but the first detailed description of knots was by the Greek physician Heraklas in the first century AD [1]. He wrote a book called *From Heraklas* that gives details of different knots that include (although named differently) the reef (square in the USA) knot, cow hitch, and clove hitch. He also described slings that were used for applying traction in fracture and dislocation reduction. Nowadays there are many hundreds of different knots described for various uses.

U. Akgun et al. (eds.), *Knots in Orthopedic Surgery*, https://doi.org/10.1007/978-3-662-56108-9_1

The reef knot is one of the oldest and is used for hand-tying ligatures (using single- or doubled-handed techniques). The first description of a surgeon's knot (a reef knot with an initial double turn) in the literature was in 1733 according to the *Merriam-Webster Dictionary* but does not give the reference. The surgeon's knot lends itself to an instrument-tying technique.

1.2 Components of a Knot (Fig. 1.1)

- The **bight** is the middle part of the suture and is any curved section, slack part, or loop between the ends. The term "in the bight" implies a U-shaped section of the suture which is itself being used in making a knot. Many knots can be tied either with the end or in the bight.
- The ends of a suture are known as the **limb or thread**. A suture has two independent limbs that are used to make a knot.
- A **loop** is a full circle formed by passing the working end over itself. The **elbow** is the two crossing points created by an extra twist in a loop. The diameter of the **loop** depends on the desired tissue approximation.
- The **standing end** (also called post limb) is the end not involved in making the knot, with the **standing part** being the section of suture between the knot and the standing end.
- The **turn** is a single pass behind or through an object. A round turn is the complete encirclement of the object and requires two passes. Likewise two round turns circle the object twice and require three passes.
- The **working end** (also called the working limb) is the end of the suture being used to make the knot. It is also called the "running end." The **working part** is the section between the knot and the working end.
- **Half hitch** is an incomplete knot formed by passing the working limb of a suture round its standing limb and then through the loop. It is generally used to tie the sutures on a fixed point such as an anchor. A single half hitch is not secure and can be easily untied.
- **A wrap** (also known as a throw) is formed by weaving one limb of the suture on the opposite limb. A knot is composed of various configuration of wrap or throws snugged firmly against each other.
- **Neck** is the transition points from the completed knot to the loop.
- **Ears** are the residual ends of a completed knot. Length of the ears may affect the security of the knot. Too short ears may decrease security, whereas too long ears may cause tissue irritation.

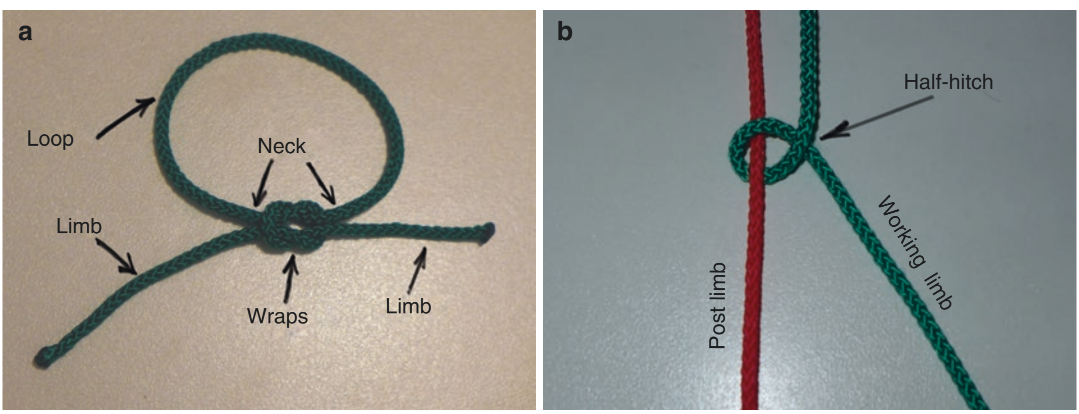

Fig. 1.1 Components of a square knot (**a**) and a half hitch (**b**)

1.3 Properties of Knots

1.3.1 Strength

Knots weaken the suture since the bending, crushing, and chafing forces that hold a knot in place also unevenly stress the suture fibers and ultimately lead to a reduction in strength. When a knotted suture is strained to its breaking point, it almost always fails at the knot or close to it, unless it is defective or damaged elsewhere. The relative knot strength, also called **knot efficiency**, is the breaking strength of a knotted suture in proportion to the breaking strength of the suture without the knot. Determining a precise value for a particular knot is difficult because many factors can affect a knot efficiency test such as the material it is made from, the style of suture, its size, whether it is wet or dry, how rapidly it is loaded, or whether it is repeatedly loaded. The efficiency of common knots ranges between 40 and 80% of the suture's original strength.

1.3.2 Security

Even if the suture does not break, a knot may still fail to hold. Knots that hold firm under a variety of adverse conditions are said to be more secure than those that do not. The main ways knots fail to hold are:

- **Slipping:** The load creates tension that pulls the suture back through the knot in the direction of the load. If this continues far enough, the working end passes into the knot and the knot unravels.
  Even with secure knots, slippage may occur when the knot is first put under real tension. Tightening the knot fully and leaving the suture ends long enough can reduce the risk of this.
- **Sliding:** In knots that are meant to grip tissues, failure can be defined as the knot moving relative to the gripped tissue. While the knot itself does not fail, it stops performing the desired function.
- **Capsizing:** To capsize (or spill) a knot is to change its form and rearrange its parts, usually by pulling on specific ends in certain ways. This does not typically apply to surgical knots but is important in sailing and climbing.
- **Sawing:** The friction between two strands of suture during the tying process. Excessive sawing weakens the material.
- **Loop security:** The ability of the suture loop to stay tight as the knot is being tied.
- **Knot security:** The maximum load the knot is able to support prior to breaking (fracture) or complete slippage. A perfect knot should hold till the suture breaks on the neck of the loop.

To be secure a knot must be properly placed. The security varies depending on the surgeon, the speed of tying, and the situation found. Differences are found between surgeons and within an individual surgeon's knots. In addition to knot security, the loop must also be secure [2]. The latter is different from knot security since a suture material with a large elastic elongation (low elastic modulus) can stretch, resulting in a loose loop even if the knot is completely secure. The ideal knot would be easy to tie and reproducible and would not slip or stretch before the tissue had healed. Other biomechanical terms that affect a tied knot are:

- Loop circumference: This can affect the tension force on the knot. A larger loop circumference can increase the force on the knot because of the longer force arms.
- Coefficient of friction: This is used to measure the resistive forces encountered within the suture limbs and between tissue during knot tying.
- Strength: This is the suture's resistance to breakage.
- Stiffness: This is the resistance to bending.
- Viscoelasticity: This is the deformation of the suture under strain which is reversible. This is usually important to compensate for tissue oedema as a result of tissue trauma.

- Abrasion resistance: This is the durability of the suture. Metallic anchor eyelets, instruments, and bone edges can easily damage the sutures. New-generation sutures have higher abrasion resistance.
- Creep: This is the deformation of a solid material under constant loads.

Other problems to consider include the load to failure, cyclic loading, yield load, and elongation. To understand fully the various processes that affect the tying of a specific material and create strong and efficient knot needs detailed biomechanical investigation and analyses. Suffice it to say, understanding the basic principles is all that is needed for the clinician.

1.3.3 Knot Handling

The ease of tying a knot depends on a number of factors related to the construction of the suture material. The suture material chosen should optimise the combination of strength, uniformity, and hand:

- **Hand** relates to the feel of the suture in the surgeon's hand along with the smoothness of its passage through tissue, the ease of tying and snugging it down, and the final firmness of the knot.
- **Extensibility** is the amount of stretch during knot tying and its recovery after the release of the strain. This allows the surgeon to feel when the knot is snug.
- **Memory** is the property of the synthetic monofilament sutures to return to their original shape. This depends on the manufacturing extrusion process and the packaging.

1.3.4 Material

Sutures can be monofilament or multifilament, smooth or braided (twisted), and made of natural or artificial materials. The braided multifilament sutures are easier to tie as they have a high coefficient of friction and the knot remains in place are releasing the tension. Monofilaments have a low coefficient of friction, and so the knot tends to loosen on release as a result of its memory.

- **Monofilament:** Describes a suture made of a single strand or filament.
- **Multifilament:** Describes a suture made of several braided or twisted strands or filaments.
- **Absorption rate:** Measures how quickly a suture is absorbed or broken down by the body. It refers only to the presence or absence of suture material and not to the amount of strength remaining in the suture.
- **Breaking strength retention (BSR):** Measures the tensile strength retained by the suture *in vivo* over time.
- **Tensile strength:** The measured kilograms of tension that a suture can withstand before breaking.

1.4 General Principles of Knot Tying

Certain principles apply to the tying of all knots and suture materials.

- **Tie the knot firmly** so that slipping is virtually impossible. The simplest knot for the material should be chosen.
- **Keep the knot as small as possible** to prevent an excessive amount of tissue reaction when absorbable sutures are used or to minimise foreign body reaction to nonabsorbable sutures. Ends should be cut as short as possible but not so short as to risk loosening.
- **Avoid sawing**; the friction between the strands of suture.
- **Avoid damaging the suture material**. Avoid the crushing or crimping by the surgical instruments except when grasping the free end of the suture.
- **Avoid excessive tension**; otherwise, it will cause suture breakage and may cut the tissue. Practice in avoiding excessive tension leads to successful use of finer-gauge materials.

- **When approximating tissues do not tie too tightly**; this may cause tissue strangulation.
- **Maintain tension on one end of the suture after the first loop is tied**. This avoids loosening of the throw if being tied.
- **Make the final throw as nearly horizontal as possible**.
- **Change stance or position in relation to the patient in order to place a knot securely and flat**.
- **Extra ties do not add to the strength of a properly tied knot**; they only contribute to its bulk.
- **Pull the two ends of the suture in opposite directions with uniform rate and tension**; the knot will then be tied more securely. This maneuver can be done on square and surgeon's knot, not on the slip knots.

1.5 Types of Knots

The basic knots used in orthopedic surgery are:

1.5.1 Static Knots

In these knots, surgeon should keep the initial tissue tension between throws in order to prevent loosening. This can be achieved by the help of a surgical instrument or increasing the number of wraps.

- **Reef (square) knot:** used to tie the two ends of a single line together such that they will secure something that is unlikely to move much (Fig. 1.2).
- **Surgeon's knot:** a simple modification to the reef knot. It adds an extra twist when tying the first throw, forming a double overhand knot. The additional turn provides more friction and decreases loosening while the second half of the knot is tied.

Note: the granny knot can be confused with square knot. It has a different combination of throws and is mechanically inferior to the square knot (Fig. 1.2).

Other knots have been described, e.g., the two-strand-overhand locking (TSOL) [3], but are not in general use. Some static knots can be changed into a slip not by a simple maneuver. For example, tensioning one limb of a square knot forms a slip knot which consists of two half hitches (Fig. 1.3).

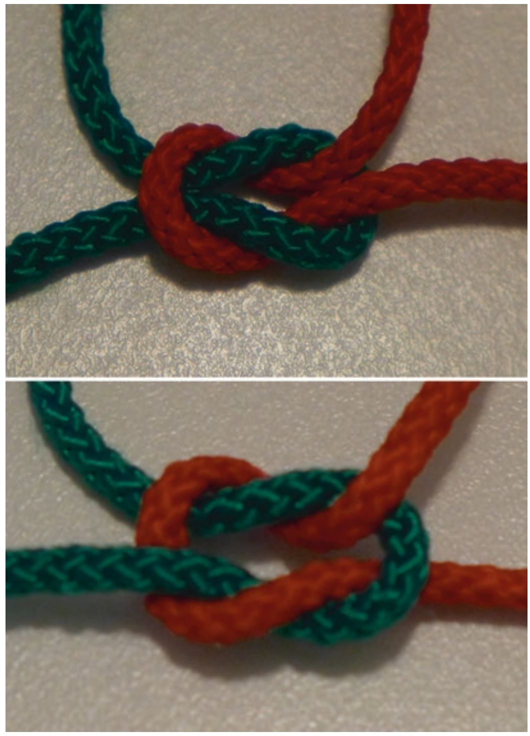

Fig. 1.2 Square knot (above) versus granny knot (below). Square knot has a symmetrical configuration, whereas granny knot is asymmetrical

Besides sutures with knots, a number of devices and products are available to oppose tissues that avoid the use of knots. These can be, for instance, barbed suture material, staples, fibrin glue and knotless suture anchors mostly used in arthroscopic procedures [4].

1.5.2 Slip Knots

These knots have a dynamic configuration; it is possible to adjust the tension while making the knot. Various combinations of half hitches are used in these knots. They are generally used for binding rope to an object.

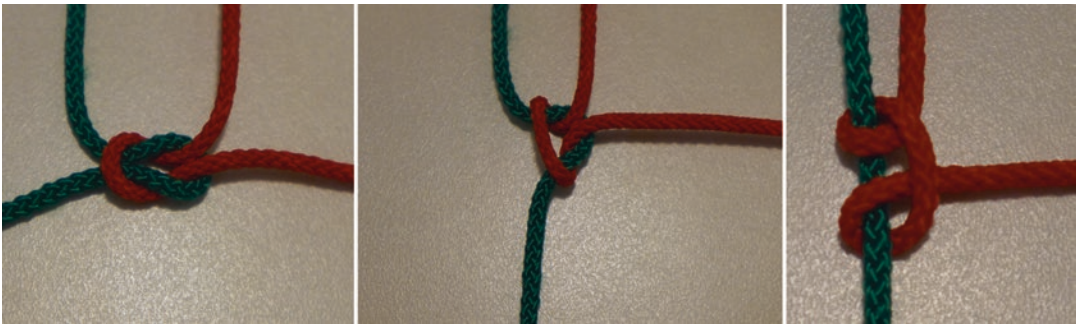

Fig. 1.3 Left to right, pulling green limb of the square knot forms two half hitches on green limb

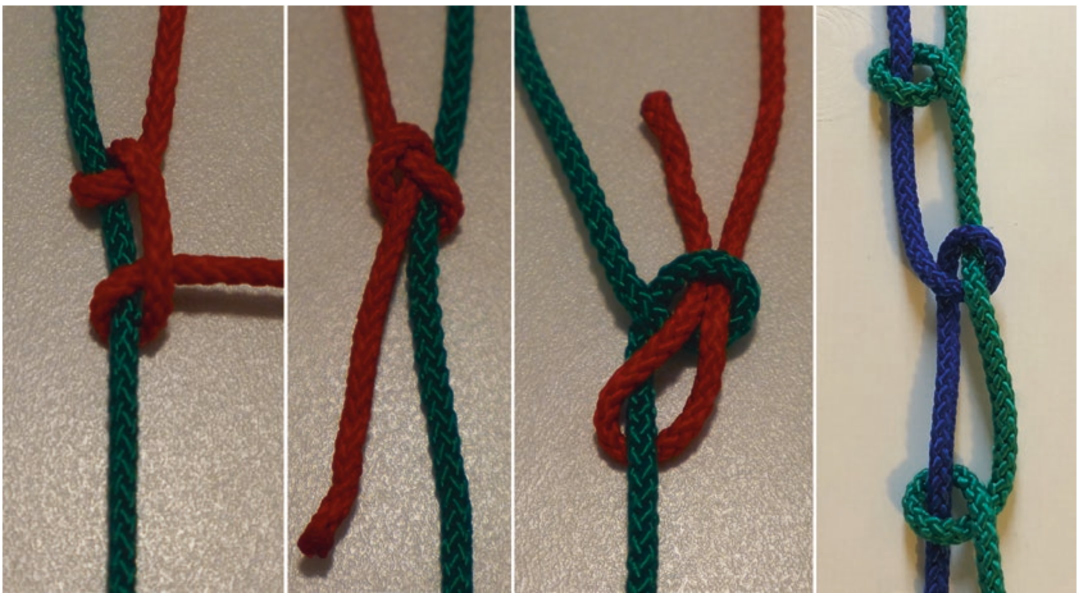

Fig. 1.4 Various slip knots. Left to right: half hitches on the same post (*above is overhand*; *below is underhand*), traction knot, bowline, half hitches on alternating posts

- **Over- and underhand half hitches** are basic hitches that can be used to form different slip knots (Fig. 1.4).
- **Traction knot** is a simple knot that can be used for traction. It looks like a simpler form of a bowline (Fig. 1.4).
- **Bowline** is a very simple knot that creates a fixed loop at the end of a rope. It is easy to tie and untie even after being loaded. Its importance is reflected by some calling it the "King of knots" (Fig. 1.4).
- **Revo** is a well-known arthroscopic knot which consists of five half hitches (Fig. 1.4).

1.5.3 Stoppers

This is a special subgroup of knots that are mainly used to make a bulk on the end of a rope. They can be used to block the passage of the free end of a suture through a hole on a bone or an implant.

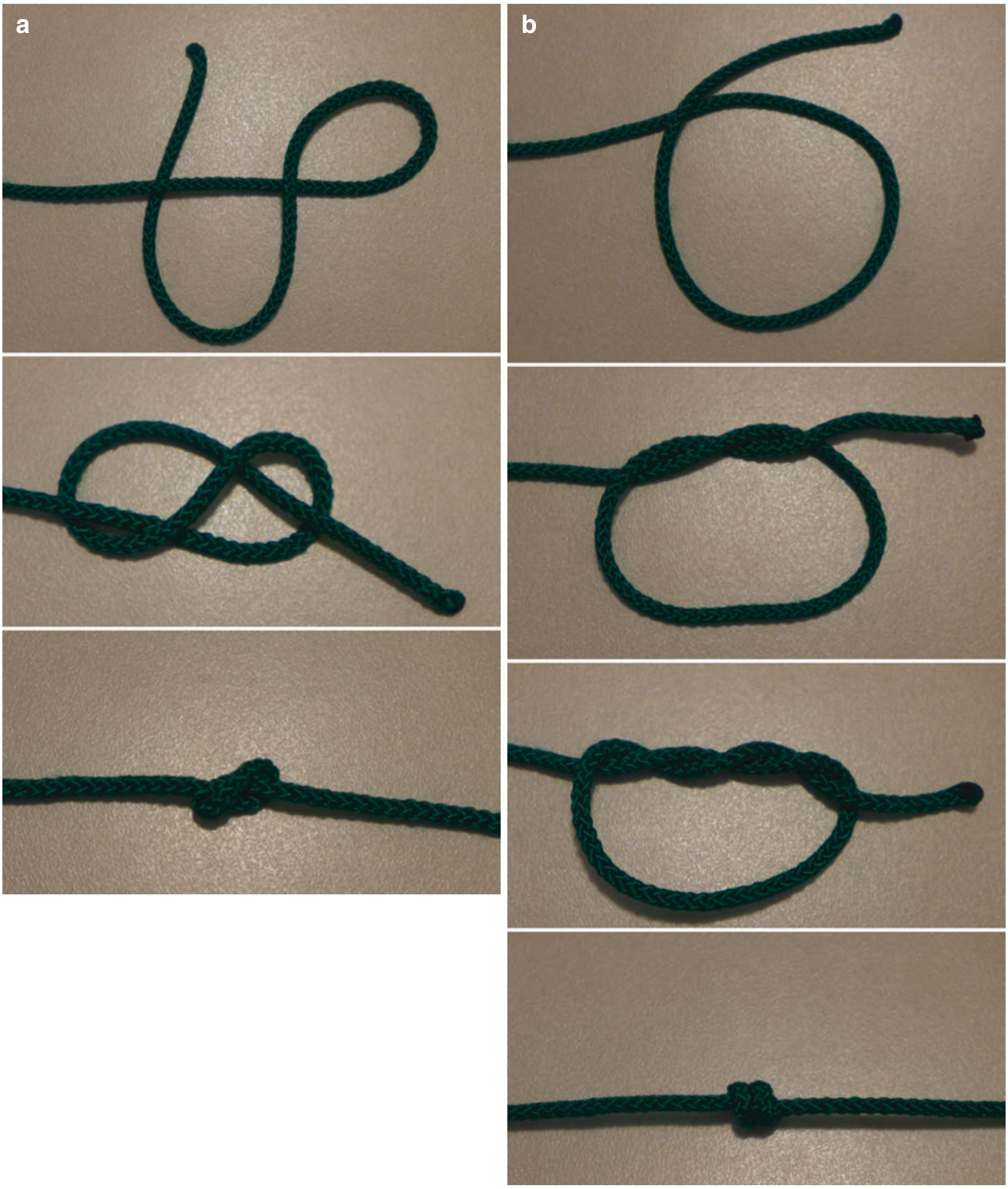

Fig. 1.5 Various stopper knots. (**a**) Figure of eight, (**b**) double overhand

- **Figure-of-eight knot** (Fig. 1.5).
- **Double overhand knot** (Fig. 1.5).

1.5.4 Bends

These knots are used to bind free ends of two different ropes (Fig. 1.6).

Knots are a key surgical skill. An understanding of the types and their uses, the importance of the suture materials used, and the manual skills to apply them are fundamental for a successful outcome from an operation. However, as Mahar et al. noted [5], despite differences between knot types, surgeons should use the type of knot they are most comfortable with, rather than attempt a knot with which they are unfamiliar in an effort to maximise security.

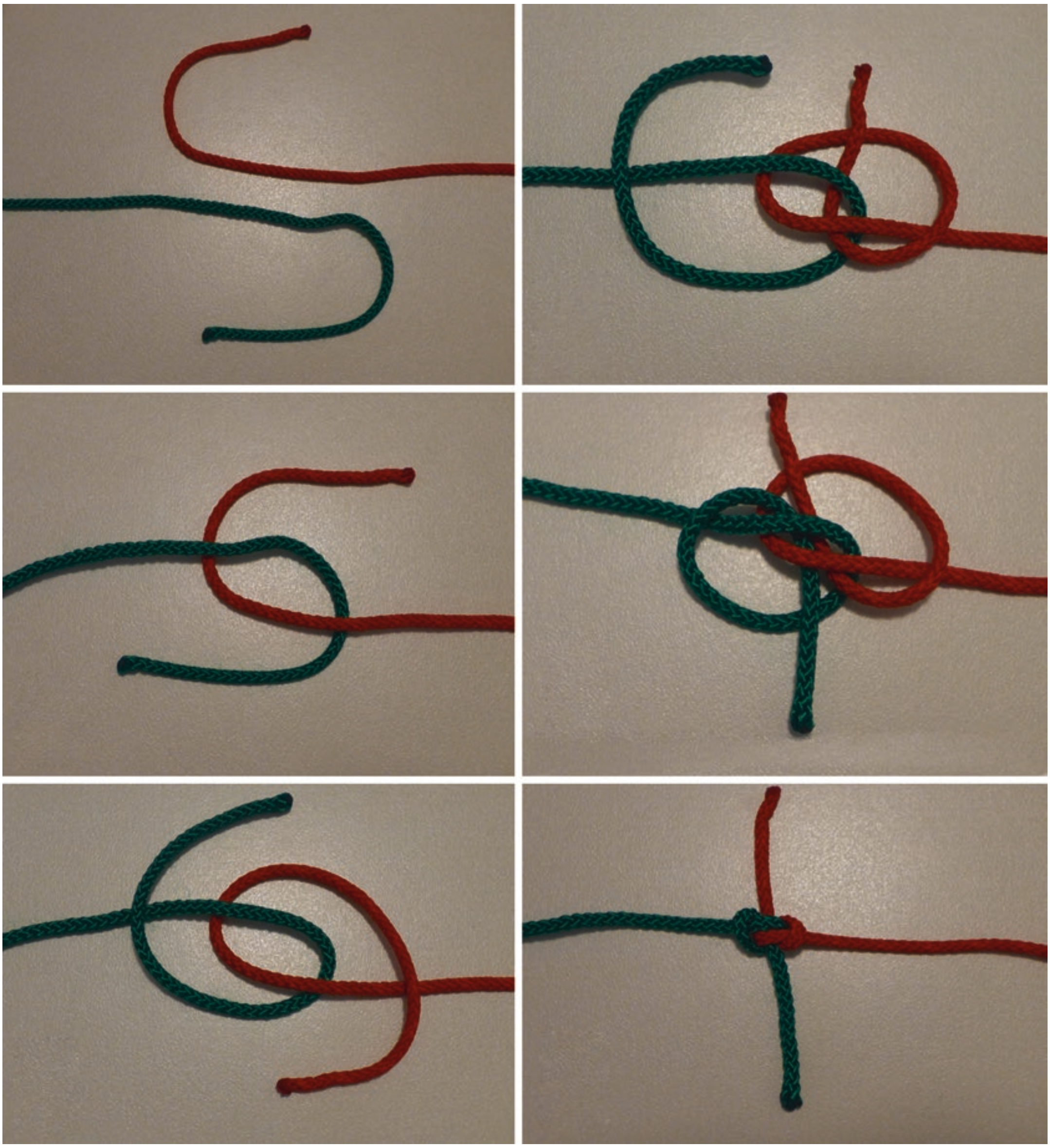

Fig. 1.6 Hunter's bend that can be used to bind free ends of two different ropes

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2 Biological Properties of Suture Materials

Onur Başçı, Umut Akgun, and F. Alan Barber

Suture is a general term for all materials used to stitch torn tissues. Sutures can be synthetic or natural and have a monofilament or braided construction. Through the history of mankind, various materials were tried to serve this purpose. Plants such as flax, hemp, and cotton and animal tissues such as hair, tendon, silk, and intestines are some examples. The oldest, known suture was on a mummy in ancient Egypt on 1100 BC, and the first written description on surgical wound suturing belongs to the Indian physician Sushruta in 500 BC.

In this chapter, the biological properties of commonly used suture materials will be discussed. Sutures may cause different host reactions in living tissues. While the suture remains in the tissue, it can trigger the inflammation cascade through different pathways such as degradation, a foreign body reaction, an allergic reaction, or abrasion. Sutures can remain inert, be partially degraded, or be totally degraded by the host. The amount of degradation is dependent upon the absorbability of the specific suture material. Generally a suture that loses its tensile strength within 60 days is considered absorbable. However, the new generation of absorbable suture materials may hold their tensile properties far beyond this limit. The absorption rate may vary due to the suture composition or the tissue sutured. Host reactions and infection also affect the absorption process. Nonabsorbable sutures do not biologically degrade but can also lose their integrity over time. Sutures that are commonly used in orthopedic procedures are listed in Table 2.1.

The biological response of the local tissues against sutures can be influenced by different factors (Table 2.2). The suture material and its absorbability, configuration, and size in particular are important. Natural materials such as catgut and silk are more immunogenic than synthetic materials because they are degraded by proteolysis in contrast to synthetic sutures, which are degraded by hydrolysis. Hydrolysis is a less immunogenic process compared to proteolysis. Nonabsorbable sutures cause less inflammation in contrast to absorbable sutures and usually induce a fibrous layer formation around the suture, which prevents a host response. More irritation is seen with braided suture than with monofilament sutures. This can be explained by the surface topography of the suture. The smooth texture of monofilaments causes less response in

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Table 2.1 Biological and structural properties of common sutures used in orthopedic procedures

	Brand name	Material	Architecture
Absorbable	Dexon	Polyglycolic acid	Monofilament or braided
	Dexon II	Dexon coated with polycaprolate	Monofilament or braided
	Vicryl, polysorb	Polyglactic acid—polyglactic 910	Braided
	Vicryl rapide	Different form of polyglactin 910	Braided
	PDS	Polyester poly (*p*-dioxanone)	Monofilament
	Maxon	Polyglyconate	Monofilament
	Caprosyn	Polyglytone P6211	Monofilament
	Panacryl	Caprolactone/glycolide	Braided
	Monocryl	Poliglecaprone 25	Monofilament
	Phantom fiber	Poly-4-hydroxybutyrate	Braided
Partially absorbable	OrthoCord	UHMWPE and polydioxanone	Braided
Non-absorbable	Ethibond	Polypropylene	Braided
	Ethilon	Aliphatic polymers Nylon 6 and Nylon 6,6	Monofilament
	Fiber wire	UHMWPE core with a braided jacket of polyester and UHMWPE	Braided
	Force fiber	UHMWPE	Braided
	HiFi	UHMWPE	Braided
	MagnumWire	UHMWPE	Braided
	MaxBraid	UHMWPE	Braided
	Prolene	Polypropylene	Monofilament
	TiCron	Polyester	Braided
	UltraBraid	UHMWPE	Braided

Table 2.2 Effect of suture properties on local tissue reactions

	Local tissue reaction	
	Less	More
Material of the suture	Synthetic	Natural
Architecture of the suture	Monofilament	Braided
Picks per inch in braided suture	More	Less
Twist angle in braided suture	High	Low
Size of the suture	Thinner	Thicker
Type of suture	Non-absorbable	Absorbable

the host. As discussed later in the text, the internal architecture of braided suture is another variable that may cause abrasion to the host tissue. Regardless of the material, as the suture size increases so does the tissue reaction. In addition, a true allergic response to a suture material may also occur. Foreign proteins found in natural materials usually trigger this type of response.

Choosing the most appropriate suture for a specific surgery is a very important issue. Any biological response to the suture material should be limited because exuberant inflammatory reactions delay or prevent tissue healing, cause scar formation, and predispose to infection.

2.1 Nonabsorbable Sutures

Common nonabsorbable sutures used in orthopedic procedures are listed in Table 2.1. Natural materials like silk are not routinely used in orthopedic surgery because their foreign proteins can cause severe reactions. Nowadays the sutures most commonly used in orthopedic procedures are synthetic. Synthetic sutures can be divided into two groups: monofilament and braided. In monofilament group, Prolene and nylon are generally used for soft tissue approximation, nerve, and vascular repairs. Braided sutures in orthopedic surgery are generally used for tendon and ligament repairs and bone fixations. Until the development of ultrahigh molecular weight polyethylene (UHMWPE) suture materials, braided polyester sutures such as Ethibond were commonly used for these procedures. Nowadays different UHMWPE-containing sutures are preferred for tendon and ligament repairs due to their high strength and handling characteristics.

Nonabsorbable sutures used in orthopedic procedures seldom cause significant host reactions. However they are not trouble free. Some of these include tissue abrasion, infection, and foreign body and allergic reactions.

Abrasion is a mechanical irritation causing tissue inflammation. The architecture of the suture is the main factor in abrasion. Monofilament sutures are made of a single strand, whereas multifilaments are composed of several strands and usually braided. Nonabsorbable monofilament sutures such as Prolene (Ethicon, Somerville, NJ) made of polypropylene and Ethilon (Ethicon, Somerville, NJ) made of long-chain aliphatic polymers Nylon 6 and Nylon 6,6 cause minimal abrasion because of their smooth surface. However most of the braided sutures do cause some degrees of abrasion due to their surface topography [1, 2]. Braided sutures are woven by twisted strands. Physical characteristics such as picks per inch (PPI) and the twist angle of these strands affect tissue abrasiveness [3] (Fig. 2.1). As the PPI and twist angle decrease, abrasion of the tissue increases [3]. Williams et al. reported that the latest generation high-strength sutures such as FiberWire, Phantom Fiber BioFiber, Collagen Coated FiberWire, and Ti-Cron are more abrasive than OrthoCord, Force Fiber, MaxBraid, and UltraBraid [3]. Some braided sutures are coated with Teflon, silicone, or wax to improve knot tying. These coatings may also affect the abrasiveness of sutures.

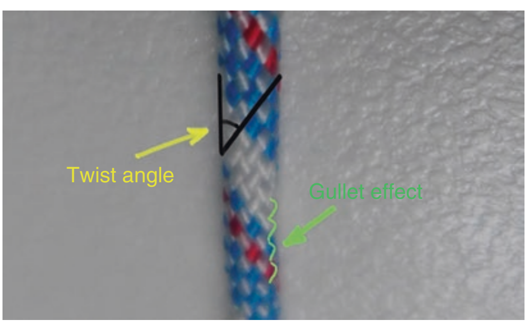

Fig. 2.1 In a suture with fewer external fibers (lower PPI), fibers must take a steeper angle to cover an inch of suture (lower twist angle). Lower twist angle creates a deeper groove between each bundle, like an increased gullet depth on a saw blade

Suture architecture may also cause an increased predisposition toward infection. Fowler et al. showed bacteria adhere less to monofilament sutures than to braided ones. The authors reported that a barbed monofilament suture (Quill) caused less bacterial adherence compared to Vicryl and Vicryl Plus braided absorbable sutures [4]. This suggests that monofilament suture might be better suited for use in surgical areas which are prone to infection.

Adverse events are occasionally reported with nonabsorbable sutures. A foreign body reaction is an early physiological response seen in all types of sutures. Microscopically an inflammatory zone forms around the suture composed predominantly of multinucleated giant cells [5]. While a normal healing response, this response in some cases becomes severe and may result in aseptic drainage. More intense foreign body reactions are commonly seen with absorbable sutures [6]. Esenyel et al. showed that a foreign body reaction is more severe with braided polyester than polypropylene and polyethylene suture [5]. In an experimental study, Carr et al. compared foreign body reactions for eight different braided sutures [7]: Ethibond (Ethicon, Somerville, NJ), Ti-Cron (Tyco, Waltham, MA), HiFi (Linvatec, Largo, FL), UltraBraid (Smith & Nephew, Memphis, TN), MaxBraid (Biomet, Warsaw, IN), OrthoCord (Mitek, Raynham, MA), MagnumWire (Opus Medical, San Juan Capistrano, CA), and FiberWire (Arthrex, Naples, FL). These authors reported that MagnumWire and Ti-Cron demonstrated a more intense inflammatory response than the others in a rabbit model.

Rarely delayed allergic reactions can occur. In a case report, Al-Qattan and Kfoury reported a delayed allergic reaction to polypropylene in a flexor tendon repair [8]. In this special entity, patients usually do not have a history of allergy to sutures. In delayed allergic reactions, the main histopathological findings are foamy histiocytes, lymphocytes, and plasma cells. A skin test is needed to confirm the diagnosis [8]. Suture removal is usually required for resolution.

For nonabsorbable sutures, monofilaments such as nylon and Prolene cause less host reaction than braided sutures like Ethibond or the new generation of UHMWPE-containing sutures. Natural materials such as silk can cause severe foreign body reaction because of their foreign proteins.

2.2 Absorbable Sutures

Absorbable sutures degrade over time and therefore have a complex interaction with the host tissue. Depending upon the material, the time needed for degradation may be as little as 6 days up to several months. Other factors affecting the time needed for suture degradation are the presence of infection and the surgery site. Since the historical catgut suture, many synthetic absorbable sutures have been developed. The common absorbable sutures used in orthopedic surgery and their characteristics are listed below.

2.2.1 Older Materials (Chromic, Gut)

Catgut was the first absorbable suture. It is made by twisting together purified strands of collagen taken from the submucosal or serosal layers of healthy ruminants' (sheep, cattle, and goats) small intestine or beef tendon. Amino and carboxyl groups of collagen are sensitive to pH levels. Alterations in tissue pH may weaken the fiber structure, further causing loss of strength and mass in highly acidic and alkaline conditions. Thus, the strands are treated with formaldehyde to resist the pH alterations and enzymatic attack and twisted together forming the "plain gut" suture. When further processed with chromium trioxide, "chromic gut" is created which is more resistant to absorption and has less tissue reaction.

The plain gut suture retains its tensile strength for 7–10 days and fully absorbs over 60–70 days. In contrast, chromic gut retains its tensile strength for 10–14 days. Fast-absorbing gut is created when plain gut suture is heated to begin the collagen breakdown within the suture prior to use. This suture retains its tensile strength for 3–5 days [9].

2.2.2 Newer Materials

(a) Polyglycolic acid (Dexon), (Dexon II Bicolor): Polyglycolic acid was the first synthetic absorbable suture polymerized either directly or indirectly from glycolic acid. Because of its predictable absorption characteristics and low tissue reaction, it often replaced the use of catgut [10]. It maintains 89% of its tensile strength at 7 days, 63% at 14 days, and 17% at 21 days [11]. Full absorption of polyglycolic acid is reported to occur in 90–120 days [12, 13]. Due to hydrolytic absorption, Dexon has minimal tissue reaction, compared to surgical gut which is degraded by proteolytic enzymes [13]. Polyglycolic acid is available as in a monofilament and a braided form as well as either coated or uncoated. Dexon II is the polycaprolate coated form allowing for easier handling and smoother knot tying. The coating also decreases the risk of bacterial colonization [14]. Dexon sutures were also shown to maintain vascular integrity long enough to permit healing of small canine femoral vein grafts and performed well compared to Prolene [15].

(b) Polyglactic acid (polyglactin 910), (Vicryl, Polysorb): Polyglactin 910, a copolymer of glycolide and L-lactide, is a synthetic braided suture material mainly introduced to take the place of polyglycolic acid. The high concentration of the glycolide monomer in polyglactin 910 (90:10 molar ratio of glycolic to levo-lactic acids) is crucial in maintaining the mechanical and degradation properties. The level of crystalline or amorphous structures impacts the tensile force and retention rate of the suture [13, 14, 16]. Less amorphous structures result in longer strength retention times and stronger tensile properties in sutures.

The primary absorption of polyglactin 910 occurs by hydrolysis. Because of its hydrophobic properties, polyglycolic acid maintains 75% of its strength at 2 weeks and 50% at 3 weeks [13]. It is totally absorbed between 60–90 days [17]. The commercially available polyglactin 910 is either dyed or undyed. If the violet or dyed version is used, cutaneous applications should be avoided because the colored suture may be visible clinically [18]. A lubricant coated form with polyglactin 370 and calcium stearate is also available to ease tissue passage. Vicryl Rapide is another form of polyglactin 910 for cutaneous usage. This suture is a partially hydrolyzed form and does not need to be removed because it is spontaneously absorbed within 7–14 days [19].

(c) Polydioxanone (PDS): Polydioxanone (PDS II®) is a monofilament polymer manufactured from the polyester poly(*p*-dioxanone). The prolonged tensile strength of PDS is its most important advantage over polyglycolic acid (Dexon) and polyglactin 910 (Vicryl) [20]. PDS maintains 74% of its tensile strength at 2 weeks, 50% after 4 weeks, and 25% after 6 weeks [21]. Traces of buried polydioxanone have been found in 6-month postimplantation histologic preparations [22]. The primary usage of PDS is for tendon repair. Because of its slower degradation, it has a low tissue reactivity maintaining its integrity even in the presence of an infection [19]. As a monofilament suture, it retains packaging memory and can remain relatively stiff and present difficulties during knot tying [20, 22]. In subcuticular suturing, polydioxanone was associated with a lower incidence of hypertrophic scar formation compared to polypropylene, nylon, and polyglycolic acid [23].

(d) Polyglyconate (Maxon): Polyglyconate is a synthetic, monofilament absorbable suture material that is a copolymer of glycolic acid and trimethylene carbonate. It is superior to PDS providing a more supple suture handling and smooth knot formation while at the same time providing prolonged tensile strength [24]. It retains 81% of its tensile strength at 14 days, 59% at 28 days, and 30% at 42 days with complete absorption by hydrolysis observed between 180 and 210 days [25]. Maxon has 60% less rigidity than PDS and is significantly easier to handle [24]. Despite its prolonged absorption, tissue reactivity is usually minimal. Though more expensive than Vicryl or Dexon, it is considered as one of the best absorbable monofilament sutures and applicable for large surgical procedures on the trunk or extremities that need prolonged, suture-based approximation during healing.

(e) Polyglytone 6211 (Caprosyn): Polyglytone is composed of glycolide, caprolactone, trimethylene carbonate, and lactide. It can be rapidly absorbed and degraded from the body. Flexibility and superior handling in knot tying are other advantageous properties. It retains its tensile strength for 10 days and is absorbed within 56 days [26].

(f) Caprolactone/glycolide (Panacryl): Panacryl is an absorbable glycolide-L-lactide copolymer suture. It provides significant long-term mechanical strength lasting over 6 months. It retains about 90% of its original in vivo tensile strength at 6 weeks and 60% at 6 months [27]. Complete biodegradation occurs in 2.5 years. In terms of mechanical properties, Panacryl is right in the middle of absorbable and nonabsorbable sutures. The suture is coated by ε-caprolactone/glycolide copolymer for facilitating tissue passage. The braided form allows for excellent suture handling and knot tying with a little concern for knot security [28, 29]. These sutures are mainly used in tissues with slow healing capacity and which demand high tensile strength such as tendons and ligaments. Patients with low tissue healing capacity like diabetics may also benefit from these sutures because of its prolonged strength retention.

(g) Poliglecaprone 25 (Monocryl): Monocryl is an absorbable monofilament suture which is a copolymer of glycolide and ε-caprolactone. At 7 days the suture retains 50–60% of its tensile strength. Absorption is completed by hydrolysis at approximately 90 days post implantation [22]. The initial tensile strength is significantly higher which allows the surgeon to choose a thinner suture size. Monocryl offers good handling characteristics and low tissue reactivity, providing a less reactive scar when compared to Vicryl Rapide [30]. Moreover, poliglecaprone 25 has better knot tying and knot security than other absorbable monofilament sutures [22]. Due to these characteristics, poliglecaprone 25 has become the suture of choice especially in cosmetic cutaneous surgeries.

(h) Phantom Fiber (Wright, Memphis, TN): It is a high-strength absorbable suture composed of poly-4-hydroxybutyrate (P4HB) [3]. It demonstrates approximately 200 N tensile strength at time zero. This suture can retain 50% of its initial strength for 3 months. Poly-4-hydroxybutyrate (P4HB) is fully degraded to water and carbon dioxide in 12–18 months. Because of its high tensile strength, Phantom Fiber is mainly used in tendon repairs.

2.2.3 Partially Absorbable Suture

(a) OrthoCord (Mitek, Raynham, MA): It is a partially absorbable suture, combining UHMWPE and polydioxanone [7, 16, 31]. Depending upon the size, different amounts of polydioxanone will be present. For instance, No.2 OrthoCord contains 38% UHMWPE with 62% polydioxanone, while No. 2-0 OrthoCord contains 45% UHMWPE with 55% polydioxanone. This partially absorbable suture is also coated with polyglactin 910 for improved suture handling. OrthoCord has several advantages including its strength, low tissue abrasion, cut resistance, and flexibility. The main distinction of OrthoCord is the polydioxanone (PDS) core making it partially absorbable. The tensile strength is equivalent to or slightly lower than other UHMWPE-containing sutures and superior to completely biodegradable sutures [1, 32]. Ninety-two percent of baseline tensile strength can be retained through 12 weeks and 90% at 18 weeks. OrthoCord suture has a low bacterial adherence potential compared with other high-tensile sutures [33].

2.3 Biologic Augmentations for Sutures

Tissue healing is a multifactorial process and there are still many questions. Suture type is a significant factor in healing. Various biological materials have been used to increase the efficacy of sutures in different ways. Several different biological enhancement strategies have been used with sutures.

(a) Butyric acid (BA): Butyric acid is a carboxylic acid, formed as a bacterial metabolic product in the gut [34]. In its monobutyrate state, butyric acid has a proangiogenic effect by enhancing DNA transcriptional activity [34]. Leek et al. showed that butyric acid-impregnated sutures improved early Achilles tendon healing in a rabbit model [34].

(b) Polytribolate: It is a polymer of glycolide, epsilon-caprolactone, and poloxamer 188 (Vascufil, Covidien Inc., Mansfield, MA). This material is used as a suture coat in order to accommodate fray resistance, easy handling, less tissue drag, and minimal memory [35, 36].

(c) Growth factors and bioactive substrates: Growth factors and bioactive substrates are known to enhance tendon healing. Various authors studied sutures coated with different growth factors such as epidermal growth factor and basic fibroblast growth factor and reported that the presence of growth factors may facilitate tendon healing [37, 38]. Collagens and amino acids are examples of bioactive substrates. Kardestuncer et al. studied the effect of silk-RGD (arginine-glycine-aspartic acid) on human tenocyte cultures [39]. Their results suggest that the RGD substrate with silk suture increases the adhesion and proliferation of tenocytes.

(d) Mesenchymal stem cells (MSCs): MSCs can effect healing. Pluripotent cells can produce endogenous growth factors and chemotactic agents and differentiate into tenocytes. Yao et al. studied the effect of Ethibond Excel braided polyester sutures (Ethicon Inc, Somerville, NJ) coated with MSCs and bioactive substrate on Achilles tendon repair in a rat model [40]. These authors concluded that MSC-coated suture enhances the repair strength in the early period but shows no significant effect on the later stages. Adams et al. also studied the effect of stem cell and suture combination on Achilles tendon repairs. They reported higher ultimate failure strength with stem cell-coated sutures compared to suture-only repairs in a rat model [41].

(e) Antibacterial suture coatings: Triclosan (5-Chloro-2-(2,4-dichlorophenoxy)phenol) is an antibacterial and antifungal agent that has been used as a hospital scrub. Storch et al. used triclosan-coated polyglactin 910 (Vicryl Plus) suture in an animal study to evaluate the antibacterial effect [42]. The authors showed that bacterial growth was inhibited by triclosan coating without affecting the handling and absorbability of the suture.

    Triclosan has also been used on other suture materials including poliglecaprone 25 (Monocryl Plus) and polydioxanone (PDS Plus). In vitro colonization experiments showed that triclosan has an antimicrobial effect against *Staphylococcus aureus* and *Staphylococcus epidermidis* [42, 43].

    Li et al. studied the bactericidal and bacteriostatic effects of amphiphilic polymer poly[(aminoethyl methacrylate)-*co*-(butyl methacrylate)] (PAMBM)-coated sutures [43]. These authors reported that PAMBM has a significant bactericidal activity on *Staphylococcus aureus*, while triclosan has mainly a bacteriostatic effect.

    Chitin is a natural polysaccharide with an antibacterial effect. Shao et al. reported that an absorbable diacetyl chitin-based suture promotes skin regeneration with faster tissue reconstruction and higher wound breaking strength on a linear incisional wound model [44]. Chlorhexidine, octenidine, caffeic acid phenethyl ester (CAPE), and quaternary ammonium compound (K21) are some new coatings studied in the recent years with good antimicrobial effects [45].

(f) Nanoparticle suture coatings: Silver (AgNPs) nanoparticles are commonly used in urinary catheters and wound dressings. Silver's antibacterial effect comes from reactive oxygen species, which directly affects the DNA and cell membrane of the microorganisms. Rare bacterial resistance and a lower risk of toxicity are advantages of silver nanoparticles. Zhang et al. studied the effect of silver nanoparticle-coated sutures [46]. The authors used AgNP-covered absorbable sutures in intestinal anastomoses in mice. Their results suggest that AgNP-coated sutures have good in vitro antibacterial efficacy and show significantly less inflammatory cell infiltration and better collagen deposition in the anastomosis area. These authors also showed that these sutures provide better mechanical properties in the anastomosis.

(g) 1-Ethyl-3-(3-dimethylaminopropyl)carbodiimide hydrochloride (EDC): EDC (Sigma Chemical Co., St. Louis, MO) is a cross-linking agent that covalently bonds collagen molecules. It therefore creates an eyelet of stiffer material that potentially resists suture cutout [47]. In a recent study, Thoreson et al. tested the mechanical and cytotoxic properties of EDC-treated sutures [48]. They reported that EDC-treated 4-0 braided polyblend suture (FiberWire; Arthrex, Naples, FL) provided better in vitro mechanical results in flexor tendons. They also showed that a 10% EDC concentration is a threshold for cytotoxicity.

(h) Drug-eluting sutures: These sutures are produced using various methods including surface coating by the dip method, by grafting, or by an electrospinning process. Tetracycline, levofloxacin, and vancomycin are some antibiotics that can be used with sutures providing desired concentrations. Anti-inflammatory and anesthetic agents can also be used with common sutures. Weldon et al. used bupivacaine with PLGA-based sutures [49]. They reported these sutures released all the drug over the course of 12 days, while the sutures maintained 12% of their initial tensile strength after 14 days of incubation in vitro [49].

In a different study, Casalini et al. showed that lidocaine can be delivered effectively from a poly-e-caprolactone suture and provide an analgesic effect for approximately 75 h [50]. Immunosuppressive agents can also be delivered by sutures. Tacrolimus (FK506, Astellas Pharma Inc., Tokyo, Japan) is an immunosuppressive agent that prevents intimal hyperplasia. In an experimental model, Morizumi et al. studied the effect of tacrolimus-coated 7-0 polyvinylidene difluoride (PVDF) sutures on porcine vascular anastomosis [51]. Their results showed that the suture can effectively inhibit neointimal hyperplasia, the inflammatory response, and granulation tissue formation at the anastomosis site [51].

(i) Smart sutures: Recent studies have been focused on sutures with shape memory and electronic capabilities [45].

2.4 Clinical Performance of Absorbable Sutures

Newer absorbable materials show equal or better clinical results compared to nonabsorbable sutures. For more than 30 years, absorbable sutures have been used widely in various surgical procedures with good and predictable outcomes. Most of these procedures include vascular anastomosis and soft tissue approximation. However bone, tendon, and ligament surgeries are quite different. These tissues usually heal slowly, therefore sutures should retain their mechanical strength much longer. The biological response of the local tissues can also be quite different. Joint fluid may change the regular absorption process of a suture. Barber et al. suggest that meniscal repairs done with absorbable sutures such as Vicryl, Dexon, and PDS may have unfavorable mechanical strength retention because of the rapid suture absorption [52]. Their data showed that inflammatory synovial fluid accelerates the mechanical disintegration of absorbable sutures. These results suggest that nonabsorbable sutures may be the suture of choice in meniscal repairs.

Barbed sutures are widely used in plastic and general surgical procedures. The use of barbed suture for surgical closure has been associated with lower operative times, equivalent wound complication rate, and comparable cosmesis scores. In recent years, orthopedic surgeons have begun to use barbed sutures [4, 45, 53]. In a therapeutic study, Gililland et al. reported a slightly shorter surgery time in total knee arthroplasty cases when barbed sutures were used for wound closure [53]. In the future, barbed sutures may be preferred by more orthopedic surgeons.

Conclusion

Suture materials have different biological properties and may cause various tissue responses. Proper suture selection will affect the clinical outcomes; therefore surgeons should have sufficient amount of knowledge on these properties.

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3

Mechanical Properties of Suture Materials

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Suture is a generic term for all materials used to bring severed body tissue together and to hold these tissues in their normal position until healing takes place. Suturing is the joining of tissues with needle and thread. Security of the suture repair is provided by a knot. This knot is formed by interlacing the two free ends of the suture at least twice to form a construct which will not unravel when tension is placed upon the suture. The first knotting loop, called the approximation loop, performs the actual suturing function by placing the tissue in apposition and fixing the wound edges in the desired position. All knots, no matter where, must be "locked" by additional throws for adequate security. All additional loops serve only to secure the approximating loop.

3.1 The History of Suture

Surgical sutures have been used for millennia and date to as early as 3000 BC in Egypt. In 1600 BC, the Greek surgeon Galen of Pergamon reported using silk threads or catgut made from the twisted intestines of animals to suture severed tendons. Sutures were used in the Egyptian mummification process as early as 1100 BC. Historical records report sutures used to close wounds in India in as early as 500 BC. Many different materials have been used as suture. These include strands of gold, silver, steel wire, silk, linen, hemp, and flax and strands of tree bark, animal, and human hair. More recently suture has been derived from the intestines of sheep and goats.

Metal threads were introduced as a suture material in the early nineteenth century. At that time, the lack of a soft tissue reaction to the suture material was considered an advantage. However, metal threads had several major disadvantages. Their stiffness made tying a knot more difficult, suture breaking could easily occur, and as common in that era wound infections were an issue. This was not addressed until Johnson & Johnson started manufacturing sterile sutures made of either catgut or silk.

Toward the end of the nineteenth century, catgut was the standard surgical suture material. As noted by Galen, catgut suture was created from purified collagen strands which were twisted together. The collagen was harvested from small intestine serosa or submucosa of cattle, sheep, or goats. Sometimes beef tendon was also used. While catgut suture required 90 days for complete degradation by proteolytic enzymes, full tensile strength could not be maintained beyond 7 days. Catgut continued to be

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a common suture until the development of synthetic absorbable and nonabsorbable sutures. The increased awareness of issues related to bovine spongiform encephalopathy (mad cow disease) has resulted in catgut being generally replaced by synthetic absorbable polymers.

With the development of the chemical industry in the early twentieth century, synthetic suture materials were introduced. One of the first synthetic threads (nylon) was developed in the early 1930s. It was followed by the introduction of the first synthetic absorbable fiber based on polyvinyl alcohol. Later the first polyester fibers were introduced which became known as Dacron. Polyglycolic acid (PGA) was discovered in the mid-1950s, but because of its sensitivity to degradation by hydrolysis, it is rapidly reabsorbed. This response can be slowed by coating it with other polymers such as polycaprolactone and calcium stearate. A combination of 90% PGA and 10% L-lactide was released in 1974 as polyglactin 910. The suture is commercially known as Vicryl. Later in 1982 a more slowly degrading polymer polydioxanone was released as the suture PDS. This suture retained significant strength out to 6 weeks in comparison to the 2–3 weeks demonstrated by Vicryl.

New nonabsorbable polymers also appeared in this time frame. A polypropylene polymer suture was introduced in 1969 (Prolene). Braided polyester sutures both uncoated (Mersilene) and coated (Ethibond) were developed. Until the release of the first ultrahigh molecular weight polyethylene-containing polymer (FiberWire), the braided polyester sutures were the most commonly used nonabsorbable sutures.

3.2 Different Mechanical Properties

The ideal suture material should have high tensile strength, hold securely when knotted, be handled easily, not break unexpectedly, be flexible enough to be knotted, cause minimal tissue reaction, be resistant to infection, and, if possible, biodegrade when tissue repair has reached satisfactory levels. Unfortunately, there is no ideal suture material that has all these properties.

The following are basic definitions relevant to the mechanical properties of a suture:

Tensile strength—a material's ability to resist deformation and breakage [1]

Knot strength—force necessary to cause a knot to slip (related to the coefficient of static friction and plasticity of a given material) [2]

Breaking strength—limit of tensile strength at which suture failure occurs

Knot-pull tensile strength—breaking strength of knotted suture material (may be 10–40% weaker than the suture itself after deformation by knot placement) [3]

Wound breaking strength—the tensile strength of a healing wound at which wound edge separation occurs [4]

Elasticity—ability of a material to regain its original form and length after deformation [5, 6]

Plasticity—ability to deform without breaking and to maintain a new form after relief of the deforming force [7]

Memory—inherent capability of suture to return to or maintain its original gross shape (related to elasticity, plasticity, and diameter) [8, 9]

Pliability—ease of handling of suture material and ability to adjust knot tension and to secure knots (related to suture material, filament type, and diameter) [10]

Capillarity—extent to which absorbed fluid is transferred along the suture [11]

Abrasion—the wearing of a surface by friction [12–14]

3.3 The US Pharmacopeia Standard

The US Pharmacopeia (USP) system, established in 1937, seeks to promote public health by establishing official standards of quality and providing authoritative information for the use of medicines and other healthcare technologies. This specifically includes the standardization of sizes and tensile strengths of suture materials, corresponding to metric measures. A USP suture size denotes the diameter of the material, which is stated numerically in zeroes, with a larger number of zeroes indicating a smaller size of strand.

For example, 4-0 (meaning 0000) is smaller than a size 3-0. The smaller the size, the less tensile strength the strand will have. Modern sutures range from #5 to #12-0. The actual diameter of thread for a given USP size differs depending on the suture material class. However USP standards also define the corresponding minimum-maximum limits on average diameter (mm) and maximum metric size (gauge no.) for all USP sizes. The tensile strength of a suture is the measured pounds of tension that the strand can withstand before it breaks when knotted. The USP standards also define knot-pull tensile strength (kgf/N) as the minimum strength for each individual strand and the average. Furthermore, the USP standards define the requirements for packaging and storage, needle attachment, sterility, extractable color, and residual solvents.

While not as widespread as the USP classification system, the European Pharmacopoeia (Ph. Eur.) system uses the metric system for classification of sutures based on the suture size. The Ph. Eur. specifies a decimal classification and metric coding for the gauges. It quotes a thread diameter of 1/10 mm, indicating that thread gauge of 3.5 has a diameter of 0.35 mm.

3.4 Standards Change

Suture materials are usually characterized by their physicochemical composition and their construction. They can be absorbable or nonabsorbable, monofilament, or braided and made of a single material or a blend of materials.

Adequate suture strength is needed in surgery. The initial nonabsorbable polymer sutures were braided multifilament structures (i.e., Ethibond/Ti-Cron) which provided a nonreactive implant with excellent strength especially when used in open surgery. These sutures were based predominantly on polyester. As arthroscopic and endoscopic techniques developed, suture breaking during knot tying became more of an issue. Arthroscopic equipment knot pushers increased the stress placed on a suture during knot tying, and even with size #2 suture present in many suture anchors, suture breaking was an issue.

Braided polyester sutures were a common point of failure. This lead to the development of high-strength sutures containing ultrahigh molecular weight polyethylene (UHMWPE) [15]. UHMWPE is used in many ways outside the medical industry. It is capable of absorbing large amounts of energy and is therefore used in ballistic protection from bulletproof jackets to armored vehicles. It is 15 times stronger than steel, light enough that it floats on water, and commonly used in marine vessels.

Despite a well-recognized need by arthroscopic surgeons for a stronger suture with a small size, the established suture manufacturers did not respond. They held to the USP strength standards for the various suture sizes. It took an arthroscopic instrument company to change the status quo. Arthrex came out with the first high-strength suture FiberWire which was a combination of a core of UHMWPE fibers surrounded by a braided polyester sheath much like a climbing rope [16, 17]. The response was so favorable that orthopedic surgeons in particular switched rapidly to the new suture type. Since FiberWire sutures could only be found in Arthrex suture anchors, other arthroscopic companies saw their suture anchor sales decline. In an attempt to maintain the market share, these other companies looked for an alternate UHMWPE-containing suture. A suture made of braided UHMWPE fibers was produced and sold to the other companies for their anchors. With this consumer pressure, even the largest suture manufacturers recognized that UHMWPE-containing sutures were here to stay and developed their own products [17].

The new UHMWPE-containing sutures provide high tensile strength, diminished breakage during suture passage, and better handling and knot characteristics compared to traditional suture materials [15, 18–20].

There are currently three different types of UHMWPE-containing sutures: the first is the FiberWire which combines UHMWPE with braided polyester; second is the pure braided UHMWPE such as UltraBraid, MaxBraid, Force Fiber, and Hi-Fi with no central core; and the third type is the most recently introduced and combines UHMWPE fibers with biodegradable polydioxanone and a polyglactin 910 coat for improved suture handling (OrthoCord, Johnson and Johnson DePuy-Mitek, Raynham, MA). The combination of polydioxanone and UHMWPE varies depending upon the OrthoCord suture size. For instance, #2 OrthoCord has 68% UHMWPE and 32% polydioxanone, while #2-0 OrthoCord has 55% UHMWPE with 45% polydioxanone [13].

Tapes are the latest new development. In an attempt to improve the strength of tissue repair, Arthrex again lead the way by introducing a tape product called FiberTape. This is an expanded version of FiberWire also containing a blend of nonabsorbable UHMWPE filaments and braided polyester. This 2-mm-wide tape provides a broader pressure footprint than regular suture [21]. Other manufactures have followed this trend by introducing tapes of their own made from braided UHMWPE.

Larger sutures can certainly be expected to be stronger than smaller sutures, so it is no surprise that a large tape will be stronger when compared side to side with a smaller suture. How this applies to the clinical condition is currently under study. Bisson and Manohar using a bovine infraspinatus model biomechanically compared No. 2 FiberWire suture to 2-mm FiberTape. At the suture-tendon interface, significant difference was found in elongation, stiffness, and ultimate tensile load [21]. Gnandt et al. [22] used fresh frozen cadaver tendon specimens to compare the No. 2 suture with 2-mm tape performance across four different suture techniques commonly used in tendon repair. The tape had greater mean failure loads.

3.5 The Mechanical Properties of Sutures

3.5.1 Tensile Strength

Tensile strength is the measurement of a material or tissue's ability to resist deformation and breakage. The presence of UHMWPE material in a suture makes it significantly stronger than those sutures which do not contain UHMWPE [23]. A comparison of the three major groups of UHMWPE-containing suture (FiberWire, braided UHMWPE, and OrthoCord) demonstrated that braided UHMWPE is stronger in load to failure testing than FiberWire and OrthoCord in head to head testing but that all three types are significantly stronger than conventional braided polyester sutures [17]. That being said, all three are more than strong enough for arthroscopic clinical applications.

3.5.2 Knot-Pull Tensile Strength

The breaking strength of suture material is significantly reduced by tying a knot. To increase knot strength, reinforcing the knot with three or four reversed half hitches and alternating the post are required to ensure non-slippage of the knot under tension [15, 18]. The actual strength of the knot varies with the suture material and its size. Surgeon experience also has a significant effect on failure mode and tensile failure load.

3.5.3 Stiffness

Variations in suture stiffness may have clinical implications. A stiffer material may be more likely to cut through degenerative tissue. This may have clinical implications in that younger tissue may be more suitable to a stiffer suture material, while more frail tissue is more suited to less stiff materials which "take up the slack" rather than cut through.

3.5.4 Flexibility

Flexibility is also known as pliability. This suture characteristic refers to how easily the suture conforms to variations in tissue or instrument interaction. A more pliable suture is easier to handle, tie into a knot, and pass through tissue. A monofilament suture often has a "memory" and resists deforming during knot tying. A braided suture conforms to tissue variations more readily and is therefore more pliable or flexible.

Knot fixation is a determining factor of surgical thread as it guarantees the security of the suture and depends on the thread stiffness, coefficient of friction, elasticity, and plasticity. In addition to these parameters, knot fixation differs according to whether the thread is monofilament or braided. Monofilament sutures have a lower coefficient of friction, glide more easily due to their smooth surface, and are usually stiffer than braided ones.

3.5.5 Knot and Loop Security

Knot and loop security applies to how the suture is used while tying a knot [3, 19, 24]. While the type of suture plays a role, the type of knot, the skill of the surgeon, and the environment in which the knot is tied are also important.

Knot security is the ability of the suture to maintain knot strength without slippage and is inversely proportional to the memory of the suture material because of a tendency to untie their knots as they try to return to their kink form [25]. A secure knot is one which breaks rather than slips or becomes untied. This is dependent on the presence of friction, internal interference, and slack between throws [26, 27]. Loop security relates to how well the knot works. It is the ability of the knot to maintain a tight suture loop as a knot is tied [24, 26, 27]. Different suture materials can affect both the knot security and loop security of different arthroscopic knots. More abrasive suture materials generate more friction between suture loops and can be expected to have better loop security than less abrasive sutures.

Lo et al. showed loop security for many of the knot and suture configurations was not significantly different but FiberWire consistently showed the smallest loop circumference when compared with the other suture materials tested [27]. Livermore et al. evaluated load to failure and cyclic loading elongation of FiberWire, Hi-Fi, OrthoCord, and UltraBraid in five different sliding arthroscopic knots. All knots elongated less than 0.45 mm by the 1000th cycle but showed higher suture slippage in the initial 50 cycles of loading [28]. The conclusion is that some sutures have less abrasion and some have more. The performance of UHMWPE sutures is dependent in part on the type of knot tied and the stresses to which it is subjected.

3.5.6 Suture Slippage

In the treatment of soft tissue injuries, surgeons often have to repair injured soft tissues that experience high loads and have suboptimal blood supply [29]. In certain situations, such as in tendon and soft tissue repairs, a high load event may result in suture failure in two ways: slippage of the knots, resulting in gapping and clinical failure, and catastrophic failure (breakage) of the suture [25, 30]. With the knot slippage, gapping at the repair site would seem unlikely to heal [26, 31]. Several authors have used 3 mm of suture-knot elongation to define clinical failure [25, 26, 30, 31].

The main source of concern is that the new UHMWPE-containing sutures seem to slip more easily than braided polyester sutures [18]. This observation was confirmed, and different knot patterns have been tested to identify which knots are more appropriate for the UHMWPE-containing sutures [15].

Knots which have an internal locking mechanism perform better with less slipping in biomechanical testing of UHMWPE-containing suture. Specifically Swan et al. reported that the surgeon's and SMC knots were superior [31]. Pedowitz highlighted the performance of the San Diego knot [18]. The take-home message of the cyclic knot strength testing is that sliding knots without an internal locking mechanism (Fisherman's knot and Duncan's loop) are more likely to slip in a submaximal level than those knots with an internal locking mechanism (SMC, Tennessee slider, San Diego, surgeon's knot).

3.5.7 Damaged Sutures

Damage to a suture may occur during suture passage or manipulation. Sharp-tipped penetrators, antegrade suture passers, knot-tying devices, and sharp bone edges can cause this damage [32, 33]. Wright et al. evaluated the mechanical properties of damaged sutures [32]. Using a razor blade to cut 20% of the suture's width No. 2 PDS, Ethibond, Tevdek, OrthoCord, and FiberWire were subjected to straight-line pulls. Not surprisingly the UHMWPE-containing sutures (OrthoCord and FiberWire) showed the highest load to failure and ultimate tensile strength. It is not surprising since these sutures start off being stronger than the others tested. Suture stiffness was not significantly affected by the cut [32]. The takeaway point is that the superior properties of UHMWPE-containing sutures are maintained even when cut. On the other hand, PDS which had equivalent or superior strength with Ethibond and Tevdek once cut was weakened significantly more than all the other sutures. Monofilament sutures seem more susceptible to a partial cut than braided sutures.

3.5.8 Material Abrasion

Abrasion can be evaluated by considering the impact of the suture on its environment or the impact of the environment on the suture. High-strength UHMWPE-containing sutures have superior breaking strength and holding power but are also more abrasive to the tissue (i.e., rotator cuff) and joint cartilage than monofilament sutures [14, 34]. Different sutures have their own abrasion profile. This abrasion may damage the anchor eyelet and adjacent bone or tendon tissue as the suture cycled during placement or knot tying [33, 34]. This abrasion may also release potentially harmful wear particles into joints or the surrounding tissue leading to an adverse biological reaction [13].

Savage et al. investigated resistance to bending abrasion fatigue and consequent failure in seven different suture materials (FiberWire, UltraBraid, MaxBraid, Ethibond Excel, OrthoCord, Force Fiber, Hi-Fi) [13]. The sutures were oscillated over a stainless steel wire at low frequency until load to failure, and changes in suture morphology and the fatigue-failure method were recorded. Suture structure had a significant effect on abrasion resistance. Sutures with UHMWPE cores had significantly better performance than other braided sutures. These resisted bending abrasion failure better and had higher resistance to tensile failure [13]. The superior performance of UHMWPE suture to braided polyester was also demonstrated by others [27].

Suture abrasion on tendon can be potentially significant especially in rotator cuff surgery. Williams et al. compared the abrasiveness of eight high-strength sutures (FiberWire, Collagen Coated FiberWire, OrthoCord, MaxBraid, Force Fiber, UltraBraid, Phantom Fiber BioFiber, and Ti-Cron) and one monofilament as a control group (Surgipro). Each suture was cycled 50 times through the tendon, which was fixed to a mechanical testing system under a constant load in saline solution. Significant differences were found. Collagen Coated FiberWire was the most abrasive of the high-strength sutures. Four of the sutures (Collagen Coated FiberWire, Phantom Fiber BioFiber, FiberWire, Ti-Cron) had a mean displacement rate greater than 0.150 mm/cm. The remainder of the sutures had a mean displacement rate less than 0.050 mm/cm (OrthoCord, Force Fiber, MaxBraid, UltraBraid). The significant displacement rate difference between these two groups ($P < 0.0001$) was related to both the twist angle and the picks per inch [35].

Deranlot et al. compared abrasiveness in No. 2 FiberWire, FiberTape, OrthoCord, and Force Fiber. Again OrthoCord and Force Fiber showed a significantly lower abrasion than FiberWire and FiberTape ($P < 0.05$) and demonstrated the increased abrasive effects of FiberWire and FiberTape compared with OrthoCord and Force Fiber [12].

The weakest part of a rotator cuff repair is the interface between the tendon and suture. The suture running through the tendon when tying a sliding locking knot may cause damage if the suture is too abrasive. Savage et al. evaluated the effect of sliding knots on the suture-tendon interface comparing four stitches (simple-static, simple-sliding, mattress-static, mattress-sliding) tied in No.2 FiberWire. A mattress-static stitch (116 N) was significantly stronger than a mattress-sliding stitch (70 N; $P < .001$). The ultimate loads for the simple-static (46 N) and simple-sliding (50 N) stitches were not statistically different. Importantly after cyclic elongation, the mattress-sliding stitch had more laxity than the simple-static ($P = 0.01$) and simple-sliding ($P = 0.04$) stitches [36]. The take-home message is that because of the "sawing" effect, sliding a suture through the tissue weakens the suture-tendon interface especially with a mattress stitch but not with a simple stitch. If the tissue quality is questionable or the repair may have more tension in it than normal, a non-sliding knot is a better choice than placing a sliding mattress stitch [36].

Lambrechts et al. compared the "cheese-wire" or "sawing" effect of No. 2 OrthoCord, Ethibond, and FiberWire [37]. The distance of cut through in supraspinatus tendons for OrthoCord, Ethibond, and FiberWire was 2.9 mm, 3.2 mm, and 4.2 mm, respectively. There was statistically significant less "cheese-wiring" in OrthoCord suture than in FiberWire suture [37]. Kowalsky et al. also noted the increased cutting through in a tendon construct by the "cheese-wire" effect of FiberWire suture [14].

3.5.9 Suture Memory

Suture memory is an inherent capability of suture to return to or maintain its original gross shape [8, 9]. This is related to its elasticity, plasticity, and diameter. Sutures with high memory are less pliable, maintain their original shape, and can be more difficult to work with. In general, monofilament sutures have more packaging memory than braided ones. Monofilament sutures such as nylon, polypropylene, PDS, and Maxon have a high memory. Monocryl, Biosyn, Gore-Tex, and Pronova are monofilaments that are exceptions.

3.5.10 Anchors or Bone Tunnels?

Before Goble et al. developed the first suture anchor in 1985, rotator cuff tendon sutures were passed through transosseous tunnels in the greater tuberosity [38, 39]. Now, suture anchors are the gold standard for soft tissue fixation to the bone and have replaced transosseous sutures. Craft et al. compared the strength of classic transosseous suture repair with suture anchors [40]. No significant difference was seen between the strengths of repairs performed with the anchors compared with the transosseous suture technique, and suture anchors were considered equivalent to more traditional suture-only techniques [40]. Burkhart et al. also compared suture anchors to transosseous sutures and found greater variability in the bone tunnels than the anchors suggesting that the anchor performed more consistently than the bone tunnel [41]. The variable nature of older osteoporotic bone found with rotator cuff tears makes it more unsuited to consistently retain a suture during cyclic loading. This finding was further supported by Barber et al. [15, 17].

Klinger et al. compared the open transosseous suture technique with modified Mason-Allen stitches (group 1) to double-loaded suture anchors with arthroscopic Mason-Allen stitches (group 2) in sheep rotator cuff repairs harvested at intervals out to 26 weeks [42]. No significant difference in load to failure and stiffness was observed between the two treatment groups at 6, 12, and 26 weeks. However, at time zero, the suture anchor group had higher failure loads than the transosseous sutures. They concluded that a double-loaded suture anchor technique provides superior stability [42]. Pietschmann et al. also compared transosseous sutures to suture anchors and found that suture anchors provided higher ultimate failure loads than transosseous double U-sutures both in healthy and osteopenic bone. They concluded that osteopenic bone does not constitute a valid indication for open surgery using transosseous sutures [43].

Both Petri et al. and Ettinger et al. compared suture anchors to transosseous sutures in quadriceps tendon and patellar tendon ruptures in cadaveric knees, respectively [44, 45]. Both studies demonstrated that tendon repairs with suture anchors yielded significantly less gap formation during cyclic loading and resisted significantly higher ultimate failure loads than transosseous sutures. The conclusions of both studies were that the use of suture anchors yields significantly better biomechanical results than transosseous sutures in these locations [44, 45].

3.5.11 Alternative "Suture Materials"

While the development of UHMWPE-containing sutures has significantly increased suture strength, the weakest point of a tendon-suture-anchor-bone construct is still the tendon-suture interface [46]. Stronger suture or tape repairs fail when the intact suture cuts through the tendon or the tendon ruptures in mid-substance [47–49]. To try to address these issues, alternative materials such as 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDC) hydrochloride and cyanoacrylate have been developed. Cyanoacrylate, a tissue adhesive, works as a glue and has been used in dental, vascular, nerve, and skin repair for many years [50–52].

Bresnahan et al. studied the tensile strength of lacerations closed using cyanoacrylate, cyanoacrylate and subcutaneous sutures, percutaneous sutures, and a combination of percutaneous and subcutaneous sutures. The cyanoacrylate adhesive alone exhibited significantly less tensile strength at 4 days than the other methods. The combination of percutaneous and subcutaneous sutures was the strongest [4].

EDC is a cross-link activating reagent that can facilitate the covalent bonding between carboxyl and amino groups such as those in collagen molecules [46, 53]. Several studies have evaluated its effects on tissue repair. Zhao et al. investigated the use of EDC and cyanoacrylate on the tendon-suture interface strength in canine flexor tendons repaired with the single loop technique [46]. Cyanoacrylate- and EDC-reinforced suture loops were 91% and 64% stronger, respectively, than controls. The authors concluded that cyanoacrylate and EDC improve the pullout failure strength of single loop suture constructs [46]. Thoreson et al. evaluated EDC suture coating on tendon repair strength and cell viability in canines [53]. Three different concentrations of EDC (1, 10, or 50%) diluted with saline were applied to 4-0 FiberWire suture. Pullout strength, stiffness, and loop elongation were compared to a control group using 0.9% saline. The 10 and 50% EDC groups were significantly stronger than the control. The dead to live cell ratio was significantly increased at all distances from the suture in the 50% EDC-treated group. Suture treated with 10% EDC solution provided the best combination of mechanical reinforcement and limited toxicity [53].

Barbed suture is a knotless surgical suture with surface directional projections (barbs). The suture can be easily passed through tissue in the direction opposite to the barb angle. When a force is applied in the opposite direction, the suture barbs engage the surrounding tissue and resist pullout [54]. Barbs along the entire length of the suture provide multiple anchoring points allowing a more uniform distribution of forces along the length of the suture [55].

The advantage of a barbed (knotless) suture is that bulky knots can be avoided decreasing the cross-sectional area of a tendon repair and may improve gliding through a pulley system. It eliminates a knot which may be a weak point in the tendon repair because of decreased suture tensile strength. Knots placed between tendon ends decrease the approximation of the repair tissue. This can be avoided with a barbed suture.

A 2014 literature review of tendon repair with barbed sutures found a statistically significant higher failure load with barbed sutures than traditional sutures in four reports [56–59], no significant difference in three [60–62], and one reporting traditional sutures performed better [63]. Shah et al. emphasized the great variation in the repairs studied including the use of ex vivo studies [54]. The review concluded that barbed suture have theoretical advantages; however, due to the lack of uniform studies and live model data, no absolute conclusions can be made [54].

There are also several studies in literature relevant to the comparison of barbed versus standard sutures for usage in total knee arthroplasty (TKA). In prospective, randomized controlled trials, Smith et al. and Gililland et al. compared barbed and traditional knotted interrupted closures in TKA [64, 65]. Both studies reported decreased mean closure time and total closure cost with the barbed suture. Although Gililland et al. [64] reported similar complication rates in both groups, Smith et al. [65] reported increased frequency and severity of wound complications with barbed sutures. The concern that barbs may act as a place for bacteria to hide was addressed by Fowler et al. [66]. Several commonly used sutures were compared to a barbed monofilament suture [66]. The barbed monofilament suture showed the least bacterial adherence. Another retrospective study by Maheshwari et al. reported no significant difference in complication rate or wound closure time between conventional and barbed sutures, but material costs were lower with barbed sutures in TKA [67].

Conclusion

Suture materials vary in strength, size, composition, and performance. Their mechanical properties influence their performance, and a knowledge of these properties is required for the surgeon to fully appreciate how they will perform clinically.

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Biomechanics in Knot Tying

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Biomechanics in knot tying is a crucial part of knowledge about forces affecting the results of surgical procedures. As the knot is the very important part of almost every operation, incorrect tying of sutures can lead to failure of the procedures and decreasing the rate of good results. In the chapter all basic terms and processes influencing the strength and effectiveness of surgical knots tying will be explained.

4.1 Loop Security, Loop Elongation, and Loop Circumference

A lot of definitions of loop security could be found in current literature. One of the simplest explanations of loop security is the ability to maintain a tight suture loop when a knot is tied [1]. The term can also be explained as the ability of the suture loop to stay tight as the knot is being tied. Another definition found in the literature is that loop security is the ability to conserve loop diameter, before any load is applied. In general, the term describes the ability of the basic knot to secure the suture loop in position and protect it against elongation. It refers to the capacity to keep the suture loop close once tension is released on the post strand and the knot is tied as well as gives an idea of readapting of the tissue margins.

The importance of loop security was initially emphasized by Burkhart et al. [2] and further examined in other studies. Loop security is the measure of tightness of the suture loop because a loose suture loop will not hold tissue apposed regardless of the force to ultimate failure [3]. The method of Lo et al. [4] was used to determine loop security (see below).

Loop security depends on tensile properties, such as failure load, elasticity, or plasticity of the suture material, which in turn determines suture elongation. Sliding knots are favored over surgeon's knots when using polyblend suture material to avoid poor loop security that leaves significant gaps in the repair approaching clinical failure before the load is applied [5]. Loop security, which refers to the initial tightness of the knot, is also dependent on the initial throws [6].

The loop security is used as the marker of knot quality, but direct measurement of loop security is impractical in the laboratory. Some authors have suggested an indirect measure of loop security: the change in loop circumference after it is transferred to a material testing system and tensioned to 5 N [7]. According to this way of

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thinking, loop circumference is a parameter to describe knot failure during load testing—elongation of the original loop circumference (for instance, 3 mm) during subsequent load to failure is considered a failure.

Loop elongation is tightly connected to loop security, and it refers to the maximum displacement or growth in length of the knotted loop at peak load under cyclic loading. A suture loop that is loose will cause loss of tissue apposition no matter how tight the knot is tied [8].

Results describing the analysis of loop elongation in the comparative study by Li X et al. are consistent with those reported by the others. In the study Duncan and Snyder knots as well as four types of sutures were compared. The authors show that Duncan knots appeared to have a greater loop elongation than Snyder knots when tied with Maxon and Tycron [8]. In another comparative study, authors surprisingly observed no changes in loop circumference when using PDS suture as the effect of elasticity of the suture [9].

Direct measurement of loop security is challenging. Loop security is a measure of the knot's ability to maintain a tight suture loop as the knot was tied and was defined by the circumference of the loop at 5 N preload and was calculated by the formula described by Lo et al. [4]. The smaller the loop diameter correlates to greater loop security [3].

As mentioned above, the most commonly accepted surrogate measurement in the literature is a change in loop circumference after applying a load of 5 N. All knots tested in the laboratory are removed from the dowel and placed on the MTS crossheads. The crosshead displacement is measured and used to calculate the loop circumference as described by Lo et al.: loop circumference = (2 × crosshead displacement) + (4 × rod radius) + rod circumference. Loop security is calculated as the difference between the loop circumference at 5 N and the circumference of the knot-tying dowel (30 mm) [7]. As Baumgarten et al. revealed, locking knots were not shown to have improved loop security when compared to non-locking knots for both Ethibond and PDS [3].

By increased popularity of polyester- and polyblend-braided sutures, providing superior strength compared with traditional suture materials, arthroscopic soft-tissue repair has changed in the past few years. The mentioned sutures allow easier knot tying with decreased risk for suture failure and give excellent loop security for tissue stabilization. Most new-generation sutures have been shown to have similar tensile strengths. FiberWire (Arthrex, Naples, Florida), Herculine (Linvatec, Largo, Florida), Orthocord (DePuy Mitek, Warsaw, Indiana), and Ultrabraid (Smith & Nephew, Memphis, Tennessee) have attempted to differentiate themselves in the ability to throw arthroscopic sliding knots with more ease and security [10].

4.2 Knot Security

Knot security is defined as the effectiveness of the knot in resisting slippage when a load is applied [1]. Namely, the knot security is the measure of the strength of a knot. It refers to the maximum load the knot is able to support prior to breaking (fracture) or complete slippage. Many studies have shown that loop-holding capacity and knot security are influenced by the type of knot, the knot configuration, the type of suture material, and the size and coating of the suture, as well the technique used for the knot [1]. Another definition often used in the literature is that knot security refers to a knot's capacity to maintain its integrity, without loosening or breaking, in the face of significant loads. The mentioned loads may be rapidly increasing linear loads or low-level repetitive loads [11]. It is important to note that the definition of the knot security consists of the information that knot-slip resistance under distractive load (tensile force) once the knot is completed and locked with successive half-hitch throw. It is attributed by friction, internal interference, suture pliability, and slack between throws [12].

Knot security is affected by the knot type and configuration but also is highly dependent on the individual surgeon. As Hanypsiak et al. [13] revealed, substantial variation and inconsistencies in knot tying occurred not only between knots tied by different surgeons but also between knots tied by the same surgeon on the same occasion.

The appropriate "knot security" means the lower rate of knot slippage or unraveling as the result of:

1. Obtaining and maintaining tension on suture strands during tying
2. Correct knot-tying technique
3. Appropriate knot construction or "geometry" (knot configuration).

Also knot-tying speed and force can affect knot security [14].

One of the most important determinants of knot security is the tightness of the suture loop or the "loop length." The term could be explained as the presence of shorter loop lengths or absence of "gaps" between loops. In some conditions the longer loop length coupled with a propensity to unravel may be critically important, especially in instances where close tissue approximation plays a significant role [15].

According to study by Burkhart and colleagues, the factors that are the most important in tying a tight knot are friction, internal interference, slack between loops, wraps or half hitches of the knot. Internal interference can be increased by reversing direction of the half hitches or by changing the posts. Slack can be eliminated by past-pointing with the knot pusher as each half hitch is tightened [2].

Type of the suture also plays a role in knot security: knots tied with non-monofilament suture could create a construction with shorter loop lengths than those tied with monofilament thread. Although some believes that lower coefficient of friction which characterise monofilament suture can allow to obtain a wider knot. It is well proven that stretching of the knot when being tied and elasticity of the suture material could have negative effect for general knot security. This is supported by some investigators, showing that there is an increased risk of knot slippage among nonabsorbable monofilament suture materials over braided and a decrease in tensile strength over time under a tensile load for absorbable sutures [16, 17].

The failure of the knot can occur in the way of breaking, slippage, or unraveling, and the knot configuration plays a role. Lutchman et al. confirm that 3-1-1 knot (a modification of a surgeon's knot) break at a statistically significantly higher tensile force than do slipknots and thus have a higher ultimate tensile strength [18]. On the other hand, no differences were found while comparing the security of knots tied with or without instruments. All loops that failed via suture breakage failed just adjacent to the knot and not within the knot where the hemostat had been applied, meaning that no material failed at the site of instrumentation. No significant difference in mode of failure was found between instrumented and noninstrumented suture groups for any analyzed material [19].

It has been demonstrated that knot security is a function of knot configuration including the number of throws used to make the knot as well as the size and type of suture materials [8, 20]. Xi Li et al. showed that comparing Snyder to Duncan with four types of sutures (PDS, Biosyn, Prolene, Surgidac), the highest mean knot security values were achieved by tying Snyder knots with Biosyn and Surgidac sutures, but similar differences were not found with the same suture materials when tied in Duncan knots [8]. Jo et al showed that sliding knots perform better in terms of security when backed up with different number and type of half hitches [9].

Knot security describes the tensile strength of a basic knot that is secured with locking half hitches in both open and arthroscopic knots. The security of arthroscopic knot types is the subject of controversial debate in the literature. The results of various knot's loop security measurement confirmed believes of many authors, that significantly higher pressure and tension are generated when constructing an arthroscopic basic knot using a knot pusher. This gives the basic knot more secure seating in comparison with a hand-tied technique and consequently results in better loop security. Moreover, it confirms the security of the locking mechanism of arthroscopic knot types. Nevertheless, the placement of reinforcing half hitches is vital to the knot security of arthroscopic as well as openly tied knots [21]. Burkhart et al. have shown that loop security is as important as knot security. A loop that is initially loose will fail to the same extent as a tight loop whose knot slips [2].

In many studies evaluation of knot security was described by determining the response to both load to failure and cyclic loading [10]. However, cyclic loading is more representative of the physiologic loads encountered as a result of repair reconstruction, and this parameter is taken into consideration while analyzing the knot security.

Namely, knot security (resistance to loosening or breaking) and loop security (tightness of the initial loop) play a key role in maintaining the knot. The ideal knot configuration would maximize knot security and loop security with little to no variation in tying technique [22].

Loop security should be maximized to ensure repair integrity when tension is released on the post strand before the knot is locked with half hitches. Final knot security should be high to maintain tissue approximation after repair. Ideally, a knot with less material should be used as long as this approach does not compromise knot security, because this may decrease the risk of complications due to foreign material in an enclosed space, such as suture impingement in the subacromial space [23].

Knot failure can occur because of suture slippage or suture breakage. The type of knot affects 80% of the force required for slippage and only 20% of the force required for rupture. Therefore, a proper knot configuration can eliminate the slippage as a cause of suture failure. Three reverse half hitches (RHAPs) on alternating posts convert the failure mode from slippage to suture breakage. An adequate number and configuration of RHAPs result in a greater internal suture resistance, increasing the loop security and the knot security.

Analysis of the knot may be assessed by measuring loop security (loop circumference, e.g., at 5 N) and knot security (highest load to failure at a crosshead displacement of, for instance, 3 mm) [9].

It is common knowledge that arthroscopic soft-tissue repairs undergo many cycles of tensioning and relaxation before significant tissue healing occurs, and knot security under cyclic loads is essential for good results after these repairs. Ilahi et al. stated that post switching and reversal of loop direction are crucial to arthroscopic knot security [10].

Livemore et al. stated that while comparing many suture materials and knot configurations, the Weston knot with 3 RHAPs using Ultrabraid provided the best loop and knot security in both the load-to-clinical-failure test and the cyclic loading test when compared with all other knot configurations and suture materials tested [10].

4.3 Elongation

In assessment of the repaired construct, the term of elongation plays the important role. It is defined as the average maximum displacement of a knotted suture loop at the peak load during cyclic loading [9]. Elongation can be defined as well as “gapping” of the construct, analyzed in cyclical loading in biomechanical tests [24]. Initial elongation is the elongation after preconditioning, while total elongation is an elongation after defined numbers of cycles in biomechanical analysis [25].

Suture elongation is determined by failure load, elasticity, or plasticity of the suture material. The meaning of a term is opposite to the loop security, which is the ability to conserve loop diameter before any load is applied [3]. The unit of elongation is millimeter, and elongation more than 3 mm is defined as clinical failure [21]. This is considered an amount of suture loop elongation that might be associated with biological healing failure at the tendon–bone interface after rotator cuff repair [26]. Sometimes elongation is expressed in percentages.

Elongation is a term that could be divided into two subtypes: loop elongation or knot elongation; both play a basic role in stability of the construct.

Maximum elongation refers to the maximum displacement of a stressed knotted suture loop either when the suture breaks and the knot remain intact or when the knot slips completely off the end of the suture. It is described as the difference between length of the construct with some pre-load (in Newton) and the peak length at the defined cycle [27]. Peak-to-peak elongation is defined as the difference between the length of the construct at the peak of the first and defined numbers of cycles [27]. In many papers the authors revealed that for PDS sutures, the maximum elongation was greater than 5 mm regardless of which knot configuration was tested. This degree of loop displacement is well beyond the 3 mm limit assumed to represent clinical failure by loss of apposition [8].

As mentioned above, cyclic testing that can simulate postoperative conditions is inseparable with biomechanical assessment of elongation. First, cyclic elongation should be determined, defined as the relative increase in segment length from the peak load of the first cycle to the peak load of the final cycle of testing. Another one is elongation amplitude, defined as the peak to valley measurement of the segment elongation for the final test cycle [28]. Load elongation curves are used to calculate structural properties of the examined tissue [29].

A knot tied with an absorbable monofilament suture elongates progressively when subjected to repetitive stress, whereas in a knot tied with a nonabsorbable braided suture, the elongation is negligible [30]. However, Savage et al. have shown in the biomechanical study that there are quite important differences between particular types of arthroscopic knots. No differences were observed in cyclic elongation between simple stitches with static and sliding knots. The only difference was the mattress stitch with a sliding knot having a greater cyclic elongation than the simple stitches with static and sliding knots [31].

Elongation of the suture loop and knot slippage (loop failure) can lead to failure of the construct, as well as the suture breakage due to the material failure [12]. As revealed by Baumgarten et al., there are many differences in elongation in different types of surgical knots. Although a lot of parameters can be taken into consideration in biomechanical analysis, those of special importance are cyclic elongation, loop security, and force to clinical failure, as they provide measures of the knot performance at low-force loading [3]. On the other hand, under load, some elongation at the knot always will take place, as the result of self-seating of the knot. Even excessive pulling on the knot does not prevent knot slippage if there are a too small number of square knots [32].

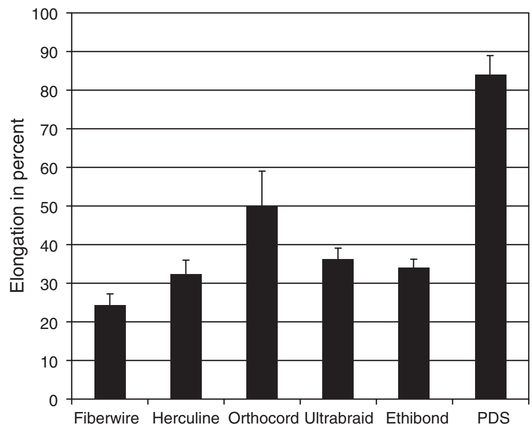

Fig. 4.1 Mean elongation at failure of a single suture strand with straight loading without a knot. Orthocord had the highest elongation among the new polyblend sutures, whereas PDS II performed with an even higher elongation [33]

In comparative analysis of six common surgical materials, Wüst et al. revealed that PDS has the highest elongation rate and Orthocord had the highest elongation at failure of the braided sutures and was therefore particularly apt to provide a snug adaptation [33] (Fig. 4.1).

4.4 Friction

The definition of friction implies that it is the force that causes a moving object to slow down when it is touching another object. The suture's coefficient of friction is a measure of forces encountered by contact of the surfaces of the suture material during construction of the knot. Next to internal interference and slack between loops of the knot, suture friction is an important factor affecting knot security [6]. By the impact on knot security, friction indirectly affects satisfying clinical outcome. Properties such as coefficient of friction, tensile strength, and others affect the ultimate strength of a knot and the efficacy of various knot configurations to resist slippage under load [11]. Friction depends among others on the type of suture material used in knot tying. According to Loutzenheiser et al., using braided, nonabsorbable suture and by reversing direction of the half hitches and reversing posts, it is possible to maximize friction and internal interference [12].

4.5 Strength

Knot strength is the term strictly related to knot security. It can be defined as knot's resistance to breakage. According to Burkhart et al. to maximize the strength of arthroscopic knot used in rotator cuff repair, all sliding knots (locking or non-locking) should be followed up by a minimum of three reverse half hitches on alternating posts. Moreover, the load per suture for a standard 4 cm tear is suggested to range from 37.7 to 60.4 N. It depends on the number of suture anchors and sutures within each construct [34]. Knot tensile strength is a measure of the force that suture can withstand before it breaks when knotted. Tensile strength is measured by the time it takes for suturing material to lose 70–80% of its initial strength. Initial tensile strength is a measure of the amount of tension applied in a horizontal plane necessary to break the suturing material [35]. Barber et al. proved that newer high-strength sutures composed of ultrahigh molecular weight polyethylene (UHMWPE) show improved biomechanical properties including greater tensile strength and provide higher resistance for suture breakage [36, 37].

4.6 Stiffness

The suture's stiffness reflects its resistance to bending and it is an important parameter that affects knot security. It is known that monofilament sutures are usually stiffer than braided ones and an increase in suture size significantly increases its stiffness. According to Najibi et al. who compared the biomechanical properties of 11 commonly used sutures in orthopedics, the highest stiffness was calculated for 5 FiberWire and the lowest for 2-0 Vicryl [38]. The stiffness of material used in UHMWPE sutures leads to more knot slippage. This property gives knots constructed with UHMWPE suture material a higher tendency for slippage. According to Barber et al., even backing up knots using four reversed half hitches on alternating posts does not guarantee definitive knot security when tying knots with this material [36, 37].

4.7 Elasticity and Viscoelasticity

The variability between the suture materials for each knot represents differences in elasticity, flexibility, and surface frictional properties of the different suture materials. Elasticity, stress, and strain are the tensile characteristics of a material used to tie the knot. The term "elasticity" is a measure of the stress required to effect a standard elongation of the distance between the clamps in biomechanical testing prior to reverse slippage of the knot and could be defined as stress-to-strain ratio. In the biomechanical analysis of five knots performed by Shimi et al. the authors revealed that silk, polyamide, and Dacron manifested similar elasticity in all the knots examined [39]. This was lower than the elasticity of lactomer and polydioxanone. On the other hand, Melzer and Roeder knots had similar elasticity for the ligature materials tested, but this was lower than the elasticity of Tayside, Cross square, and Blood knots. From the mentioned analysis, it is known as well that slipknots tied with materials of small diameter (2/0) tend to be more elastic than those tied with thicker materials (1/0, 0/0) although the differences between ligature sizes for this variable were not significant in the investigation.

Elasticity is one of well-known parameter in load-to-failure tests in biomechanical studies when assessing knot, and it is inversely related to its ability to stack. For the knots of a similar configuration (for instance, Melzer and Roeder knots), a similar "knot elasticity" could be observed. For these two knots, less stress is required to effect a standard elongation since some of the energy is expanded in incremental stacking of the knots [39]. However, it is an obvious fact that different suture materials give a different elasticity according to used material. Silk, polyamide, and Dacron are relatively inelastic materials and were found to have a lower elasticity than polydioxanone or lactomer in all the knots examined in the analysis by Shimi et al. Polydioxanone exhibited the highest elasticity in all the knots. As expected, the smaller-diameter suture materials resulted in slightly more elastic knots [39].

It is important to note that elasticity can alter after sitting a knot in a human body, as the effect of hydration causing swelling of the material and changing of the surface frictional properties, torsional stiffness, and elasticity to varying extent depending on the nature and composition of the ligature material [39]. As a result of its higher elasticity, a well-known Orthocord tended to offer subjectively more elastic tension for knotting than FiberWire and Herculine. This and the findings of a trend toward better results in knot slide ability in comparison to Ultrabraid and in the general handling ability compared with FiberWire seem to be the reasons for a better overall ranking of Orthocord in the subjective testing of suture properties. With the best results for each tested handling property, Orthocord performed better than FiberWire and Ultrabraid in the summary of all handling qualities. The subjective impression of greater injuries to the surgeon's fingers by cutting with polyblend sutures could be attributed to stronger knot tightening by the surgeon. However, in the laboratory setting, the occurrence of injuries was not significantly higher with the polyblend sutures than with Ethibond [33].

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. The response of many materials depends not only on the load magnitude but also on its duration and time course. Deformations lag behind the load, and the indenter continues penetrating into the specimen even under constant load. Such materials are called viscoelastic or viscoelastic–plastic (Fig. 4.2). Parameters, characterizing viscoelastic–plastic properties, can be estimated from a simple five-step procedure. In the first step (I), the indenter is rapidly loaded to the nominal load. Then, a long dwell under this load follows (II), then rapid unloading to a very low load (III), followed by a long time under this load (IV), and finally unloading to zero (V). The response during dwell II provides the base for the determination of viscoelastic and viscoplastic parameters. In principle, the back creep in the low-load dwell IV could also be used for the determination of viscoelastic parameters. However, due to irreversible processes around a pointed indenter during loading, the unloading imprint profile differs from that during loading, and the extraction of material parameters from dwell IV requires a special procedure.

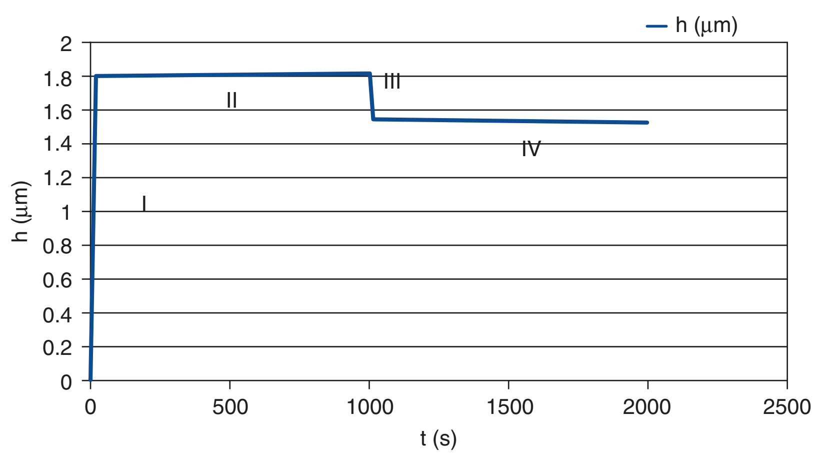

Fig. 4.2 Chart explaining viscoelastic materials maintenance on loading in five steps [40]

Nevertheless, this period can be used for verification of the duration of reversible viscoelastic processes [40].

Important factors in analyzing viscoelasticity of suture materials (polymers) are:

1. Creep (time-dependent deformation that occurs during application of constant load)
2. Relaxation (time-dependent decrease in load that occurs during application of constant deformation)
3. Strain rate dependence (material property dependence on rate at which loading occurs)
4. Material recovery (ability of suture to return to original size after removal of load)

In many investigations MagnumWire, Ethibond, FiberWire, Orthocord, and Force Fiber were compared and evaluated. In results FiberWire showed the greatest stiffness, smallest initial extension, and smallest creep during creep testing and the smallest peak-to-peak displacement during cyclic testing. Orthocord showed the smallest relaxed elongation on both creep and cyclic testing [41]. These data have many clinical relevance. It should be noted that mechanical properties of the suture interfere with tissue directly and have an increased effect on healing and rehabilitation process. The stiffness of sutures may in fact be correlated with a higher likelihood of repair failure, because of cutting effect of stiff materials. That is why using stiffer than usual materials should be promoted for adequate and less intense rehabilitation process.

In the investigations analyzing stress relaxation of the materials, Vizesi et al. [40] *have compared* (Fig. 4.3):

1. Prolene – a monofilament polypropylene
2. Ethilon – a monofilament nylon
3. Ticron – a braided polyester fiber

Prolene has the largest stress relaxation ratios (ratio of force from the initial 2 mm displacement to the force after the 10-min stress relaxation period) with a significant increase in the body temperature group. Both Ethilon and Ticron exhibited significantly lower amounts of stress relaxation when compared to Prolene and showed no significant temperature effects.

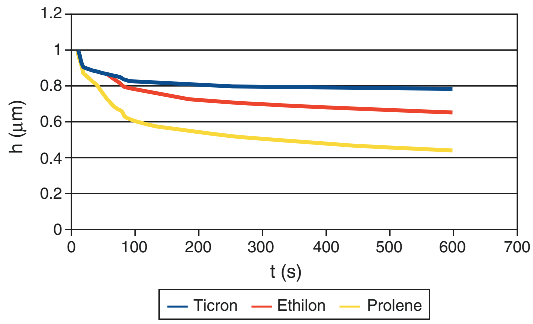

Fig. 4.3 Stress relaxation curves of Ticron, Prolene, and Ethilon sutures [40]

Differences between knot types' viscoelastic properties were analyzed by Vaibhav and colleagues [42]. After testing of viscoelastic properties of six common arthroscopic sliding knots (Tennessee slider, Roeder knot, SMC knot, Duncan loop, Weston knot, and Nicky's knot), the authors concluded that stress relaxation and knot types were similar, except Roeder knot which presented significant increase of relaxation and elongation. Furthermore, results lead to conclusion that suture material is responsible for at least 75% of the stress relaxation. These results suggest as well that using knotless techniques for securing the rotator cuff will not change the stress relaxation characteristics of the suture bridge as it relates to the knot.

4.8 Abrasion Resistance

Abrasion resistance as the ability of materials to withstand the effects of abrasion was hardly studied in the field of surgery. Most studies focused on abrasion resistance of suture materials or influence of different factors on abrasion effects of the sutures. Nowadays it is a well-known fact that suture abrasion differs according to the:

1. Suture material
2. Anchor type
3. Knot type
4. Testing conditions

As a result of studies comparing monofilaments and braided materials, it was proven on soft-tissue testing that the monofilament sutures showed the least amount of abrasion, followed by the braided polyblend and then the braided polyester sutures. On bone testing the braided polyblend sutures showed significantly increased suture failure resistance through a trans-osseous tunnel [43].

According to the results of comparative investigation of FiberWire and Ethibond By Lo et al. it is known that FiberWire has superior resistance to abrasion when compared with Ethibond under all anchors in common clinical using [4]. However it was also shown that Orthocord braided suture was by far the least abrasive and therefore had the least cutting effect on the absorbable anchors. Higher abrasion resistance of the sutures can be unfortunately the risk factor of cartilage injury. A study showed that intraarticular placement of the high strength braided material caused significantly more cartilage injury by friction than the monofilament degradable suture [25]. All in all, we have to remember that suture eyelets formed from biodegradable materials can fail even at low numbers of cycles, as a result of cutting by the suture going through the biodegradable eyelet during cyclic loading [11]. However, there are plenty of factors which can change the pace of failing.

Testing conditions also have relevant influence on results of abrasion resistance of the sutures. In wet conditions or using lubricate, sutures failed at significantly higher cycles of loading when compared with dry conditions. What is more, suture-to-anchor angle may play a role as well, and an angle of 45° increases suture abrasion in biomechanical testing.

Influence of knot type on suture abrasion was analyzed in the investigation by Longo and colleagues, when they have compared sliding knots with others. They revealed that sliding knots had many advantages because that kind of knot can be slid down the post limb without allowing the loop to loosen. However, one should be careful with that type of knots, because there is a risk of sliding the suture through the tissue, or along the anchor, causing abrasion and weakening of the suture itself [5].

Type of the anchor is another factor influencing risk of abrasion. In metallic anchors the surfaces tended to be rough with sharp edges and the absorbable implants typically had smoother edges. As a result sutures for the absorbable devices tended not to abrade or break when subjected to cyclic loads [44].

The results suggest unambiguously that material of suture, anchor type, knot type, and intraoperative conditions have influence on suture breakage and finally effect of reconstruction in continuance. As mentioned above, it should be underlined that suture breakage might occur during knot tying secondary to abrasion from the anchor eyelet as well [11]. If a suture abrasion is present, the second anchor should be placed to protect the first knot.

4.9 Static Creep and Dynamic Creep

Static creep is a physical property of materials that results in progressive deformation when a constant load is applied over time; it allows soft tissues to tolerate applied loads by lengthening [45]. It is defined as time-dependent deformation during application of constant load. In the investigations by Vizesi et al. [40], the authors have compared Prolene (a monofilament polypropylene), Ethilon (a monofilament nylon), and Ticron (a braided polyester fiber) (Figs. 4.4 and 4.5). The largest creep ratio (ratio of total displacement after the 10-min creep period to the initial dis-

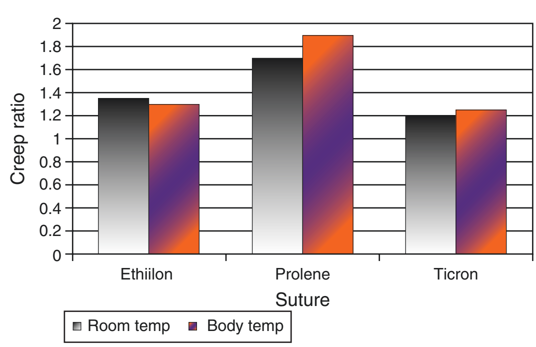

Fig. 4.4 Creep ratios of Ethilon, Prolene, and Ticron sutures in various temperatures [40]

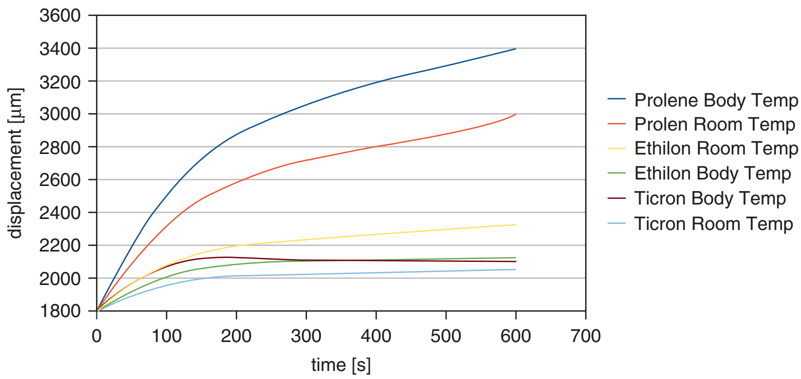

Fig. 4.5 Creep curves of Prolene, Ethilon, and Ticron sutures on various temperatures [40]

placement) was seen in the Prolene samples, with significant lower result for Ethilon. In turn, Ethilon exhibited a notably larger creep ratio than Ticron. In theory, the creep properties depend on temperature effects, but in the mentioned study, the significant temperature effects on the creep ratio were observed only in Prolene. This suggests the time- and temperature-dependent mechanical properties of sutures are influenced not only by the structure but also by the type of material. The purpose of the study by Milia et al. was to provide material property characterization of suture materials in order to select adequate sutures for specific surgical applications [46].

4.10 Load to failure and Mode of Failure

Load to failure and mode of failure are two terms used most often to describe processes of knot failing. Load to failure is the maximum tensile strength of the knot, and applying higher force than this rate leads to destruction of the knot. Clinical load to failure is usually defined as force which causes knot elongation of 3 mm after loading [36]. Ultimate load to failure is defined as force causing complete fracture of the knot. There are plenty of factors determining failure properties of the knots, and the most significant are knot type, suture material, throw quantity, surgeon experience, and use of tying instruments in arthroscopic surgery.

Studies comparing knot types' influence on failure resistance showed that double-twist knot was superior to other knots when evaluating ultimate load and load to clinical failure [3, 10, 37]. Unfortunately this knot has substantial limitations like poor performance in loop security and cyclic elongation, so the French knot and Nicky's knot which were ranked in the top of biomechanical properties were recommended. In the investigation comparing open and arthroscopic knot tying, the authors showed that openly tied knots achieved significantly higher values for the maximum tensile strength at load to failure [36].

Also suture material is substantial factor of biomechanical properties of the knots. Studies by Loutzenheiser et al. showed that braided polyester sutures had smaller displacement in load-to-failure test compared with monofilament sutures [11]. From braided sutures, Ethibond showed a significantly lower and FiberWire statistically higher failure load [25, 37]; however some tests revealed that the SMC knot using MaxBraid braided suture provided the strongest knot/suture combination of knots and sutures [1].

The tests evaluated load to failure revealed that to confer knot security, at least five flat square throws should be used, based on a binomial proportion score 95% confidence interval. FiberWire requires six flat square throws per knot for security at either 95% level. For surgeons usually based on own knowledge and experience for specific application, the default should be a minimum of four throws, with five conferring additional security in most situations, and six throws when FiberWire is used [14].

Studies comparing instrumental and hand-tied knots revealed that using braided suture, knot displacement for the mechanical end-splitting knot tightener did not differ statistically from hand-tied knots. Knots tied with this device also withstood the greatest load to failure and were statistically similar to hand-tied knots. The single-hole pusher and the cannulated double-diameter pushers were statistically less secure than hand-tied knots or those tied with the end-splitting tightener. Studies provided that the specific knot-tying instrument that is selected for use in arthroscopic shoulder surgery may play an important role in the degree of ultimate knot security achieved in suture repair, so end-splitting tightener which provides the most secure arthroscopic knots might be recommended. Surveys comparing instrumental and hand-tied knot using braided and monofilament sutures revealed no differences in the strength of hand-tied and pusher-tied knots for braided suture, but differences have been shown for monofilament suture [11, 46].

Surgical experience and proper surgical training have essential meaning for tying secure and consistent knots. Some studies revealed that either surgeons with less than 10 years in practice or surgeons who performed >200 shoulder arthroscopies per year are able to tie more stronger and consistent knots than surgeons who are practicing longer, but performs less than 200 shoulder procedures yearly. Those results are probably caused by training during residency under the auspices of very experienced superiors. This study showed as well that testing of the ability to tie secure knots as part of a surgeons' training was meaningful [11, 12].

Mode of failure is used to define the mechanism of the knot failure. Unraveling or knot break, loosening or slippage are some examples. Slippage tendency depends on knot's type, suture type, and other conditional factors like surgeon experience or instruments used for knot tying. The survey on the suture materials revealed that braided sutures had higher tendency for knot slippage with FiberWire than with Ethibond, as a result of the surface properties and specific construction characteristics of FiberWire suture [5, 25, 41, 47]. Some papers comparing arthroscopic knots revealed that Duncan loops and Weston knots slipped more than other knots, while the SMC and Revo knots slipped least. What is more, all static surgeon's knots outperform Tennessee sliding knots. It is worthwhile to note as well that at least one switched-post is necessary to avoid slippage for all knot configurations regardless of suture material. Adding additional switched-posts augments knot security [1, 7, 11, 37].

4.11 Cyclic Loading

Cycling loading is a type of mechanical testing used for evaluating knot security, next to load to failure. However, ultimate loads to failure may not reflect accurately the clinical condition. As pointed out by Burkhart et al., cycling loading compared to load to failure is more representative of the physiologic loads as regards rotator cuff repairs. It better represents the type of load to which the shoulder is subjected in daily activities during repeated movements [48]. Barber et al. suggested that cyclic load testing would provide practical information about how successful suture anchor repairs might be in the clinical setting. They concluded that most displacement with cyclic loading occurring between the anchor and bone takes place in the first 100 cycles [49].

Livermore et al. tested four braided polyblend sutures (FiberWire, Herculine, Orthocord, and Ultrabraid) with various sliding knot configurations during cycling loading at a frequency of 1 Hz from 6 N to 30 N for 1000 cycles. The authors found all knots appeared to be durable with respect to resistance to loosening under cyclic loading conditions, and the Weston knot with three RHAPs using Ultrabraid provided the best loop and knot security [10].

4.12 Yield Load

Yield load is the load beyond which a repair construct is permanently deformed and will not retain its original shape. In the study mentioned previously by Barber et al., the yield load was the force required to elongate 5 mm the suture anchor–bone construct from its baseline insertion [49].

Conclusion

For a knot to be effective, it must have both knot security and loop security [10]. Loop security is distinguished from knot security by the fact that a suture material with a large elastic elongation (i.e., low elastic modulus) can stretch, resulting in a loose loop even if the knot is completely secure. The ideal knot would be easy to tie and reproducible and would not slip or stretch before the tissue has healed [10]. Other biomechanical terms influencing a tied knot are loop circumference, friction, strength, stiffness, and viscoelasticity, as well as abrasion resistance and static and dynamic creep. Problems connected with running down forces, load to failure, cyclic loading, yield load, and elongation also play a role. A lot of biomechanical analyses and investigations were done to better understand the processes coexisting of tying a specified material and to create efficient and strong knot, leading to a good result of surgery.

Taking all information from the chapter into consideration, we can extrapolate that there are multiple determinants of knot security and all factors need to be analyzed when trying to obtain a secure knot. Nevertheless, according to analysis by Mahar et al, and colleagues [6], one has to remember that without differences between knot types, surgeons could use the type of knot they are most comfortable with, rather than attempt a knot with which they are unfamiliar in an effort to maximize security.

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5 Failure Modes of Knots and Sutures

Ali Öçgüder and Michael Medvecky

The purpose of a surgical knot is to hold the tissue in a desired position and resist tension until biological repair and healing are achieved. Different types of knots and sutures are used in orthopedic procedures. Moreover, in the recent years, open knot tying have been replaced by arthroscopic techniques.

Knots are commonly used on tendon-to-tendon, tendon-to-bone, ligament-to-bone, or bone-to-bone interface and needed a high resistance against tension. Although surgeons try to keep their repair zone free of tension, there will always be some amount of tension. Knots and sutures [1, 2] are not stand-alone variables in a repair construct. The quality of the bone [3, 4] and tendon [5], contact surface [6, 7], and anchor type [8] are other variables that directly effect a repair construct. Failure of any of these factors can destroy the repair construct. In this chapter we will focus on the failure modes of knots and sutures. Common failure modes of knots and sutures are suture breakage, knot loosening, knot breakage, and tissue breakage.

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5.1 Suture Breakage

Suture breakage is the loss of the architectural construction of the material. By the use of new-generation sutures, this failure mode decreased significantly. When choosing a suture, the surgeon can learn the strength by checking the ultimate load to failure data regarding the suture type. Ultimate load to failure represents the suture's maximum resistance against a constantly increasing force till total suture breakage. Suture breakage usually occurs on weakened sutures. Anchor eyelets, bone edges, implants, surgical instruments, or needles can damage sutures during surgery. Proper attention may decrease unwanted suture damage. Wright et al. studied the mechanical properties of different sutures damaged by a razor cut involving 20% of the suture width. Authors reported that damaged UHMWP sutures show less compromise to their biomechanical properties compared to PDS [9]. Sutures may also break due to too much tension during knot tying. In order to prevent this complication, tissue tension should be minimized before tying the knot.

5.2 Knot Loosening or Slippage

This usually occurs due to technical errors while tying the knot. In the literature it is shown that experienced surgeons are tying better arthroscopic knots compared to inexperienced ones [10]. Two biomechanical terms should be kept in mind to

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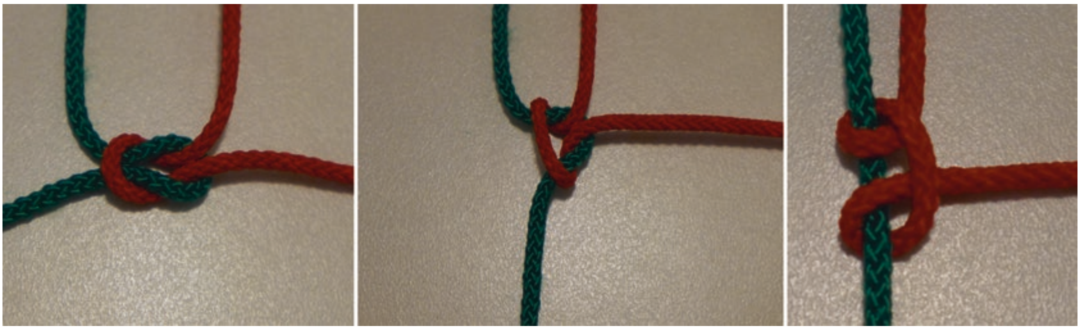

Fig. 5.1 From left to right; pulling the green limb of the square knot, converts the knot to a slip configuration consisting of two half-hitches on green limb

understand the causes of loosening; loop and knot security. Loop security is the ability to conserve loop diameter, before any load is applied while the knot is tied [11]. Knot security is the ability to resist complete slippage [12]. Knot loosening is the loss of knot security. These features are tested mechanically by two procedures, cyclic loading and load to failure. Cyclic loading mimics daily activities, and load to failure tests the maximum load that a knot and/or a loop withstands [13–15]. Usually a 3 mm increase in the loop means permanent loss of security [11]. The main factors effecting loosening are technical errors and knot characteristics.

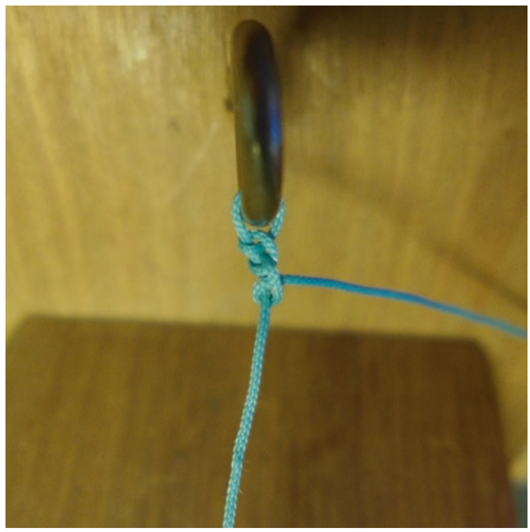

Fig. 5.2 Improperly placed three consecutive half hitches with evident slacks

5.2.1 Technical Errors

- Too much tissue tension on the repair zone may decrease the loop security before tying the knot. This will usually end up with an increased loop diameter and reduced tissue apposition.
- Applying tension on the wrong limb will usually affect the loop security. For example, while making a square or a surgeon's knot, tension should be applied oppositely and evenly on both limbs. If the surgeon applies tension on a single limb, then these knots shift to a sliding knot configuration (Fig. 5.1). This can decrease the loop security at time zero.
- On sliding knots, the surgeon should apply a constant tension on the post limb by pulling it; this maneuver slides the knot on the soft tissue and helps reduction. This tensioning should not be ended till the knot is securely locked; otherwise the loop may not hold the tissues together. Sliding knots with higher loop security have a better resistance against such a scenario.
- Leaving slack within the knot configuration decreases the loop security (Fig. 5.2).
- Improper selection of knots may end up with knot loosening. Some knots have superior loop and knot security performances. Knots with superior loop security performance should be used in repairs where higher displacement forces are predicted.
- Inability to construct a proper interference within half hitches. A minimum of three

reverse half hitches on alternating posts are generally advised on slip knots; otherwise knot slippage is inevitable [1].

- Before locking a knot, loop diameter should be controlled; if needed, a surgical instrument can be used to keep the desired loop diameter (Fig. 5.3).
- Immature locking of slip knots ends up with increased loop diameter and reduced tissue apposition.
- Tissue interposition within the loop will relatively affect the loop security. A neighboring soft tissue can be trapped within the loop, and this tissue usually goes to necrosis after the surgery and causes an unwanted slack within the loop.
- Improper selection of sutures is an important issue. Different sutures have various handling capabilities and strength, which affects the outcome. For example, monofilament sutures have lesser coefficient of friction compared to multifilament sutures; therefore, it is much more difficult to maintain desired security. Manipulation of monofilament sutures can be much more demanding in arthroscopic tying because reducing slacks is difficult compared to multifilament sutures.

5.2.2 Knot Characteristics

Selection of the proper knot for the suture type and the desired tissue fixation is an important point. Some sutures may not provide the desired security with all knot types [16]. For example, monofilament sutures have a tendency to leave slack between half hitches. Therefore they are not a good option for arthroscopic sliding knots. On the other hand, new-generation ultrahigh molecular weight polyethylene (UHMWPE) sutures are easier to handle and slide; these features make them a good option for arthroscopic surgeries [16].

Surgeon should know differing knot characteristics. Various knots have different internal constructs which are also known as interference. The architecture of the knot provides its loop and knot security. The surgeon should choose the proper knot due to the security needed on the tissue. A knot used while closing the subcutaneous tissue can be a simple knot such as a square knot. On the other hand, while reducing a fracture or completing a tenodesis, a knot with sufficient interference and sliding capability is generally needed.

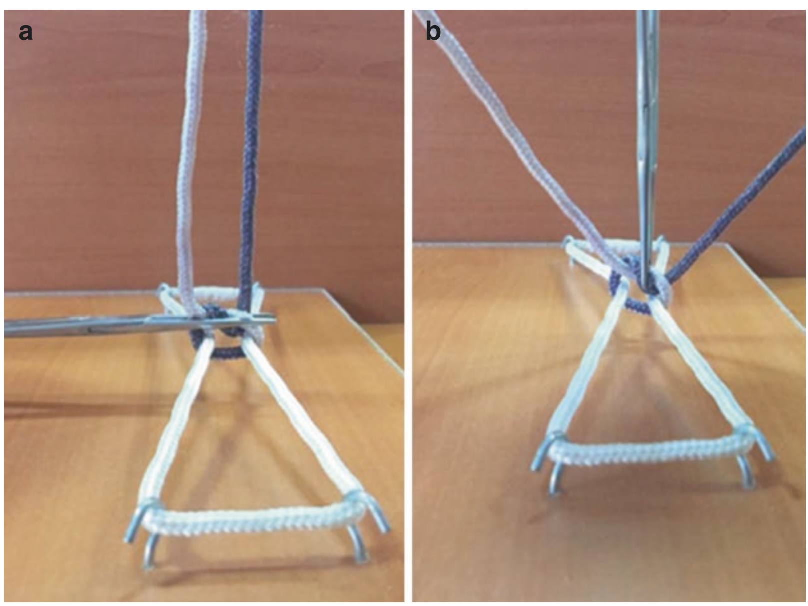

Fig. 5.3 In case of tissue tension, instruments are needed to keep loop diameter before securing the knot (**a**) Parallel placement of the instrument on the wraps that prevents suture damage during tying (**b**) Vertical placement of the instrument may cause suture damage during tying

5.3 Knot Breakage or Unraveling

Knot breakage is the loss of the knot security. Many of the failures due to knots are cause by knot breakages [17]. When the knot breaks, the loop of the suture will no longer be able to hold the tissues together. Physiologically all suture loops may extend minimally due to tissue edema and tension due to daily activities. This effect can be changed between various sutures and tissues. It is advised that free limbs (ears) of a completed knot should not be cut less than 3 mm length. Ears less than 3 mm may cause unraveling of the knot.

5.3.1 Knot Breakage Usually Occurs Due to Technical Errors

- Surgeon should know the correct construct of the knot and be able to tie it on dry models. Most of the time, inability to complete the desired knot configuration ends up with knot breakage.
- Slack within the knot usually cause elongation on the loop site and cause improper loads on the knot (Fig. 5.2).
- Inability to secure arthroscopic locking knots. Most of the arthroscopic locking knots have a special construct that should be flipped to be locked. Usually the surgeon shifts the tension applied on the limbs in order to complete this maneuver. Improper usage of the knot pusher or tensioning the wrong limb will also end up with an unsecure knot.
- All sliding knots (even the locking ones) need backup half hitches for an effective security. Many authors suggest reverse half hitches on alternating posts (RHAPs) even in locking arthroscopic knots [18].
- Improper selection of a knot may also cause a breakage. In some cases tissue approximation should be done under some tension; in such a scenario, the surgeon should choose a mechanically competent knot. Biomechanical studies of different knots are very helpful for the surgeons to decide on their knots.

5.4 Tissue Breakage

It is defined as the suture cutting through the tissue. Studies showed that besides new-generation sutures and implants, the weakest point on the rotator cuff repair is the suture—soft tissue interface. Factors causing the tissue breakage are tension on the repair zone, improper selection of suture, tying technique, and suture configuration.

5.4.1 Tension on the Repair Zone

Too much tissue tension is a serious enemy of the surgeon. It can interfere with biological healing of the tissues or cause tissue breakage. Tension on the repair zone can be static and cyclic. Static tension is the time zero tension on the repair zone that will continue or increase after the surgery. Cyclic tension is the tension caused by daily activities after the surgery. Cyclic tension can be controlled by different types of immobilization techniques. Surgeon should complete the repair with the minimum tension that can be obtained by proper tissue release. Otherwise sutures will cut the tissue like a cheese saw, or the tissue will be torn on the medial site of the repair (Fig. 5.4).

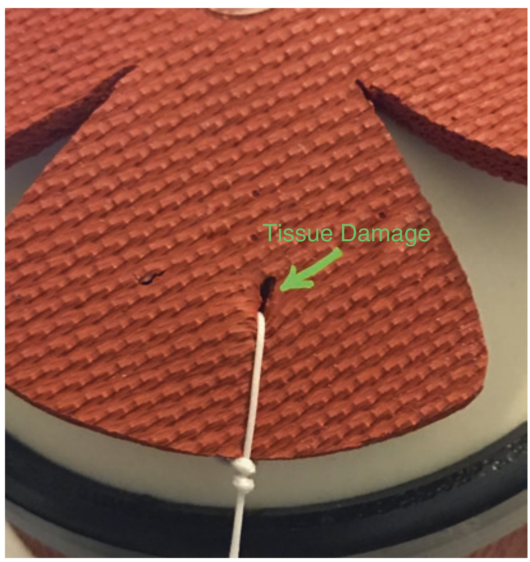

Fig. 5.4 Cheese saw effect of suture on tissue

5.4.2 Improper Selection of Sutures

The sawing effect of the suture on the tissue can be decreased by choosing the correct size and material. Sutures with a smooth surface can decrease the risk of tissue damage. Thinner sutures can cut through soft tissues with less forces compared to thicker ones.

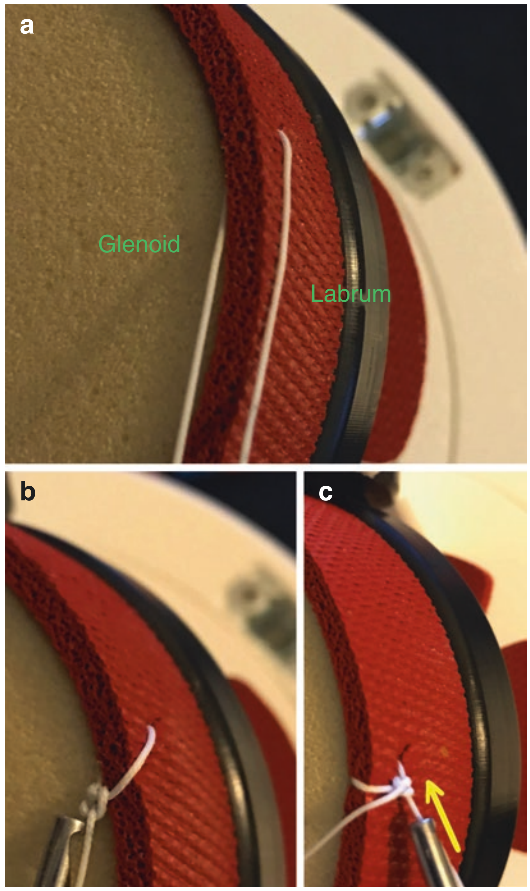

Fig. 5.5 (**a**) Anchor placed on glenoid edge; one suture limb is passed through the labral tissue. (**b**) If the limb on the glenoid site is selected as post, the knot will be seated on glenoid surface. This is a technical fault. (**c**) If the limb on the labral site is selected as post, the knot will be seated on the labrum. Sliding of the knot will further reduce the labrum on glenoid edge. This is the correct technique

5.4.3 Tying Technique

While tying the knots, soft tissue can be injured by two different mechanisms, suture slide and post limb on the wrong site.

- Sliding knots are usually advised to be used in reducing a tissue on an anchor. In such cases, the suture slides within the eyelet of the anchor and does not cause high amount of a cutting effect on the tissue. Using a sliding knot in reducing soft tissues without an anchor can generate a high amount of cutting effect though should not be a first-line option. For example, it is not advised to use sliding knots on meniscal repairs. In such cases, using half hitches can be a safe way to reduce the soft tissues.
- The post limb of the sutures should be placed on the tissue that needs to be reduced (Fig. 5.5). For example, in a Bankart repair with a simple suture configuration, post limb should be on the labral tissue; by this technique knot formed on the post will push the labrum against the glenoid edge. This is like a washer effect on a malleolar screw (Fig. 5.5). On the other hand, by this maneuver, the knot will be seated far from the glenoid edge and cause less irritation. If the post limb is selected on the glenoid site, the knot will not have any reducing effect on the labrum, and the working limb may also cause a cheese saw effect on the labral tissue.

5.4.4 Suture Configuration

Passage of sutures through the soft tissues is an important factor on relieving the tissue tension. Simple suture configuration usually causes high stress on the tissue edges. In a case with higher tension on the repair zone, this tension can be distributed by increasing the suture passages. Horizontal suture configurations or special suture configurations such as Mason-Allen technique will decrease the tissue breakage risk by relieving the tension. Increasing the soft tissue suture interface will also help to decrease the tension on the tissue. Good examples for this effect are classical tendon-to-tendon suture configurations such as Kessler and Krackow stitches.

Conclusion

Most of the knot and suture failures exist due to technical errors in tying and wrong selection of sutures or knots in different scenarios. Therefore, proper exercises on models will decrease such failures in real surgeries.

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Part II

Open Knot Tying

Square Knot

6

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and João Espregueira-Mendes

Square knot is a reliable and easy technique which can be used with various surgical sutures. It can be tied with free hand or a surgical instrument depending on the suture material. Parallel structure of the loops is the basis of square knot, and it is essential. The leg of the suture on the top during the preparation of the first loop should be on the top again in the second loop. Otherwise parallel structure of the loops can't be achieved, and the knot turns into a "granny knot."

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6.1 Square Knot Tying by the Hands

6.1.1 Left-Handed Square Knot Tying (Figs. 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10, and 6.11)

6.1.2 Right-Handed Square Knot Tying (Figs. 6.12, 6.13, 6.14, 6.15, 6.16, 6.17, 6.18, 6.19, 6.20, 6.21, and 6.22)

These steps can be repeated depending on the suture material, tissue tension, or surgeon's choice.

6.2 Tips and Tricks to Maintain Security in a Square Knot

- Equal tensioning of the threads is an important point to secure the square knot.
- Direction of the threads should be opposite and parallel to the wraps (Fig. 6.23). If not, threads and loop will be twisted.
- If one thread of the square knot is pulled, square knot will transform to a sliding knot consisting of two half hitches. This configuration tends to slip and does not lie flat (Fig. 6.24).

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- On the other hand this conversion can be used intentionally in deep tissue tying or reduction of tissues under tension (Fig. 6.25). In such a scenario, it may not be easy to convert the knot back to square configuration; surgeon can use RHAPs to secure the sliding configuration.

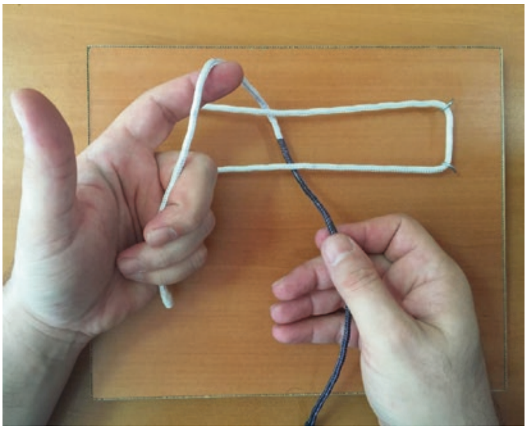

Fig. 6.1 (Step 1) Hands are on the both sides of the incision in the direction of the thread. White thread is supported by radial side of the left index finger, and free end is held loosely by the third, fourth, and fifth fingers. Free end of the black thread is held by right first and second fingers

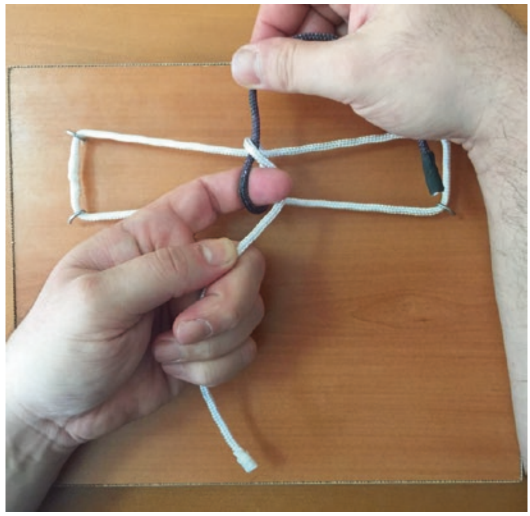

Fig. 6.3 (Step 3) By moving the free end of the white thread right and flexion of the distal phalanx of the left index finger, white thread is flipped under and the index fingernail leaned to it

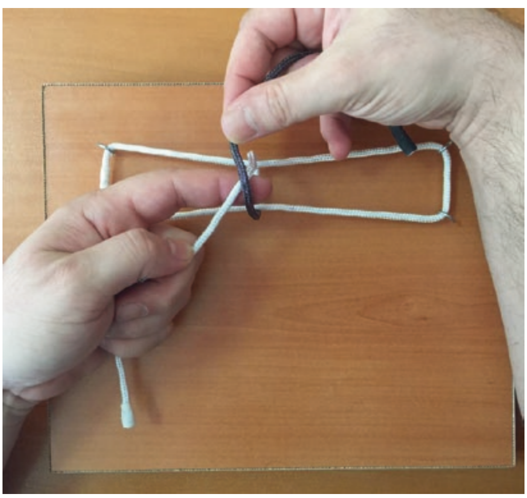

Fig. 6.2 (Step 2) Threads are crossed on the distal phalanx of the left index finger by moving the left hand downward and the right hand upward. In this manner a loop formed between black and white threads. Black thread is on the top (should be the same in the second loop)

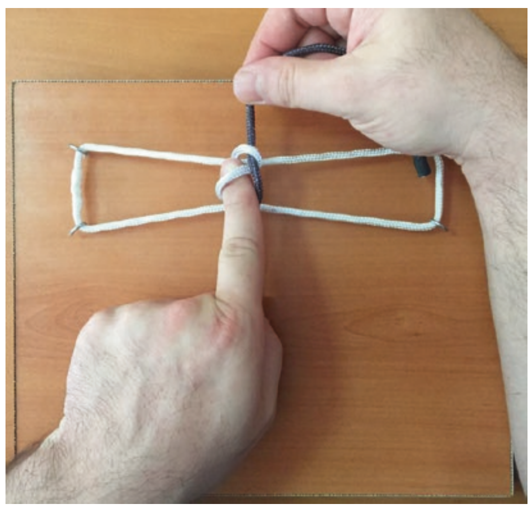

Fig. 6.4 (Step 4) White thread pulled through the loop by extension of the distal phalanx of the index finger

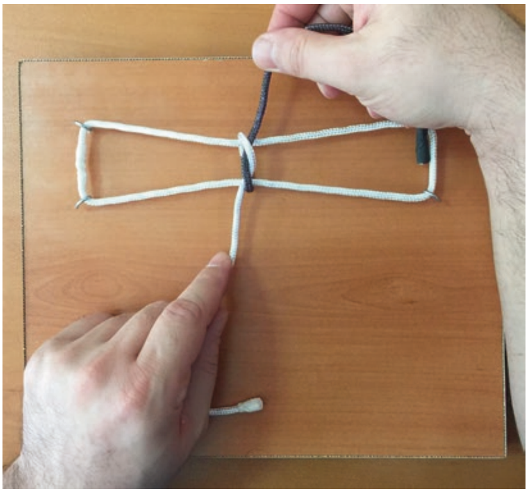

Fig. 6.5 (Step 5) White and black threads are pulled with equal tension across the incision and the loop pushed forward. In this step threads should be perpendicular to the incision, and pulling the threads to opposite directions is essential

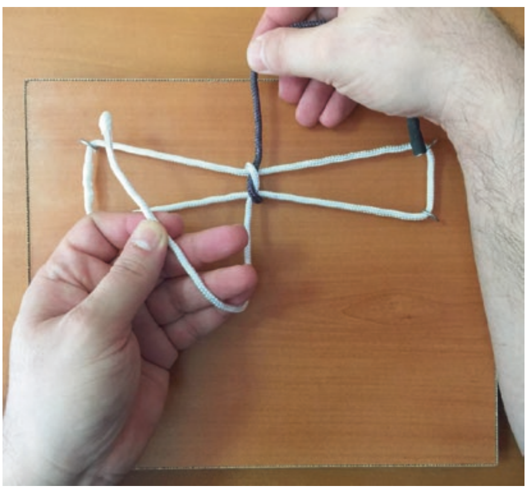

Fig. 6.6 (Step 6) White thread is supported by the ulnar side of the left fifth finger; free end of the white thread is held in the palm and black thread is held with right first and second fingers

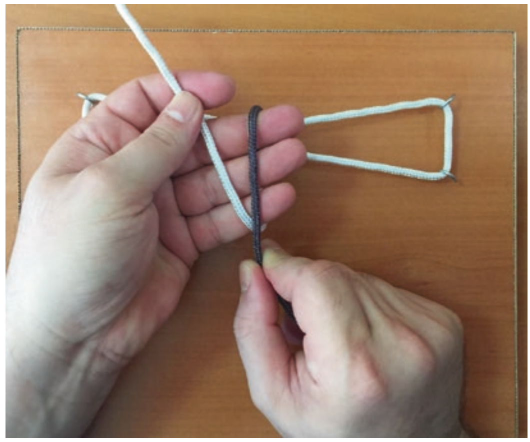

Fig. 6.7 (Step 7) Black thread is moved downward and supported by radial side of the third finger. In this manner threads crossed forming a loop. Black thread is over the white thread (same as the first loop)

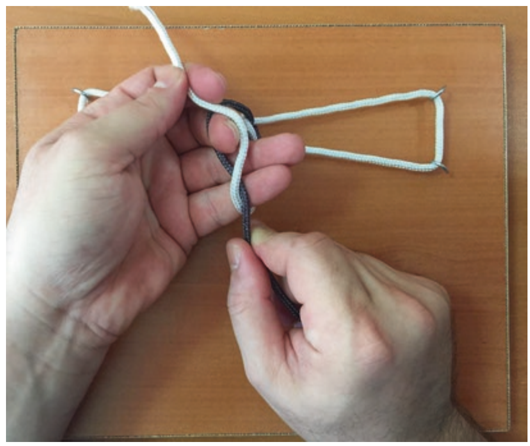

Fig. 6.8 (Step 8) Distal phalanx of the left third finger moved under the white thread by flexion, and white thread leaned on the nail of the left third finger

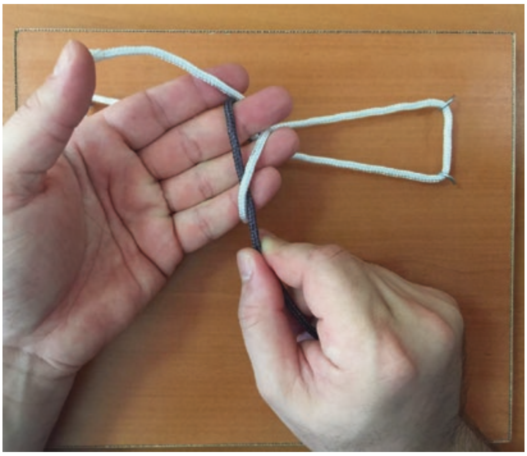

Fig. 6.9 (Step 9) White thread is pulled into the loop by dorsiflexion of the distal phalanx of the left third finger

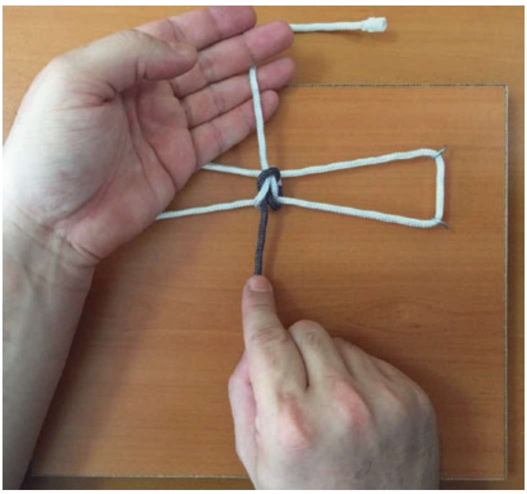

Fig. 6.10 (Step 10) White and black threads are pulled with equal tension across the incision and the loop pushed forward. Note the position of the white and black threads just the opposite of step 5

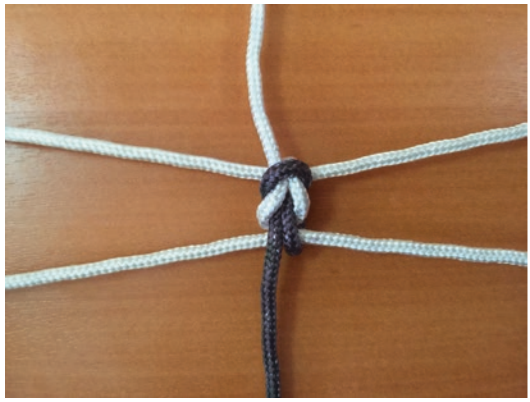

Fig. 6.11 “Square knot” is completed. Note the symmetry and the parallelism of the loops

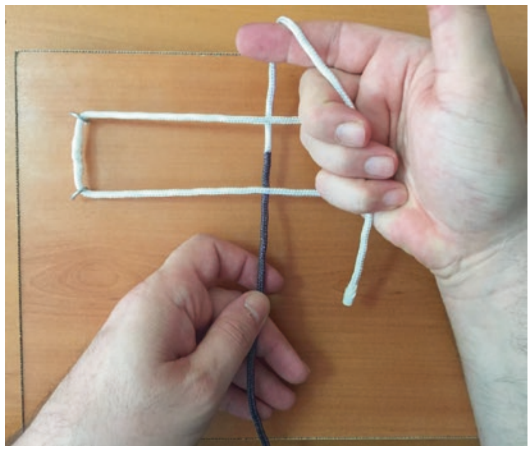

Fig. 6.12 (Step 1) Hands are on the both sides of the incision in the direction of the thread. White thread is supported by radial side of the right index finger, and free end is held loosely by third, fourth, and fifth fingers. Free end of the black thread is held by left first and second fingers

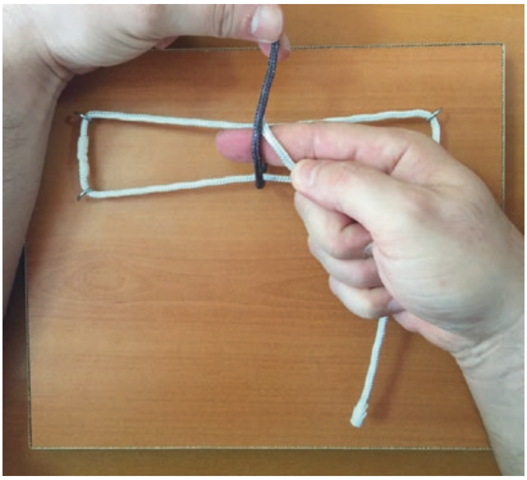

Fig. 6.13 (Step 2) Threads are crossed on the distal phalanx of the right index finger by moving right hand downward and left hand upward. In this manner a loop formed between black and white threads. Black thread is on the top (should be the same in the second loop)

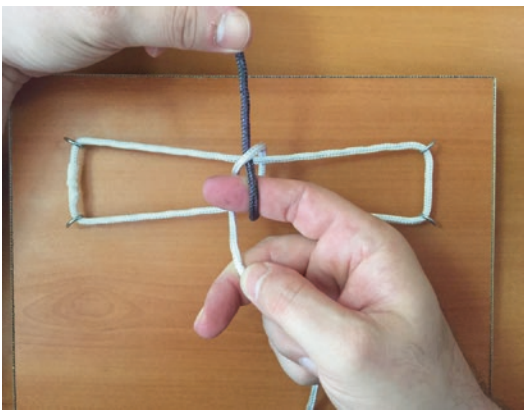

Fig. 6.14 (Step 3) By moving the free end of the white thread right and flexion of the distal phalanx of the right index finger, white thread is flipped under and the index fingernail leaned to it

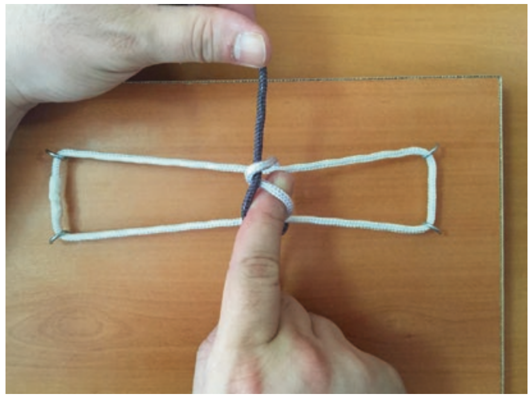

Fig. 6.15 (Step 4) White thread pulled through the loop by extension of the distal phalanx of the index finger

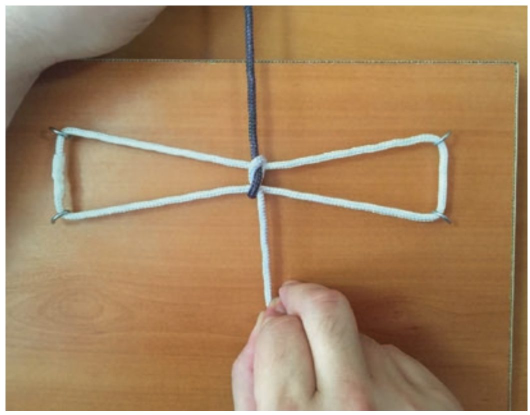

Fig. 6.16 (Step 5) White and black threads are pulled with equal tension across the incision and the loop pushed forward. In this step threads should be perpendicular to the incision, and pulling the threads to opposite directions is essential

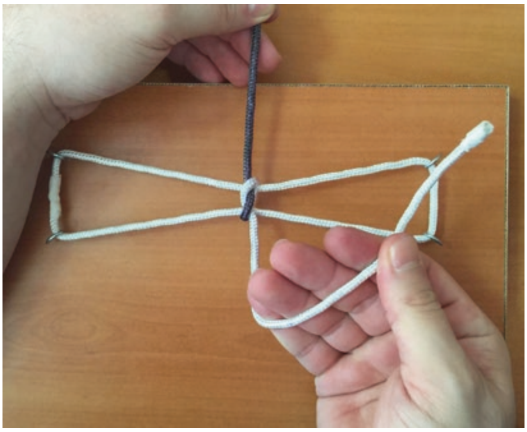

Fig. 6.17 (Step 6) White thread is supported by the ulnar side of the right fifth finger; free end of the white thread is held in the palm, and black thread is held with left first and second fingers

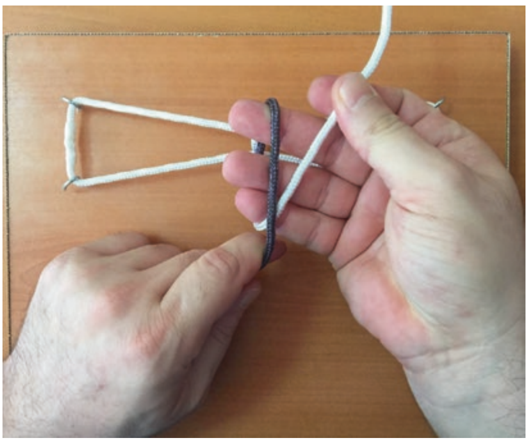

Fig. 6.18 (Step 7) Black thread moved downward and supported by radial side of the third finger. In this manner threads crossed forming a loop. Black thread is over the white thread (same as the first loop)

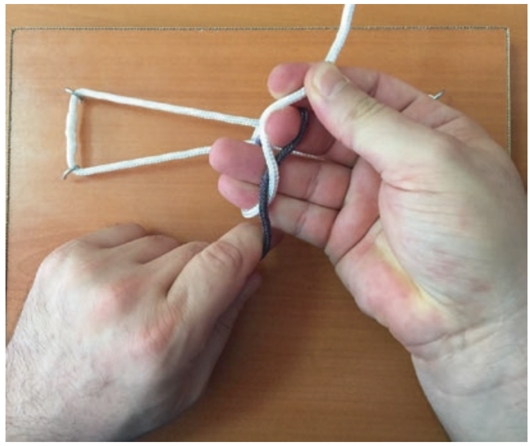

Fig. 6.19 (Step 8) Distal phalanx of the right third finger moved under the white thread by flexion, and white thread leaned on the nail of the right third finger

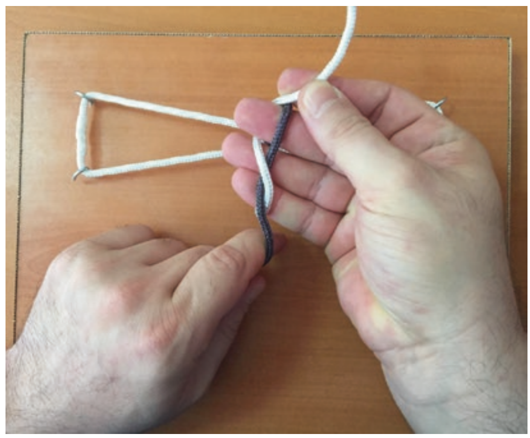

Fig. 6.20 (Step 9) White thread is pulled into the loop by dorsiflexion of the distal phalanx of the right third finger

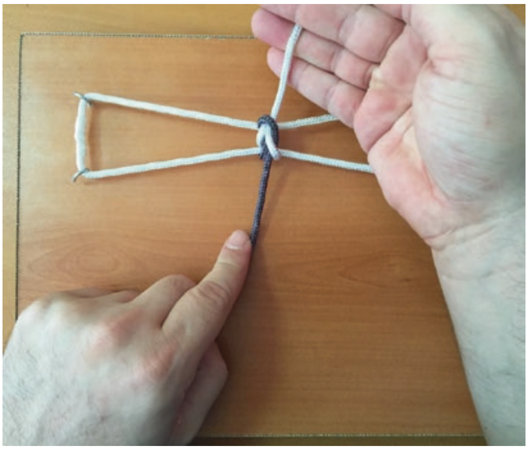

Fig. 6.21 (Step 10) White and black threads are pulled with equal tension across the incision and the loop pushed forward. Note the position of the white and black threads is just the opposite of the step 5

Fig. 6.22 Finished "square knot." Note the symmetry and the parallelism of the loops

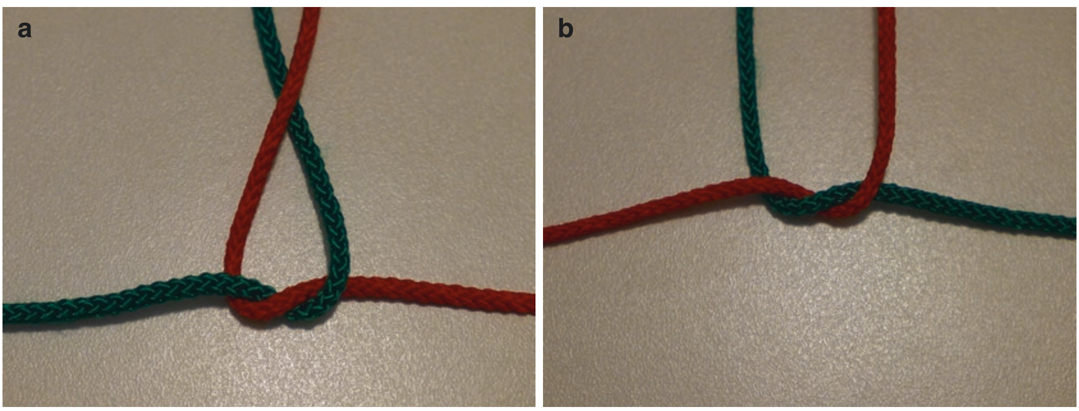

Fig. 6.23 (**a**) Improper pulling direction of threads causing twist on the loop. (**b**) Correct pulling direction of threads

Fig. 6.24 Square knot turns into a sliding half-hitch knot if more tension is applied to one end (in this case, white end).

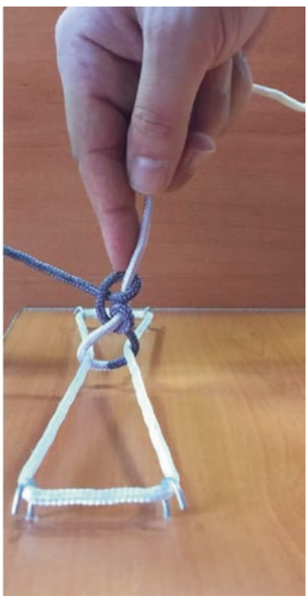

Fig. 6.25 Sliding half-hitch knot can be used intentionally for approximating the tissues

6.3 Square Knot Tying by an Instrument

Surgical instruments should be used when working with the threads with needles. Steps of square knot technique with surgical instruments are shown in the figures (Figs. 6.26, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32, and 6.33).

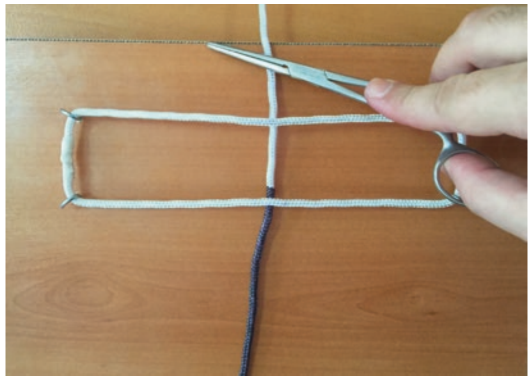

Fig. 6.26 (Step 1) White end of the thread assumed as needled end in this exercise. Surgical suture passed through the tissue and ready to be tied. Surgical instrument put on the white thread

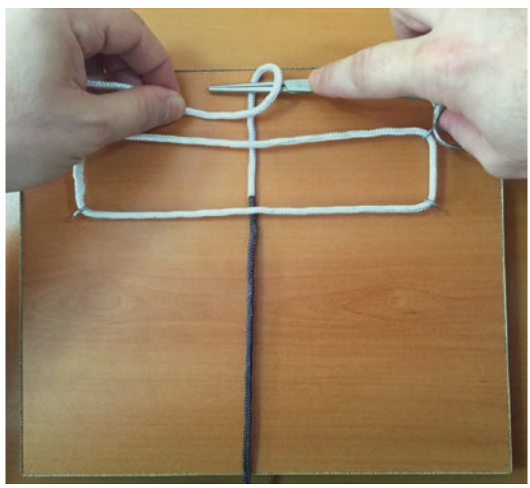

Fig. 6.27 (Step 2) White thread rolled over the surgical instrument to form a loop

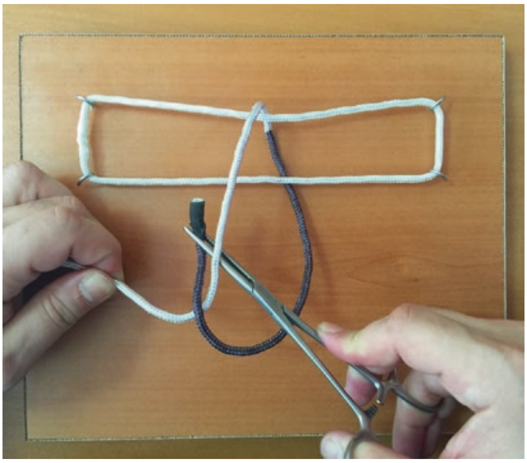

Fig. 6.28 (Step 3) Black thread end is caught with the surgical instrument without breaking the loop

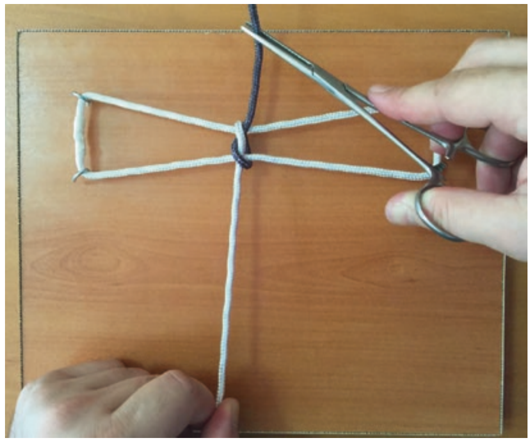

Fig. 6.30 (Step 5) Black and white threads are now on the opposite side to the prior positions and pulled to opposite directions with equal tension and perpendicular to the incision. First loop is set

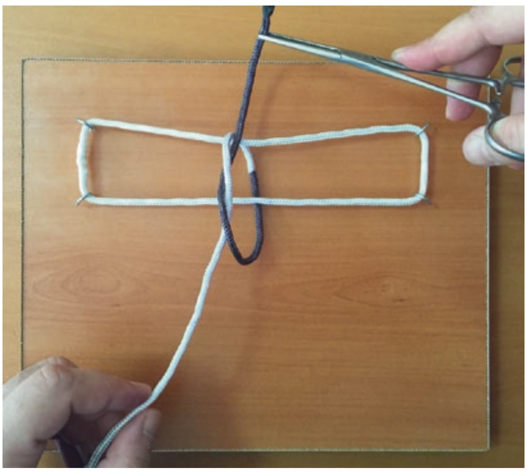

Fig. 6.29 (Step 4) Black thread passed through the white loop with the help of the surgical instrument

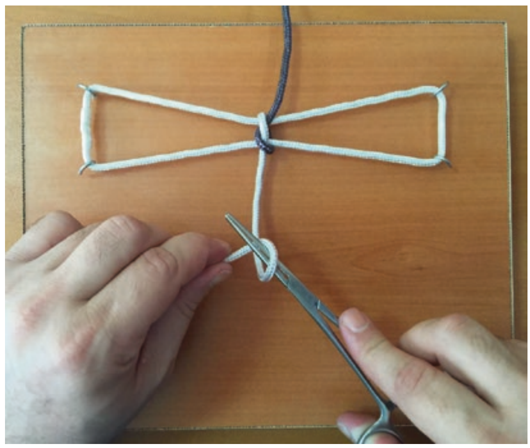

Fig. 6.31 (Step 6) Surgical instrument is put on the white thread again and white thread rolled over the surgical instrument to form a loop

Regardless of which hand is used to hold the surgical instrument, the key point is putting the instrument on the needled side of the thread and to wrap the thread around the surgical instrument (Figs. 6.26 and 6.27). In every step of tying a square knot with a surgical instrument, equal tension should be applied on both sides of the thread. The success and reliability of the knot depend on that fact. Note the parallelism of the consecutive loops in the completed square knot (Fig. 6.34).

Square knot is usually used in low-tension tissue sites but can also be used in higher-tension sites by utilizing the convertibility to a half-hitch configuration for approximating tissues as described above. It is also possible to resist the tissue tension without converting the square knot into a half-hitch configuration. In such a scenario, a surgical instrument is needed to keep the loop security in the first loop of the square knot, till the knot is secured. A needle holder can be used to grasp the wraps of the square knot in the first throw. As the instrument grasps the wraps, the loop is secured without loosening. One should grasp the wraps till the second throw of the square knot is completed. If the instrument is placed perpendicular to the wraps, this may damage the sutures. Parallel placement of the instrument on the wrap is an atraumatic method (Fig. 6.35).

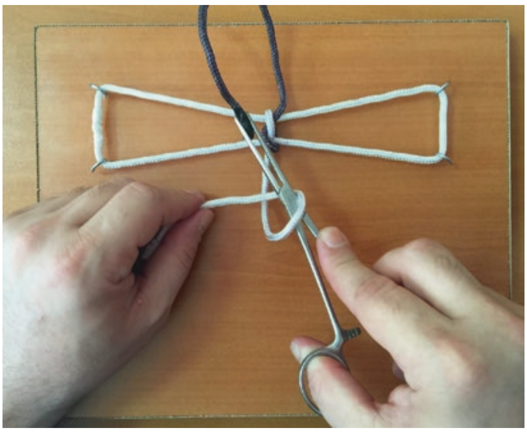

Fig. 6.32 (Step 7) Black thread end is caught with the surgical instrument without breaking the loop

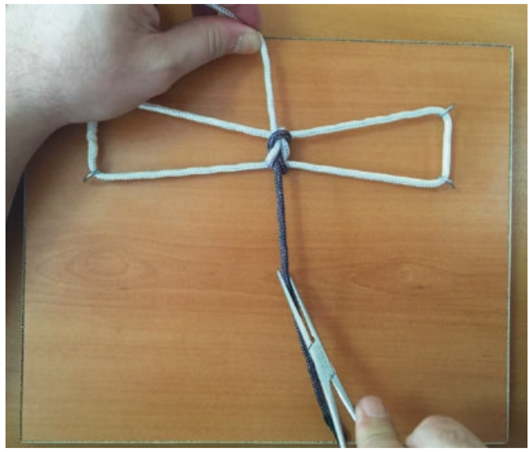

Fig. 6.33 (Step 8) Black thread passed through the white loop and pulled to opposite directions with equal tension and perpendicular to the incision. Square knot is completed

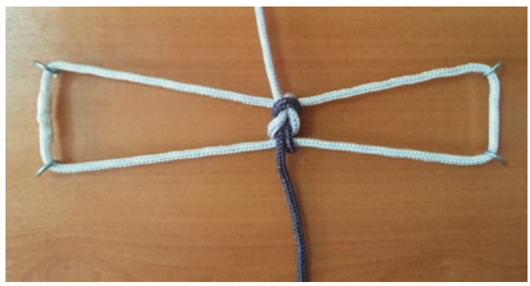

Fig. 6.34 Completed “square knot”

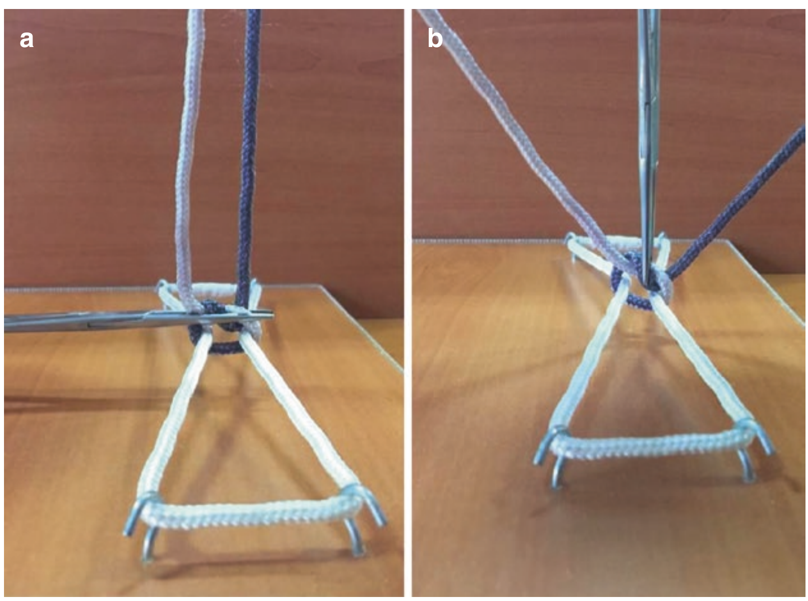

Fig. 6.35 Securing the loop of the first throw by grasping the wrap. (**a**) Parallel placement of the instrument may decrease suture damage. (**b**) Perpendicular placement of the instrument may cause suture damage

7 Surgeon's Knot

Katja Tecklenburg

Tying an open knot with an extra twist when tying the first throw should be one of many surgeon's basic skills. Such a knot is called a surgeon's knot. Therefore, the surgeon's knot is very similar to a square knot, except for the double twist in the first throw (Figs. 7.1 and 7.2). Any type of wound closure and sutures of the fascia and of the subcutaneous tissue are usually fixed with a surgeon's knot. Depending of the knotting technique—either by using hands only or by using a needle holder—there are several subtypes of a surgeon's knot. One-handed as well as two-handed techniques with numerous technical modifications have been described in the literature [1–7]. However, in many situations a surgeon prefers to use a needle holder when performing a surgeon's knot. The first throw of the knot again includes an extra twist around a needle holder, before two more throws with one twist each are being added. One of the three throws has to be performed in the opposite direction in order to achieve interlocking of the knot. Again, modifications do exist [8].

Biomechanical testing procedures show reliable strength and sufficient load to failure testing of an openly tied surgeon's knot, providing that an adequate suture material has been used. Baums MH et al. [9] interestingly found that any openly tied knot type achieves significantly higher values of tensile strength than arthroscopically tied knots.

Fig. 7.1 Surgeon's knot is very similar to a square knot, except for the double twist in the first throw

Fig. 7.2 Surgeon's knot after tying its ends

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7.1 Step-By-Step Demonstration of Surgeon's Knot by Using Left and Right Hands

7.1.1 Two-Handed Technique

Fig. 7.3 The orange suture is in the left hand; the black suture is in the right hand

Fig. 7.4 Bring the orange suture over the black suture while forming a 'U' with the left thumb and index finger

Fig. 7.5 Touch the left thumb and index finger and form a sling between the two suture strands

Fig. 7.6 Bring the left thumb through the suture sling as shown

Fig. 7.7 Throw the black suture over the orange suture while holding the left thumb as described in step 3

Fig. 7.8 Use the left index finger to push the black suture through the suture sling which is secured by the left thumb

Fig. 7.9 Release the black suture strand from the right hand, and complete the first twist while pushing the black suture through the sling with the left index finger

Fig. 7.10 Keep the left index finger in the sling while repeating step 5 in order to get an extra twist in the first throw. Keeping the left index finger in the sling facilitates this step

Fig. 7.11 Take the black suture strand with the right hand after pushing it through the sling for the second time

Fig. 7.12 Complete the first throw by pulling the black suture strand with the right hand and the orange suture strand with the left hand

Fig. 7.13 Tighten the first throw by pulling the black suture strand with the right hand and the orange suture strand with the left hand

Fig. 7.14 The tightness of the first throw can be reinforced by pushing down the throw with the left index finger while holding on to both suture strands

Fig. 7.15 To begin with the second throw, bring the black suture strand with the right hand back to the orange suture strand which remains in the left hand

Fig. 7.16 Form a sling around the left index finger and pass the black suture strand to the left thumb

Fig. 7.17 Push the black suture strand through the sling and toward you with the left thumb

Fig. 7.18 Take the black suture strand with the right hand while holding the orange suture strand in the left hand

Fig. 7.19 Pull the orange suture strand with the left hand toward the upward direction while holding the black suture strand in the right hand

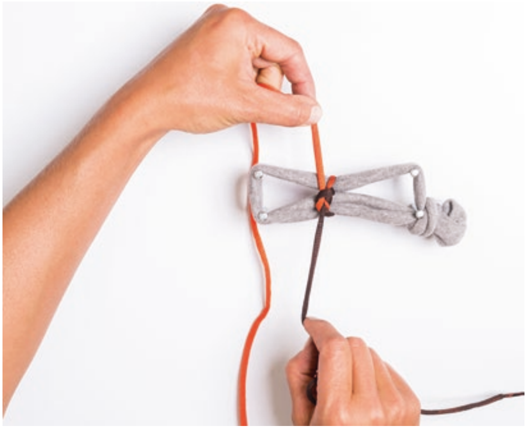

Fig. 7.20 Tighten the knot

Fig. 7.21 If necessary, reinforce the knot by pushing the orange suture strand down with the left index finger

7.1.2 One-Handed Technique, Left Hand

Fig. 7.22 Hold the orange suture strand in the left hand and the black suture strand in the right hand. Form a sling with the orange suture strand around the left index finger, and hold the orange suture string over the black suture string

Fig. 7.24 Complete the first twist by pulling the orange suture strand with the left index and middle fingers

Fig. 7.23 Push the orange suture string upward with the left thumb and catch the orange suture strand with the left index finger

Fig. 7.25 Pass the orange suture strand over to the left thumb

Fig. 7.26 Position the left index finger in the sling again, and push the orange suture strand with the left thumb underneath the black suture strand

Fig. 7.27 Catch the orange suture strand with the left index finger as described in step 2 to get an extra twist in the first throw

Fig. 7.28 Pull the orange suture strand with the left hand, while the black suture strand remains in the right hand

Fig. 7.29 Reinforce the first throw by pushing the orange suture strand down with the left index finger

Fig. 7.30 The first throw with two twists is completed

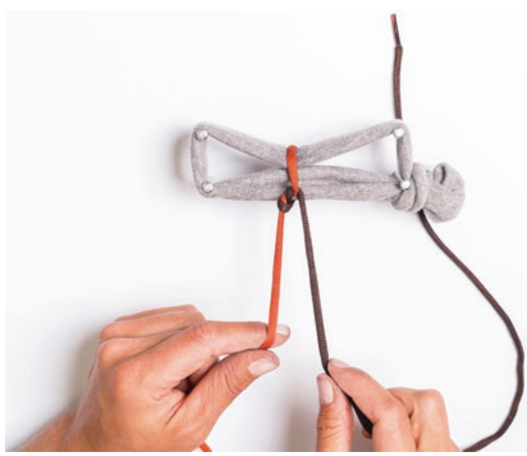

Fig. 7.31 Hold both suture strands with both hands toward you

Fig. 7.32 Form a sling by pushing the orange suture strand with the left middle finger underneath the black suture strand

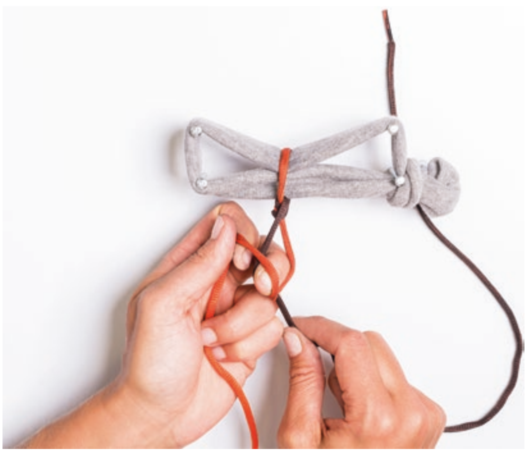

Fig. 7.33 Catch the orange suture sling with the left middle finger while holding the end of the orange suture strand with the left index finger and the thumb

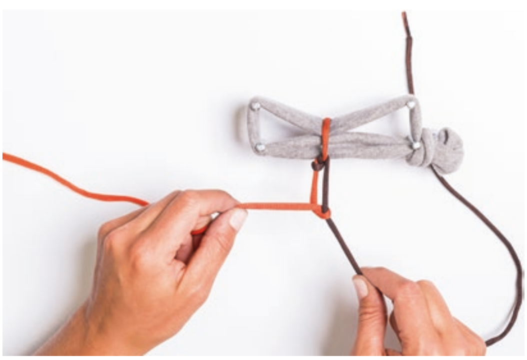

Fig. 7.34 Form the second throw after releasing and taking up the end of the orange suture strand with the left hand

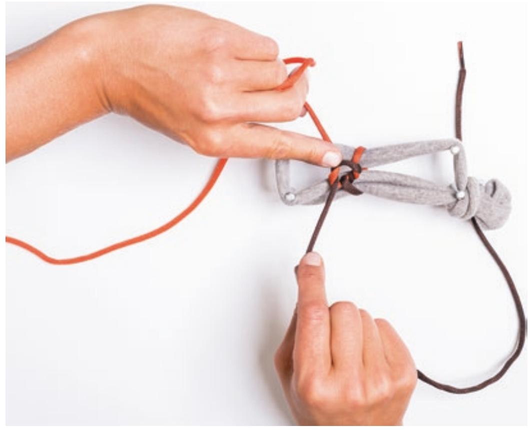

Fig. 7.35 Tighten the second throw by pushing down the orange suture sling with the left index finger

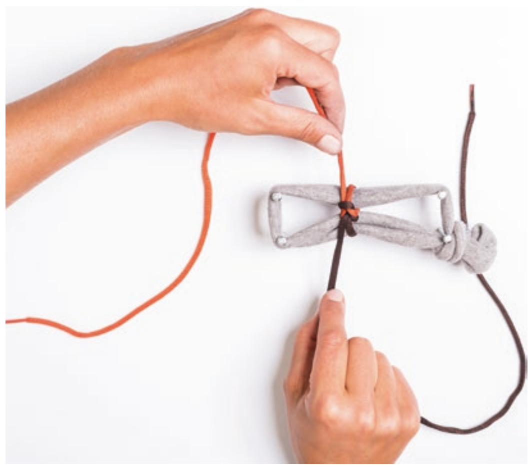

Fig. 7.36 The knot is completed

7.1.3 One-Handed Technique, Right Hand

Fig. 7.37 Hold the orange suture strand in the right hand and the black suture strand in the left hand. Form a sling with the orange suture strand around the right index finger, and hold the orange suture string over the black suture string

Fig. 7.38 Push the orange suture string upward with the right thumb, and catch the orange suture strand with the right index finger

Fig. 7.39 Complete the first twist by pulling the orange suture strand with the right index and middle fingers

Fig. 7.40 Pass the orange suture strand over to the right thumb

Fig. 7.41 Position the right index finger in the sling again, and push the orange suture strand with the right thumb underneath the black suture strand

Fig. 7.42 Catch the orange suture strand with the right index finger as described in step 2 to get an extra twist in the first throw

Fig. 7.43 Pull the orange suture strand with the right hand, while the black suture strand remains in the left hand

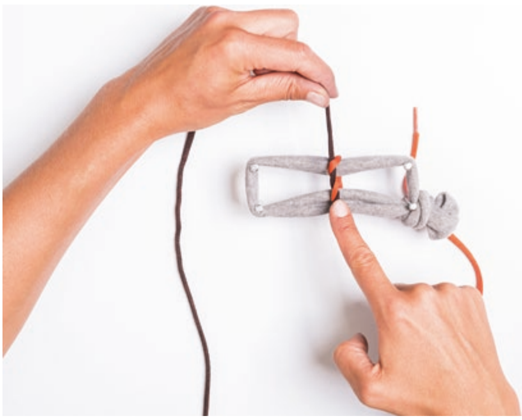

Fig. 7.44 Reinforce the first throw by pushing the orange suture strand down with the right index finger

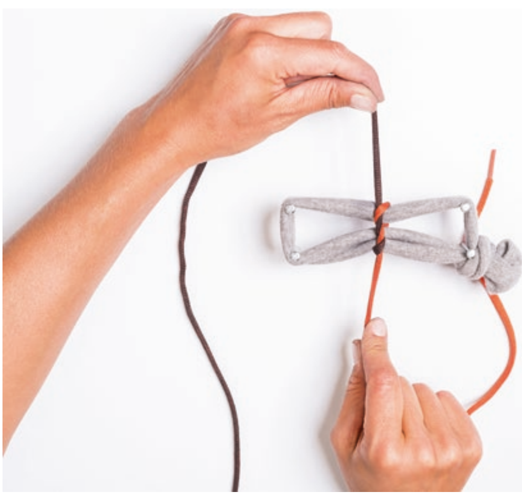

Fig. 7.45 The first throw with two twists is completed

Fig. 7.46 Hold both suture strands with both hands toward you

Fig. 7.47 Form a sling by pushing the orange suture strand with the right middle finger underneath the black suture strand

Fig. 7.48 Catch the orange suture sling with the right middle finger while holding the end of the orange suture strand with the right index finger and the thumb

Fig. 7.49 Form the second throw after releasing and taking up the end of the orange suture strand with the right hand

Fig. 7.50 Tighten the second throw by pushing down the orange suture sling with the right index finger

Fig. 7.51 The knot is completed

7.2 Step-By-Step Demonstration of Surgeon's Knot by Using a Needle Holder (Left and Right Hands)

Fig. 7.52 Hold the needle holder in one hand (in this example, the left hand is being used); hold the end of the black suture strand in the other hand. The black suture strand represents the strand with a curved needle at its end

Fig. 7.53 Wrap the black suture strand around the needle holder once

Fig. 7.54 Wrap the black suture strand around the needle holder a second time to create a double twist in the first throw of the knot

Fig. 7.55 Grasp the orange suture strand (in real life, the short strand at the other side of the wound) with the needle holder

Fig. 7.56 Pull the orange suture strand with the needle holder

Fig. 7.57 The wrapped black suture strand slides off the needle holder to encircle the orange suture strand

Fig. 7.58 Tighten the first throw so that the suture lies flat

Fig. 7.59 Position the needle holder close to the black suture strand (that would have a curved needle attached to its end in real life)

Fig. 7.60 Wrap the black suture strand around the needle holder in an opposite direction to the first throw

Fig. 7.61 Grasp the orange suture strand with the needle holder

Fig. 7.62 Pull the orange suture strand and let the wrapped black suture strand slide off the needle holder

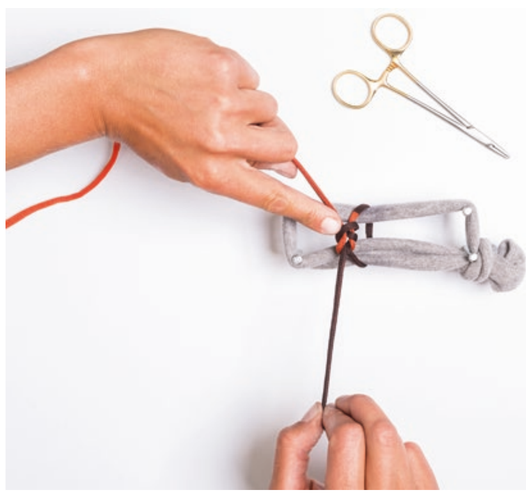

Fig. 7.63 Tighten the knot by pushing down the orange suture strand with the index finger

7.3 Tips to Maintain Loop Security While Preparing Surgeon’s Knot

In case of wound dehiscence, it might be necessary to maintain some tension on the sutures while preparing a surgeon’s knot. It is essential to make sure that the suture lies flat on the wound opening after having tied the first throw. If too much tension is needed for a double-twisted first throw, it is also possible to add a third twist in the first throw. A third twist further decreases the risk for sliding and therefore helps to maintain loop security.

7.4 Tips for Tissue Approximation

Tissue approximation can be difficult in cases of wound dehiscence. In these cases it can be helpful to alternate the pulling motion of both hands after having tied the first throw. Slow and careful pulling movements on each hand can slowly approximate the tissue. Sometimes it is further necessary to transform a surgeon’s knot into a sliding knot after the first throw. A sliding knot is useful in any type of wound dehiscence and helps to maintain the wound closure after tissue approximation.

7.4.1 Transformation of a Surgeon’s Knot to a Sliding Knot (Combination of Half Hitches on a Post Limb)

Fig. 7.64 Start with the first throw of a surgeon’s knot

Fig. 7.65 Bring the black suture strand with the right hand toward you. No tension should be applied to the orange suture strand that lies into the left hand

Fig. 7.66 The two twists of the orange suture strand turn its orientation. At the same time, the black suture strand is pulled straight

Fig. 7.67 Position the orange suture strand between the left index finger and thumb

Fig. 7.68 Use the middle and/or the left ring finger to create a sling with the orange suture strand from behind the black suture strand

Fig. 7.69 Catch the orange suture strand with the left middle finger

Fig. 7.70 Complete the second twist of the knot. The black suture strand should still be straight

Fig. 7.71 By gently pulling the orange suture strand, slack between the half hitches is removed. Knot can be advanced to the tissue by pulling the black suture strand. Left index finger can be used to push the half hitches

Fig. 7.72 The sliding knot is tightened. To secure this sliding configuration, reverse half hitches on alternating posts are needed

7.5 Where to Use Surgeon's Knot

The surgeon's knot is being used in many different surgical fields. Recent literature about this knot and about possible variations that aim at increasing effectiveness and security of the knot can be found in the field of palatal surgery [10], obstetrics and gynecology [11], general surgery as well as orthopedics and sports medicine.

Different knot types tied in an open as well as in arthroscopic procedures have different loads of failure and therefore provide different security when applied in body tissue. However, these values are highly variable depending on the type of suture material [12].

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Half Hitches

8

Radu Prejbeanu and Mihail-Lazar Mioc

8.1 Definition and Illustration of Post Limb and Loop/Working Limb

A surgical knot is the most commonly used tool that keeps different tissue and/or artificial materials together. The knot is made up of two limbs (Fig. 8.1) that wrap around each other in a variety of possibilities:

- The post (post limb)—the limb of suture that is held under tension and around which the other limb is tied or wrapped. The post is the end of the limb that is held tensioned, and it usually defines the side of the tissue that the knot will sit on.
- The loop (nonpost/wrapping limb)—the limb of suture that wraps around the post and is tied into a knot.

For the remainder of this chapter, the post limb will be represented by the blue part of the rope, while the loop limb will be represented by the red part of the rope.

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8.2 Definition of Switching Post

When a number of consecutive similar knots are tied together by alternating the post and the loop (nonpost) between each other, it is called post switching (Fig. 8.2). Post switching can be also achieved by alternately switching the tensioned loop after each half hitch has been made.

Reversing throws usually refer to the direction the loop travels around the post. These can be either overhand (loop travels on top of the post)

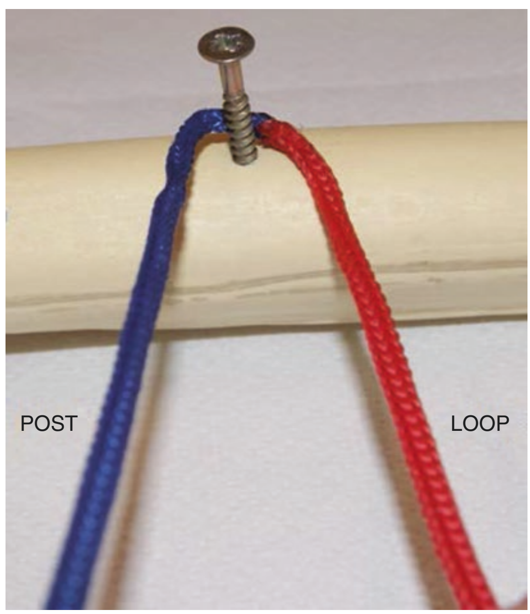

Fig. 8.1 Post limb and working (loop) limb

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or underhand (loop travels under the post). It should be kept in mind that, increasing the number of over/under half hitches following each other on the same post will only increase the friction of the construct. Without switching the post, reversing the throws can not provide knot security. In order to secure half hitches, one should switch the post at least for 3 times.

8.3 Step-By-Step Demonstration of an Overhand Half Hitch

The overhand half hitch is demonstrated step by step (Figs. 8.3, 8.4).

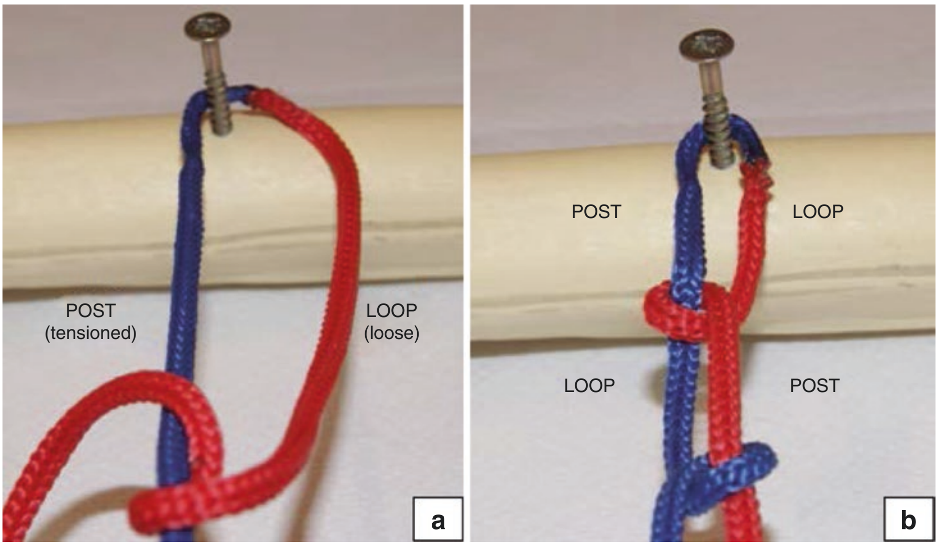

Fig. 8.2 Post switching. (**a**) First half hitch; the post limb is blue and the loop limb is red. (**b**) Second half hitch; post limb is red and loop limb is blue. You can see two overhand half hitches on alternating posts (*blue* and *red*)

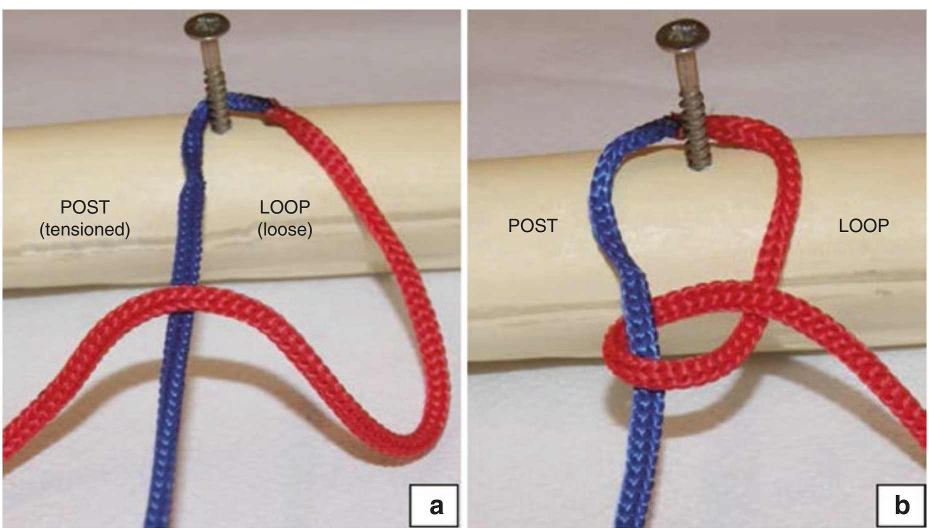

Fig. 8.3 The nonpost (red) limb is brought over (in front) the post (blue) limb —(**a**). The nonpost (red) limb is passed through the loop we just created—(**b**)

8.4 Step-By-Step Demonstration of an Underhand Half Hitch

The underhand half hitch is demonstrated step by step (Figs. 8.5, 8.6).

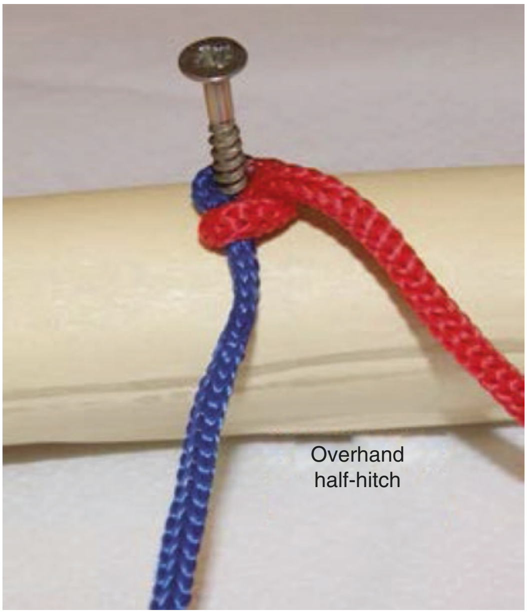

Fig. 8.4 The half hitch is tightened by pulling on the nonpost, while the post is being tensioned. The overhand half hitch is completed.

8.5 Step-By-Step Demonstration of Post Switching

Post switching is a commonly used technique when chaining up several half hitch knots (Fig. 8.7).

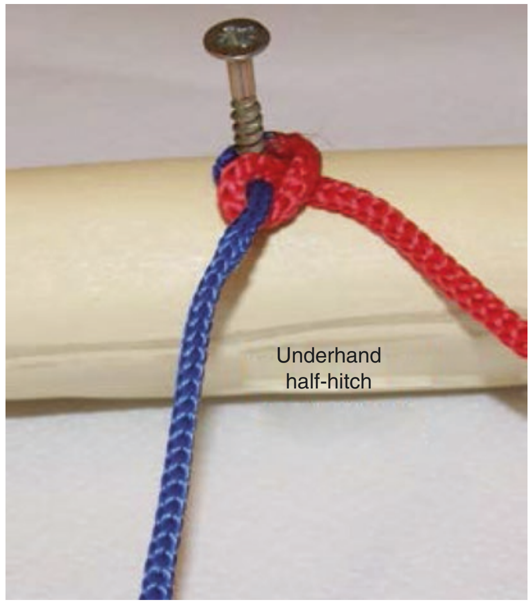

Fig. 8.6 The half hitch is tightened by pulling on the nonpost, while the post is being tensioned and the underhand half hitch is completed

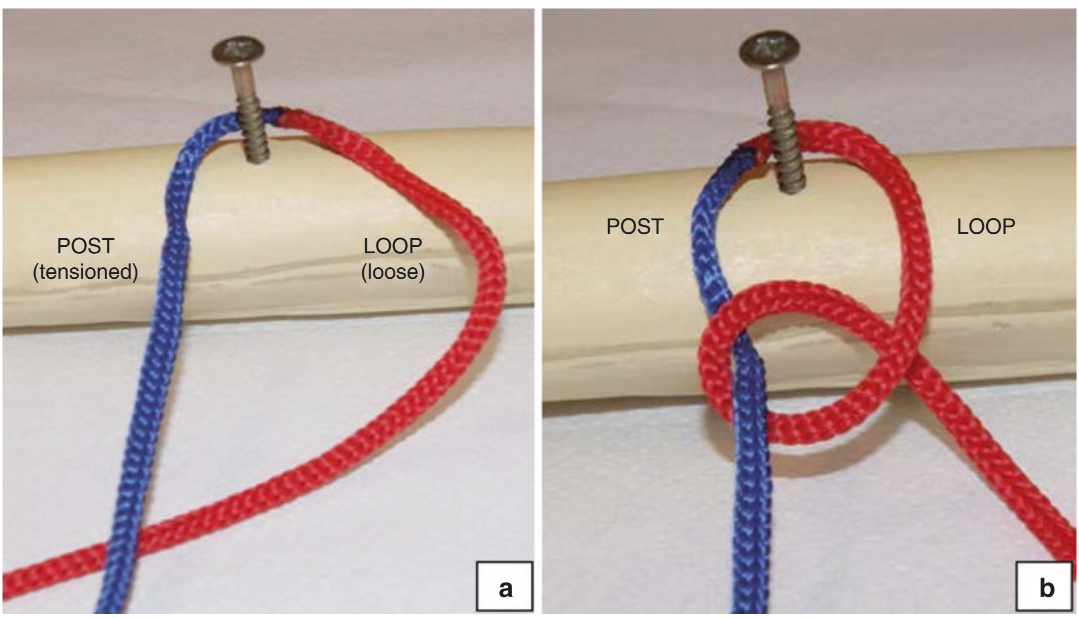

Fig. 8.5 The nonpost (red) limb is brought underneath the post (blue) limb—(**a**). The nonpost (red) limb is passed through the loop we just created—(**b**)

8.6 Step-By-Step Demonstration of Half Hitch Flipping

A common mistake that may occur while preparing reversed half hitches on alternating posts (RHAPs) is accidentally applying continuous tension on the same post. This results in a series of regular half hitches on the same post limb, ending up with an unsecure knot. Flipping the knot helps us to avoid this error (Figs. 8.8, 8.9).

8.7 Step-By-Step Demonstration of Past Pointing

Past pointing refers to the tightening process of a half hitch knot, and it is most commonly used in arthroscopic procedures. It consists of pushing the tip of the knot pusher (in arthroscopic procedures) or applying a pulling force using your fingers (in open procedures), pasting the half hitch knot, followed by simultaneous and equal tensioning of both limbs. These forces are applied on the knot in divergent directions (Fig. 8.10).

8.8 Tips for Maintaining Loop Security While Preparing Half Hitches

Performing the half hitch in a single-handed manner is an important skill that a surgeon must acquire. This manoeuver is named as "overhand throw" and it is mostly used in cases where the needle can be detached from the suture, or the suture does not have a needle (is linked to an implant such as an anchor). Proper throws without slack helps to maintain a steady force within the loop and prevents loosening until switching the post (Figs. 8.11, 8.12, 8.13). It should be kept in mind that half hitches on the same post are used to reduce the tissue. They provide a compressive effect like the head of a screw. Increasing the number of half hitches on the same post will increase friction thus holding the tissue in desired position until locking the knot by switching the post at least 3 times.

Alternatively in Fig. 8.14, we present you the steps for creating an overhand half hitch with the left hand similar to what has been shown in

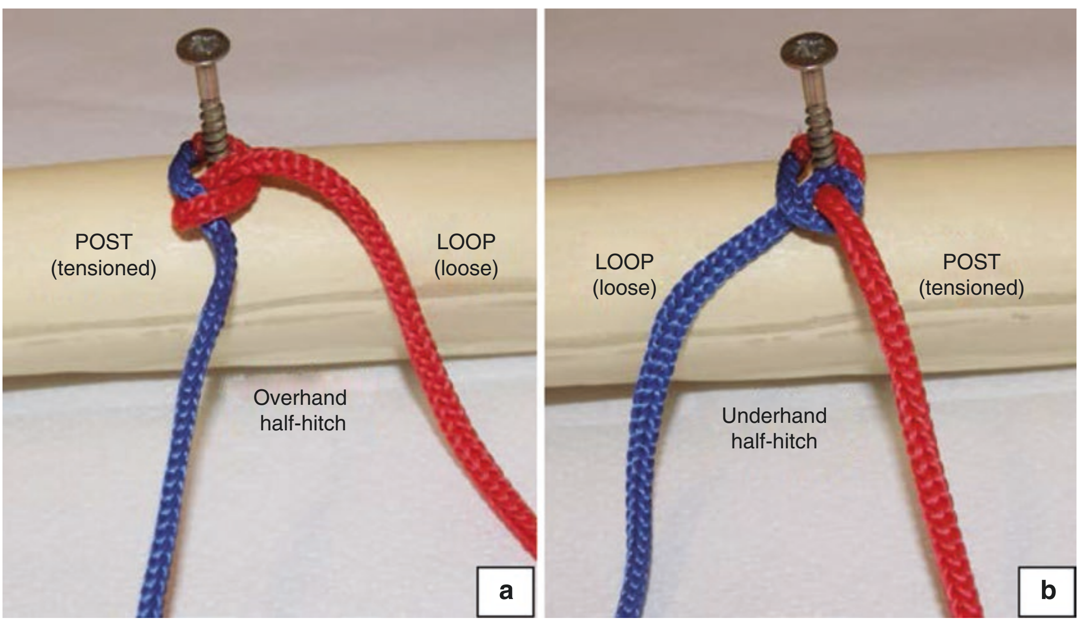

Fig. 8.7 The nonpost (*red*) limb is brought over (in front) the post (*blue*) limb, around (*underneath*) it and through the loop we just created, thus creating an overhand half hitch—(**a**). By switching tension from the post to the nonpost, we can observe that the knot has changed to an underhand half hitch on an alternated post—(**b**)

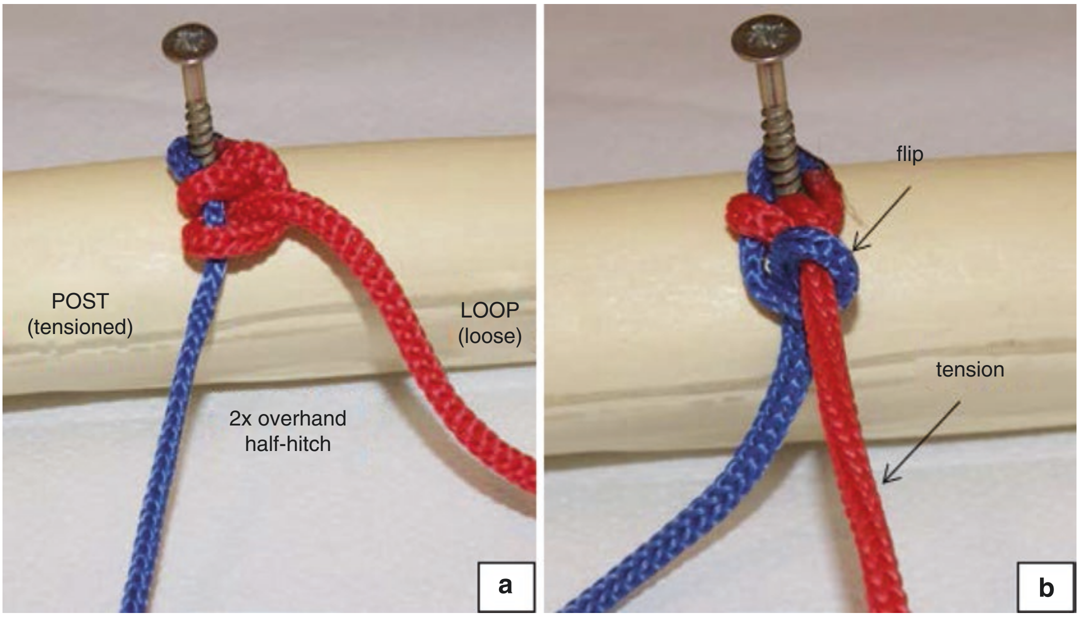

Fig. 8.8 Two overhand half hitches have been tied by the techniques previously described—(**a**). By applying tension to the red loop limb, the half hitch is flipped and transformed to an underhand half hitch on the alternating post—(**b**)

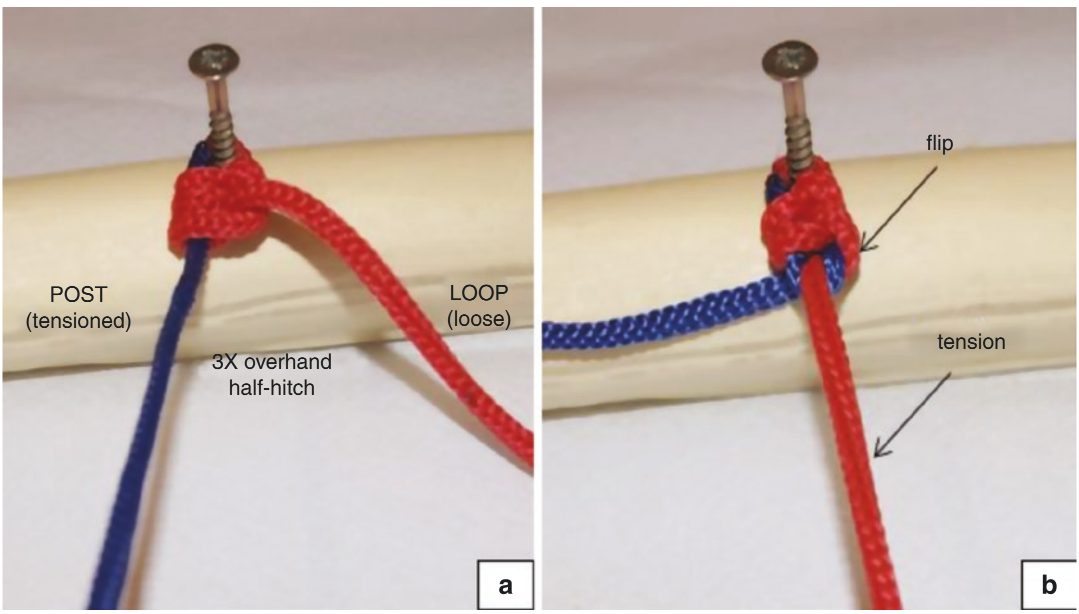

Fig. 8.9 The half hitch can be flipped back again and another overhand half hitch is made—(**a**). The tension is switched to the red loop limb, and the half hitch is flipped again (**b**); Basically flipping the half hitch also switches the post. This prevents slippage

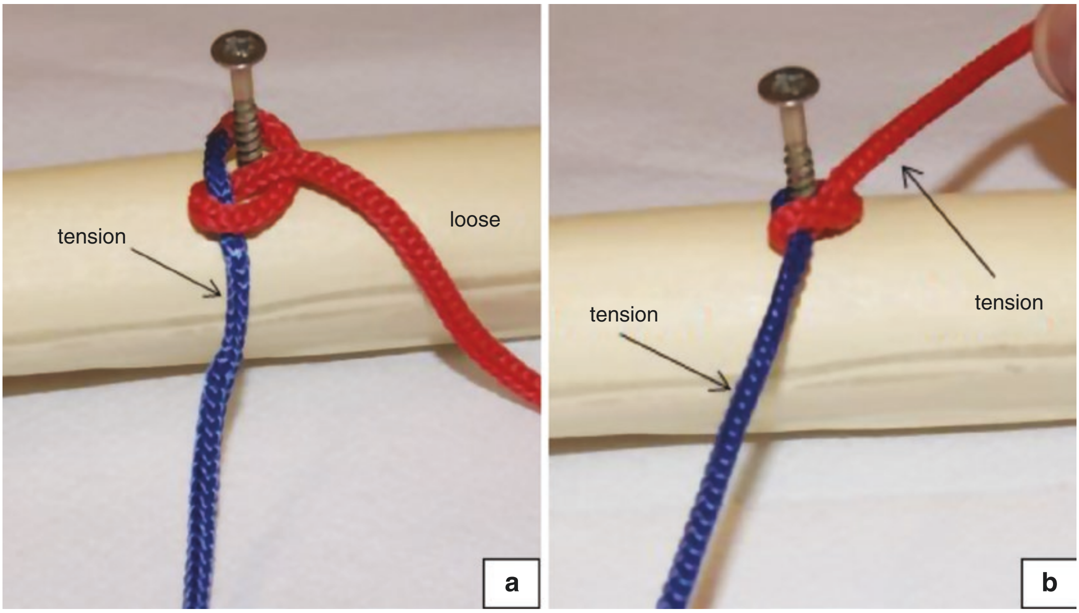

Fig. 8.10 An overhand half hitch is performed (**a**). The knot is tightened by applying divergent tensions on both limbs at the same time (**b**)

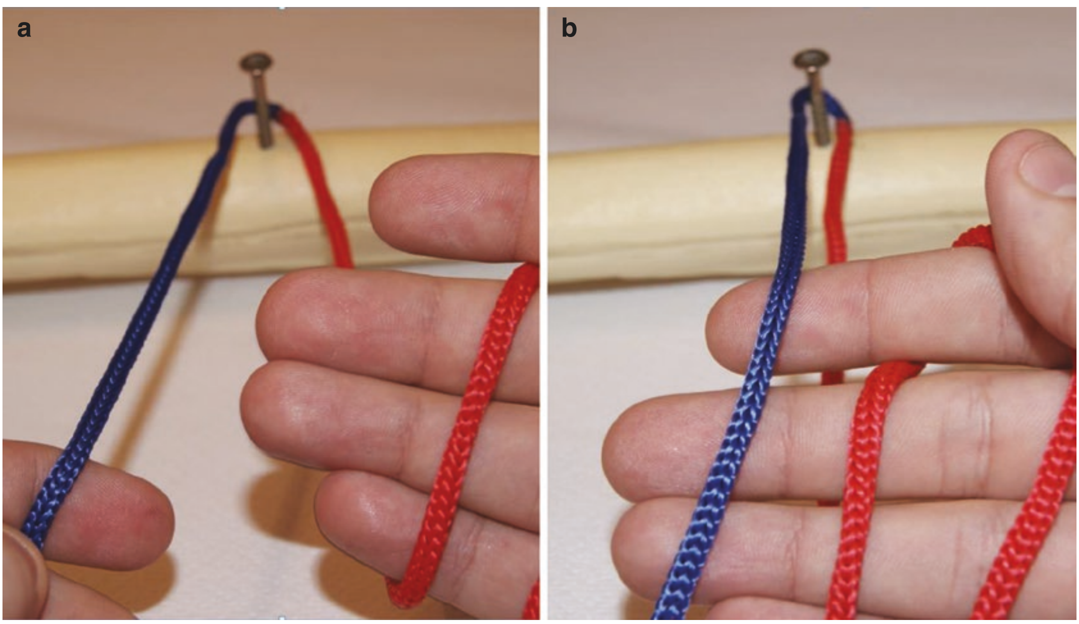

Fig. 8.11 The post (*blue*) limb is held in the left hand, while the nonpost (*red*) limb is passed under the fifth finger, on the volar face of the palm, through the third and second fingers to the dorsal side of the second finger, and again on the volar face between the second finger and the pollicis (**a**). The post and nonpost limbs are held in tension by the pollicis and index fingers (**b**)

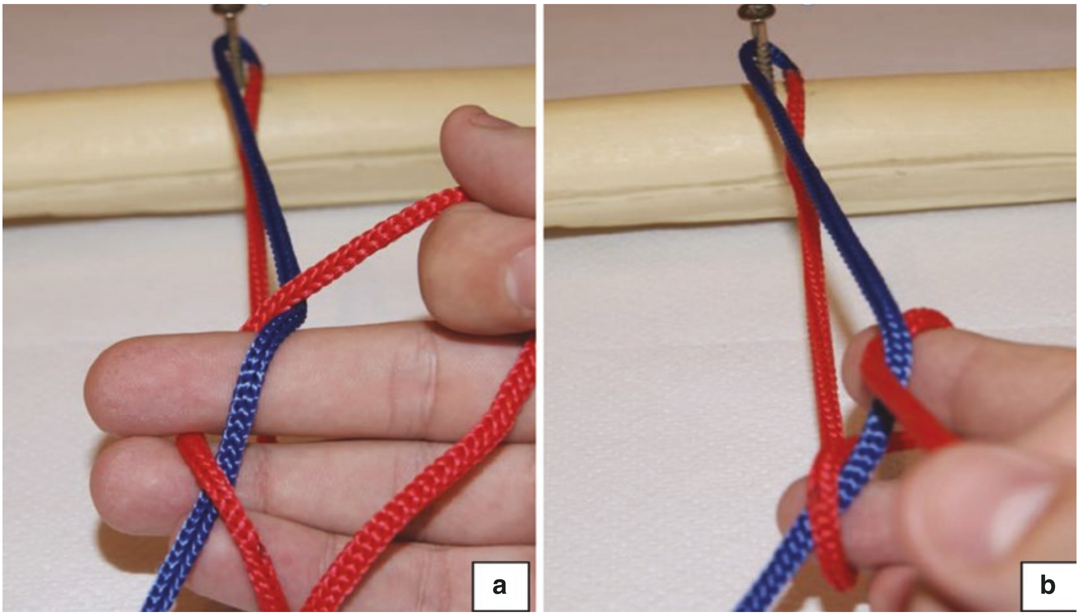

Fig. 8.12 The flexion of the third finger catches the post (blue) and brings it under the nonpost. The medius has the nonpost (red) on the dorsal side and the post (blue) on the volar side (**a**). By extending the wrist and the medius and letting go of the nonpost between the pollicis and index, we can pass the nonpost through the loop (**b**)

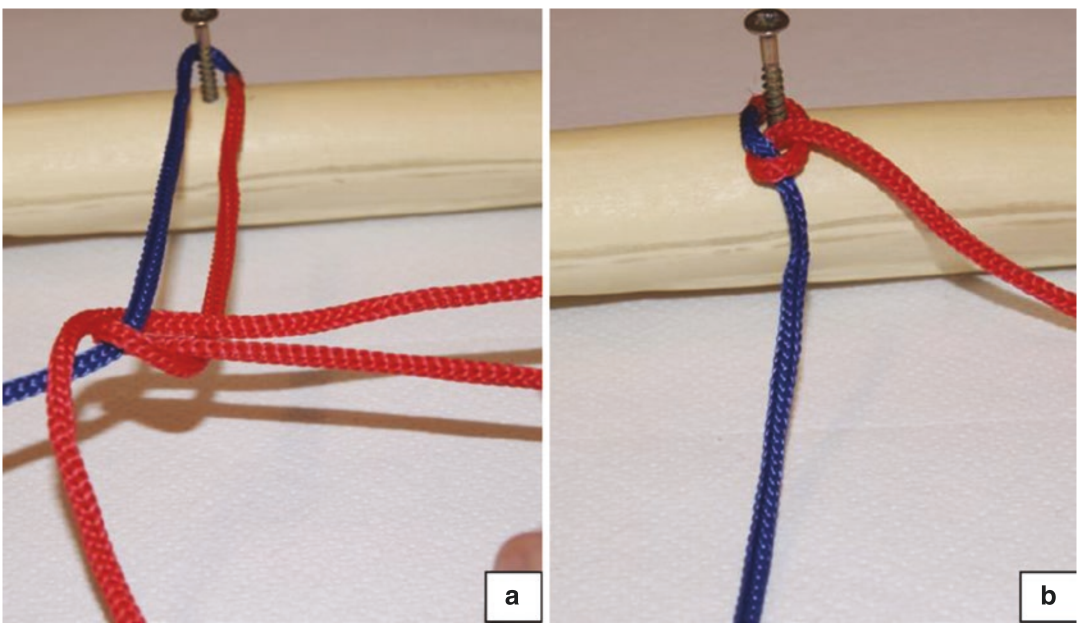

Fig. 8.13 By completely pulling the nonpost (red), we have obtained an overhand half hitch without letting go to either of the suture ends (**b**)

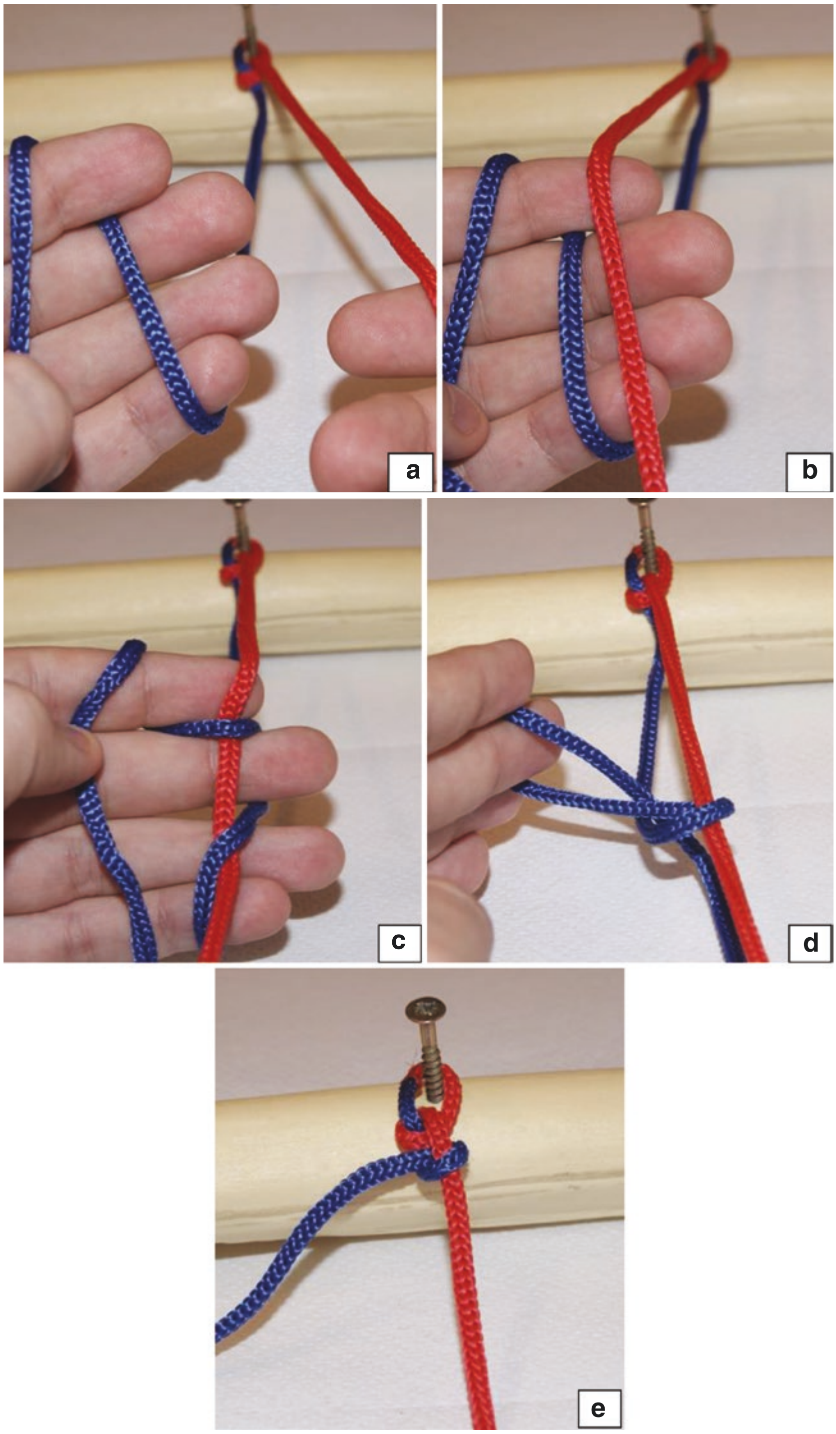

Fig. 8.14 Graphical representation of the basic steps for creating an overhand throw by using our left hand (**a**–**e**)

figures 8.11–13 with the right hand. By using right and left hands, one can prepare half hitches on alternating posts.

8.9 Clinical Settings When Half Hitch Knots Are Used

The half hitch knot is one of the easiest and most versatile knots out there. It can be used either in open interventions as well as arthroscopic procedures of the knee and shoulder joint. As a single knot, it does not offer a very high resistance to tensile strength as other knots may. The most used scenario for half hitch knots is in combinations—either of multiple half hitches on alternating posts or together with other knots (mostly sliding knots in arthroscopy).

In arthroscopy or in the so-called "mini-open" procedures (inside-out meniscal suture), the half hitches are often used to secure or back up sliding knots. Most of the meniscal repair implants used in an all-inside manner is designed to have a knot already implemented on the loop. Inside-out techniques require a small incision be made on the posterior capsule of the joint. This will serve as a small operating field where the sutures will be tied on the exterior portion of the capsule, after the neurovascular structures have been isolated and retracted. Half hitches on the same post will reduce meniscal tear. Once the desired loop tension is provided, the knot can be locked. A succession of three or four reversed half hitches on alternating posts is usually preferred by most surgeons.

During shoulder arthroscopy, the half hitches are generally used to lock sliding knots. The term RHAPs—reversed half hitch on alternating posts—is commonly used, and it is usually made up of three or more half hitches. Performing RHAPs is obtained with a knot pusher, and it involves the past-pointing and flipping techniques which will be discussed later in the arthroscopic techniques.

9 Sliding Knots

Nuno Sevivas, Guilherme França, Nuno Oliveira, Nuno Ferreira, Manuel Vieira da Silva, Renato Andrade, and João Espregueira-Mendes

It is well evident all around the world that endoscopic and arthroscopic techniques are still increasing its influence and prevalence in the surgical treatment of orthopedic lesions. However, open surgery still has its place in the surgical treatment of the musculoskeletal system pathology. Traumatic injuries (*eg,* fractures), degenerative diseases (*eg,* osteoarthrosis), and overuse injuries (*eg,* tendinopathies) are still commonly treated by open means when surgery

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is advised. In these cases, sliding knots are technical artifices that can be very useful and helpful when performing these surgeries. Every surgeon must be familiarized with its execution, and this surgical step must be performed naturally, instinctively, and comfortably, without losing time. However, perfection and refinement of the knot's technique are essential to not compromise the main purpose of the surgery with this final step.

The training and improvement of these skills are very important during the formation period of the young surgeons and medical students. It is very important learning the theory and above all practicing the technical steps until the knot is being performed "without thinking in what is being done." Furthermore, there are several knots described in the literature, but the surgeon does not need to know how to perform all of them. It is very important to master a few numbers (two or three knots), be aware of the characteristics of each one, and choose the most appropriate in each particular situation.

Most of the actions performed during surgeries need to be maintained at least until healing is accomplished which is dependent on the tissue that is involved. It would be a waste of time, energy, and an "aggression" without compensation, arriving at the end of the surgery and having a failure because this simple, but one of the most important, surgical step is not performed accurately and efficiently. This is the reason why the knot's performance techniques are so important in medical students and surgeons' education.

A sliding knot is recommended when suturing tissues in deep areas. The knot is performed first at an external level and then it is pushed to its final position. A correct technique should be paid attention to avoid that the knot can slip when subjected to increasing tension. Locking the knot to hold tissues at the desired position is essential to the final success and to achieve the purpose of the surgical act.

9.1 Technical Considerations

The clinical outcome of the surgical act is highly dependent on a number of factors, among them the knot construct and its response to load stresses are very important [1]. Knot security is a very important performance characteristic, defined as a knot's resistance to monotonic or cyclic loading, and this characteristic is required to ensure that a suture construct will not fail [2]. To provide additional security to a knot construct, half hitches are absolutely necessary but will increase the bulk of the knot with the addition of more suture material. Nevertheless, Lo et al. pointed to the absolute necessity of using at least three half hitches on alternating posts after tying a sliding knot [3].

The resistance of a knot to fail depends on several criteria including the behavior of the knot itself [4] and suture material [3]. More recently, with new advanced technology in suture materials (*eg,* high-strength polyblend sutures), the weak link in knot biomechanics appears to be the knot itself [1]. So, it is very important to improve the performance of the knot. Collin et al. [1] recently investigated and showed that there is a "settling-in" phenomenon related to the elongation in response to stress during which all construct types lose their efficiency.

Besides knot security, it is also very important holding tight suture loops (loop security) during surgery. It is obvious that a suture loop that is initially loose will cause loss of tissue fixation no matter how tightly the knot is tied. So, the moment of tying the knot is the key point because the suture loop will never be tighter than that moment. In open surgical procedures, the surgeon frequently secures the first throw of his knot by having his assistant placing a hemostat or clamp on the first throw until the second throw is securely in place for greater tissue fixation security and greater loop security [5].

9.2 Where to Use Sliding Knots

Procedures like tenodesis or ligament repairs are among the surgeries where sliding knots are frequently needed and used. Sliding knots are also a key step to reduce and hold soft tissues until healing when doing a tenodesis. Moreover in trauma or arthroplastic revision surgery, the use of loops when performing sliding knots is an important artifice to reduce and hold bone fragments (Fig. 9.1). Square knot is as useful as a sliding knot on reducing bone fragments. Basically it is not a sliding knot however it can be converted by a simple maneouvre.

There are some tricks to increase square knot's security as a sliding knot. First, the "post" should always be maintained in tension by pulling this limb. Second, half hitches should be advanced and firmly placed on the desired tissue by the tip of your index finger (Fig. 9.2). Slack within the hitches should be removed. With this sliding configuration, the knot should be properly secured once the desired reduction achieved. Reverse half hitches on alternating posts are essential and should be added to lock this configuration.

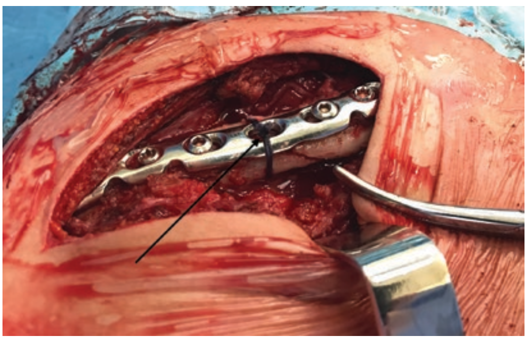

Fig. 9.1 A sliding knot is used to reduce a butterfly fragment in a clavicle fracture

Alternatively, a surgeon's knot can also be used as a sliding knot [6] (Fig. 9.3). Looping a thread twice around the other characterizes this knot, which increases the friction between both strands and therefore a stronger knot is obtained. Surgeon's knot is converted into a sliding knot by using the same maneuvre used to convert the square knot. After pulling one limb, surgeon's knot can be advanced to desired position by using your index finger (Fig. 9.3). Tension on the post limb should always be maintained by pulling the limb. Once proper reduction is achieved, it should be locked by using at least three half hitches on alternating posts.

The Nice knot (Figs. 9.4, 9.5, and 9.6) is a double-stranded self-locking knot that has been recently proposed for tuberosity osteosynthesis in the management of proximal humerus fractures [7, 8]. The Nice knot is used in open or arthroscopic surgery and could decrease the amount of knot elongation during dynamic stresses and therefore

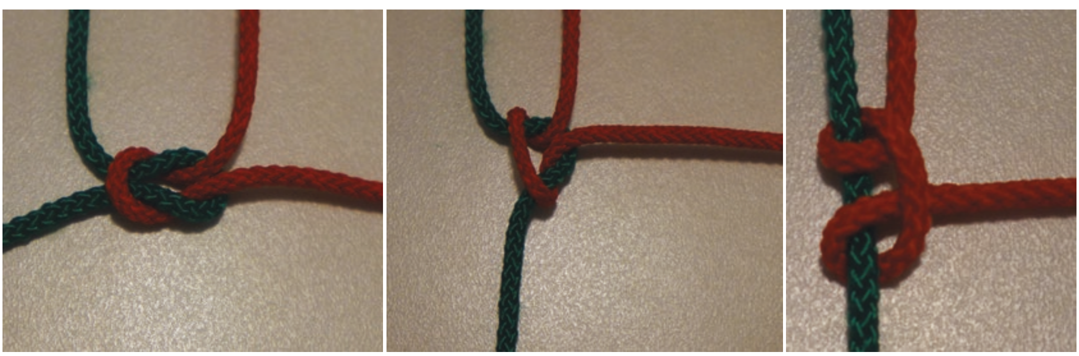

Fig. 9.2 From left to right; pulling the green limb of the square knot, converts the knot to a slip configuration with two half hitches on green limb

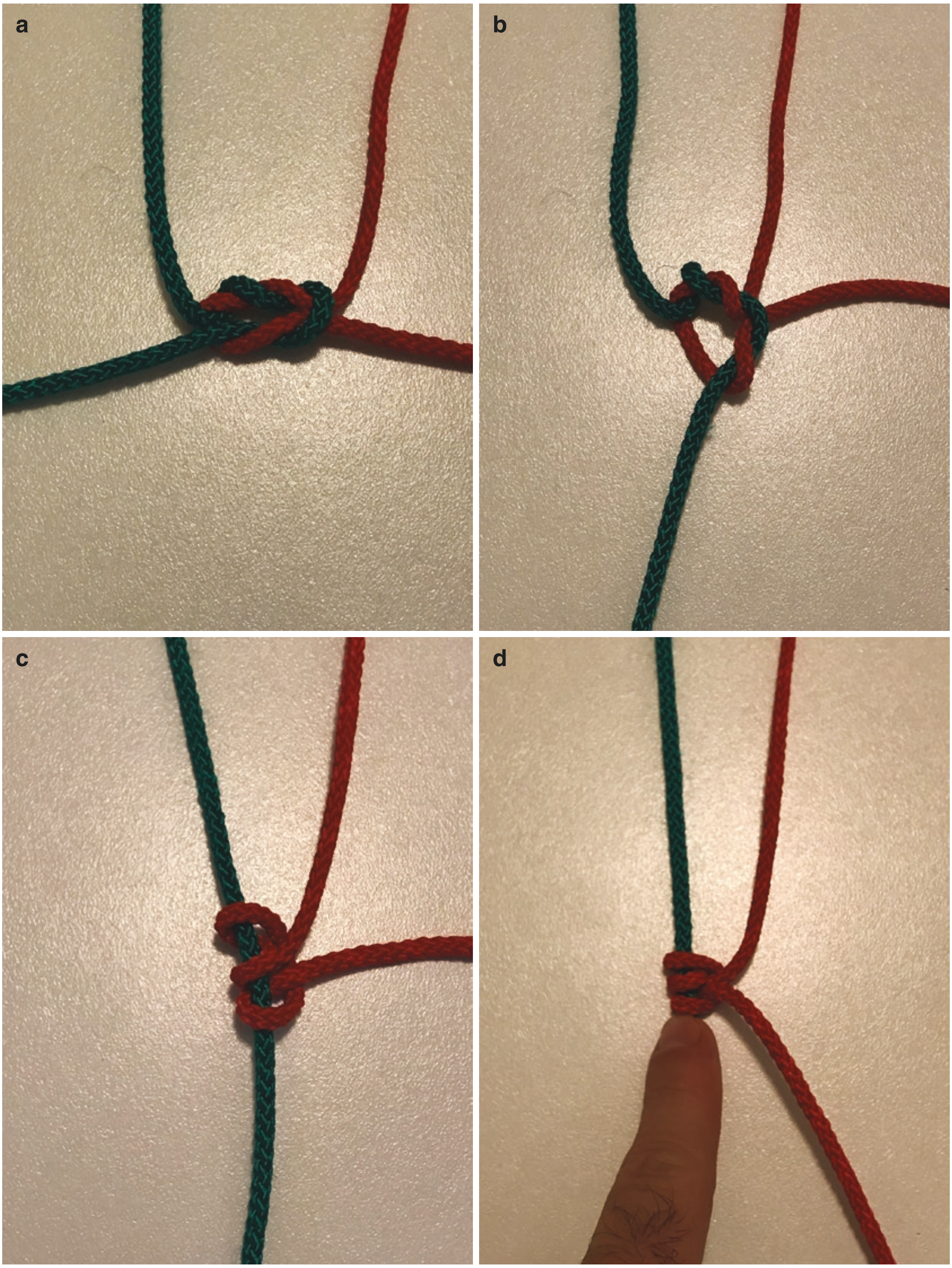

Fig. 9.3 (**a**) A surgeon's knot. (**b**) Pulling the green limb, converts the knot into a sliding configuration. (**c**) Green limb is the post; consecutive half hitches are seen. (**d**) Half hitches are pushed (slide) to the desired position by the index finger. Knot should be secured by additional reverse half hitches on alternating posts

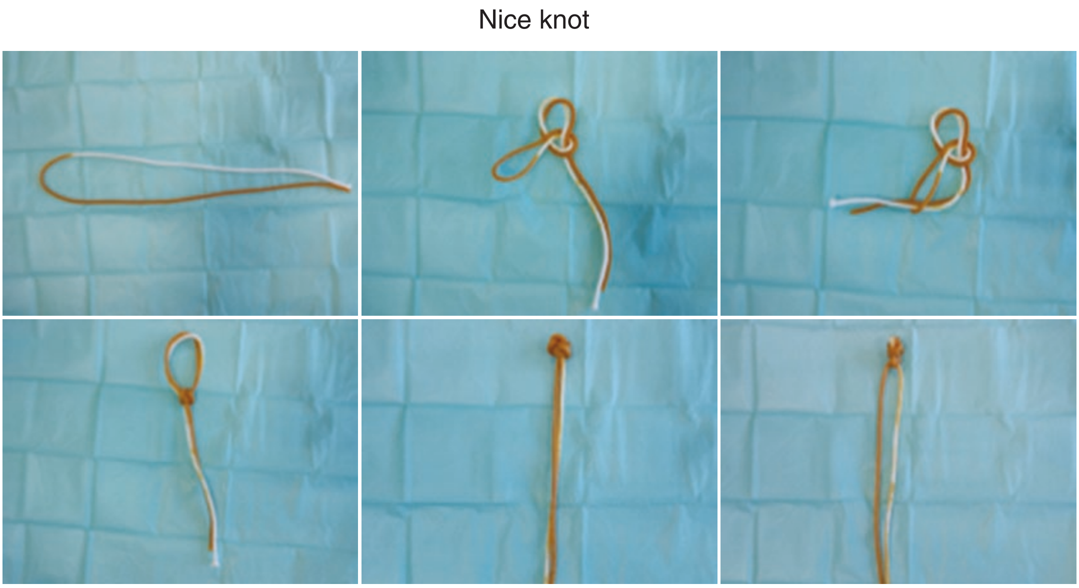

Fig. 9.4 Nice knot technique. 1 - A doubled-over suture is used (passing around the tissue); 2 - A single wrap is formed; 3 - the two free limbs are passed through the loop; 4 - The knot is adjusted; 5 - The knot is slid down by pulling the two free limbs toward the surgeon at once or alternately; 6 - The tightened knot is reinforced with two or three alternating half-hitches

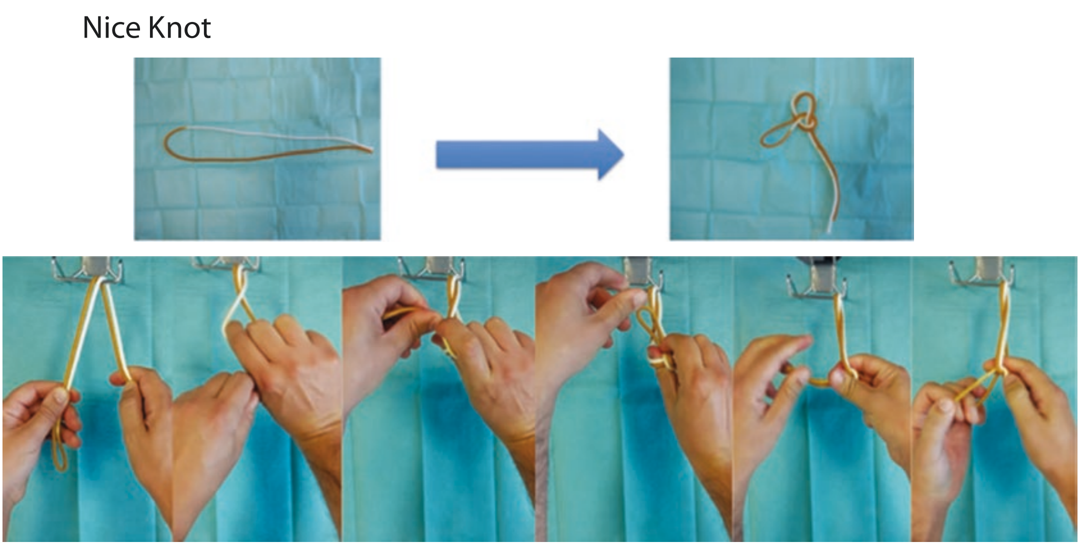

Fig. 9.5 Step-by-step preparation of Nice knot 1 - A doubled-over suture is used (passing around the tissue); 2 - A single wrap is formed

improves knot security during the rehabilitation period and tissue healing [1].

In a recent biomechanical study, the Nice knot proved to be biomechanically superior to the surgeon's knots. Two half hitches are the minimum to ensure adequate knot security [9]. However, it is practical to use the rule of "three reverse half hitches on alternating posts" for all knots.

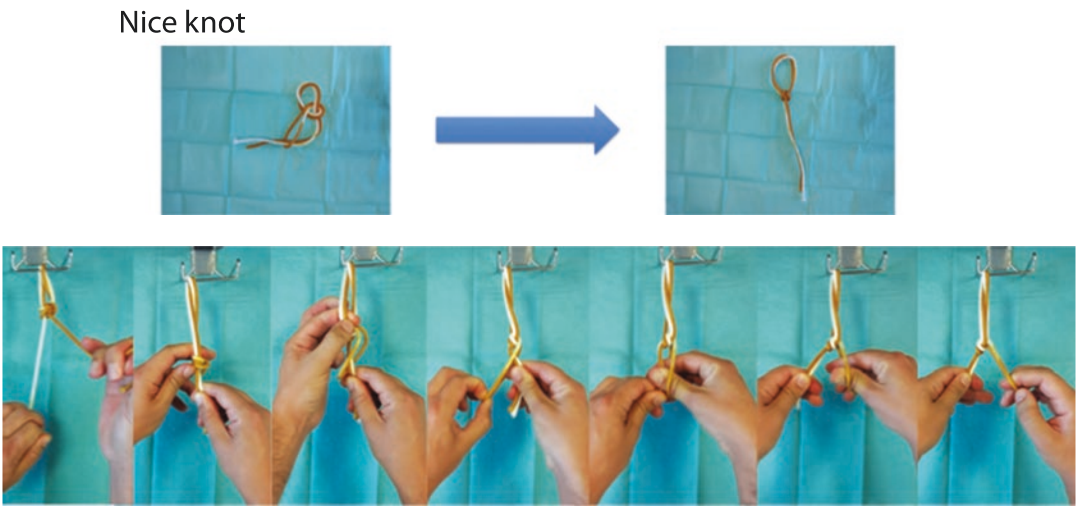

Fig. 9.6 Step-by-step preparation of Nice knot 3 - the two free limbs are passed through the loop; 4 - The knot is adjusted and slid down by pulling the two free limbs toward the surgeon at once or alternately

Conclusion

Learning and practicing surgical knots are an essential step in the career of surgeons and medical students. The ability to tie surgical knots efficiently and effectively is an essential skill that needs to be mastered. The need to hold tissues in place while the healing process is conducted is a keystone to achieve successfully the surgery's purpose and avoid complications.

The knowledge of the theoretical and technical characteristics of practical implementation of some knots is essential in order to use the most appropriate one to each situation. It is not needed to know all of the surgical knots described in the literature. On the other hand, it is very important to master a small number of different knots whose characteristics are advantageous in a specific situation.

Sliding knots are useful in open surgery when the knot should be located in a deep surface where it is difficult to use directly the surgeon's hands or surgical instruments. The addition of three reverse half hitches on alternating posts improves knot and loop security of most of the sliding knots. It should be kept in mind that sutures can easily cut the soft tissues while sliding. Therefore sliding sutures are not suggested in soft tissues like meniscal repairs.

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10 Fracture Reduction and Fixation by Knots

Baris Kocaoglu, Tekin Kerem Ulku, and Ata Can Atalar

Fixations of fragments are the main aim of orthopedic trauma surgery. Although wires, screws, and plates are the popular fixation materials, sutures also have an important role [1, 2]. Most surgeons thought that hardware have more strength at the fixation side than sutures. We can easily say that it is true for large and solid fragments. But if the fragments are comminuted, osteoporotic, and fragile, hard fixation materials may give harm to the fracture sites and makes the procedure more complicated [3, 4]. Specially, fixations with sutures are useful for the treatment of fractures with tendon or ligament avulsion. At this time use of sutures could be an option for the fixation, which can give less harm to the small and fragile fracture ends. By using sutures as fixation material, the surgeons can use bone-tendon junction as a buttress side. Suture fixations can be used in various types of fractures. In this chapter, we describe major fields that suture fixation is the most favored type of fixation.

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10.1 Tubercle Fixation in Humerus Fracture

The management of displaced proximal humeral fractures is challenging. Regardless of the treatment protocol used, it is important to obtain joint surface congruity and rotator cuff function while maintaining humeral head vascularity [4, 5]. Transosseous suture fixation is very practical and may be a gold standard for a large number of displaced proximal humeral fractures [5]. Suture fixation can be used at four-part valgus impacted fractures, three-part fractures or fracture-dislocations, and two-part fractures of the greater tuberosity with or without associated dislocation of the humeral head [4, 5]. With use of just sutures, the impacted head, the greater tuberosity, the lesser tuberosity, and the upper part of the metaphysis are sutured together in a cruciate fashion, and in three-part fractures, the displaced tuberosity is sutured to the intact one as well as through drill holes in the metaphyseal area [6–8] (Fig. 10.1a, b). In two-part tuberosity fractures, the displaced tuberosity is sutured to the intact one and to the adjacent metaphysical area. Stable fixation can be obtained in each of these fractures, allowing for early shoulder motion with a low risk of osteonecrosis and hardware-related complications [6–8].

Soft tissue attachments to the fracture fragments should carefully be preserved to prevent de-vascularization of the humeral head. The fracture lines between the tuberosities should be identified and

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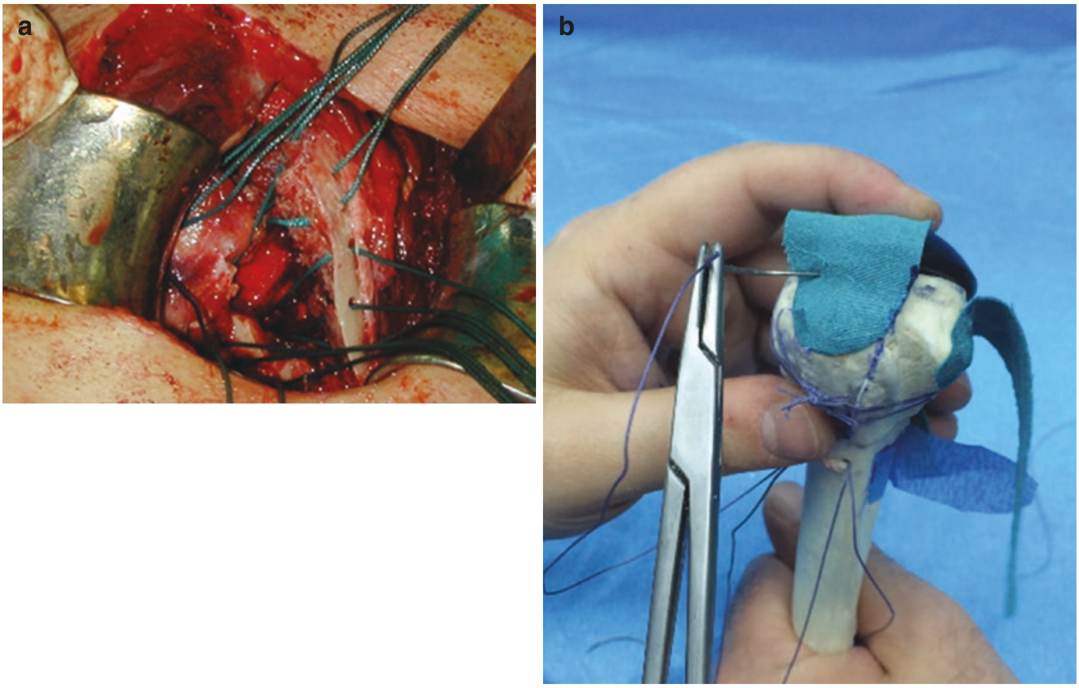

Fig. 10.1 (**a**, **b**) The displaced tuberosity is sutured to the intact bone as well as through drill holes in the metaphyseal area

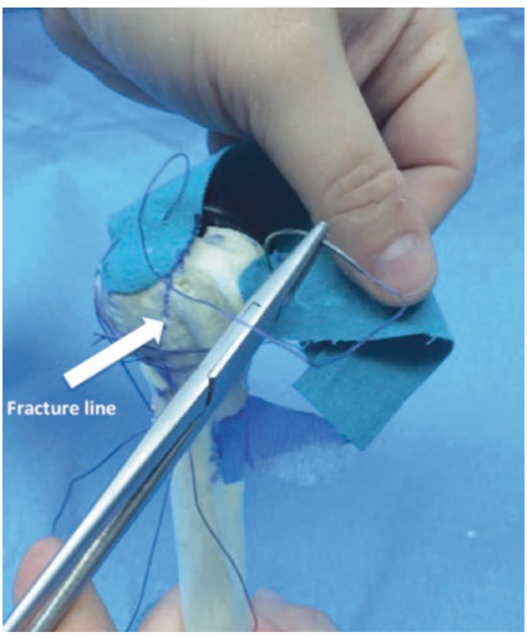

Fig. 10.2 The fracture lines between the tuberosities should be identified and gently separated, facilitating access to the humeral head

gently separated, facilitating access to the humeral head (Fig. 10.2). While the impacted valgus position of the humeral head fragment is preserved, two heavy non-absorbable sutures should be passed through bone and tendon junction, at both the medial and the lateral border of the articular surface (Fig. 10.3) [6–8]. The sutures are passed through each tuberosity fragment near the site of tendon insertion, and the rotator cuff tendons are mobilized. Finally, two additional pairs of sutures should be inserted to the lateral cortex through 3.5 mm drill holes in the diaphysis (Fig. 10.4). These sutures are then passed through the opposite tuberosity, near the musculotendinous junction from the anterior diaphysis toward the greater tuberosity and from the posterior diaphysis toward the lesser tuberosity as well as to the adjacent articular fragment [6–8]. Once all sutures are in place, the tuberosities are approximated to the diaphysis and recessed just below the top of the head fragment (Fig. 10.5). Then each suture will be tied individually and to each

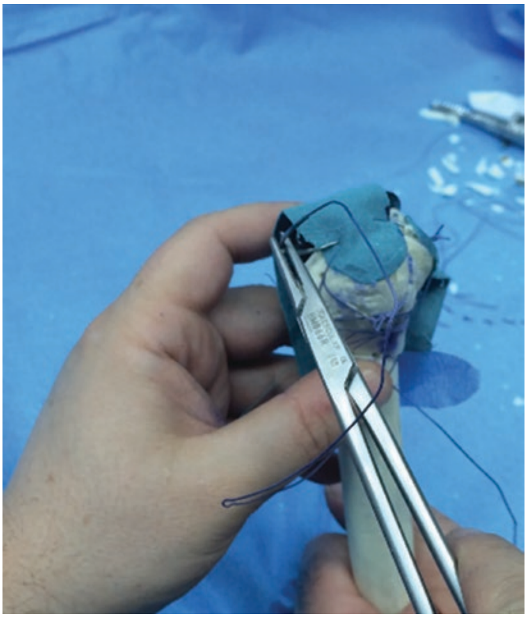

Fig. 10.3 Two heavy non-absorbable sutures should be passed through bone and tendon junction, 1 cm proximal to the fracture line at both the medial and the lateral border of the articular surface

Fig. 10.4 Sutures should be inserted laterally and medially through 3.5 mm drill holes in the diaphysis

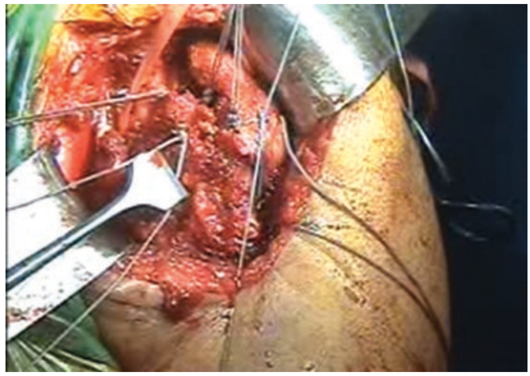

Fig. 10.5 Once all sutures are in place, the tuberosities are approximated to the diaphysis and recessed just below the top of the head fragment

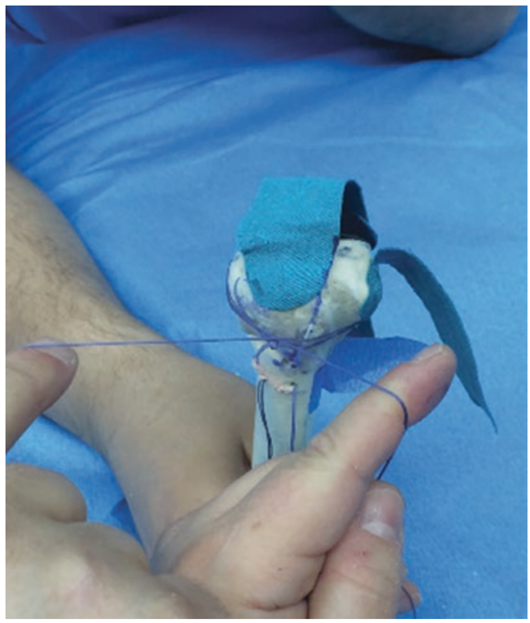

Fig. 10.6 Each suture will be tied individually and to each other in a cruciate arrangement that allows stable fixation of all parts of the fracture to all others

other in a cruciate arrangement that allows stable fixation of all parts of the fracture to all others (Fig. 10.6) [6–8]. Any further loosening of the sutures, because of fracture compression, is corrected by tying additional knots between the free suture ends [9]. Each tuberosity contains four suture ends including two distinct sutures, one to

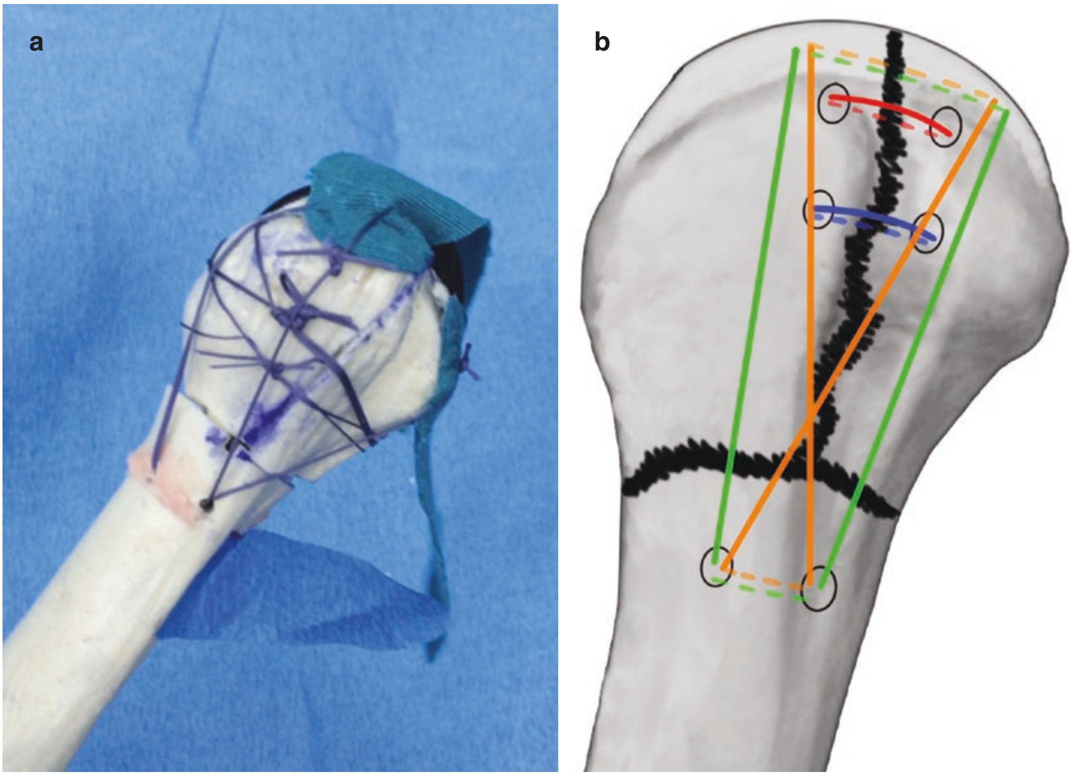

Fig. 10.7 (**a**) Head fragment contains two distinct sutures of which going through the proximal holes in the shaft fragment. (**b**) Configuration of the tubercle sutures. "Each colour demonstrates a distinct suture"

each side of the shaft fragment, and two shared sutures to the neighboring tuberosity, and the head fragment contains two distinct sutures of which going through the proximal holes in the shaft fragment [10] (Fig. 10.7).

10.2 Eminence Fixation in ACL Avulsions

Tibia eminence avulsion fracture is commonly seen in the skeletally immature population and usually attributed to injuries caused by traffic accidents, sports, and falls [11, 12]. However, it can also occur in skeletally mature individuals. Fractures in the skeletally mature patient population often result from high-energy trauma mechanisms and are more commonly associated with concomitant injuries, including meniscus tear or other ligament injuries [13, 14]. It is regarded that surgical treatment should be indicated for type III and IV fractures, irreducible type II fractures, and type I fractures with late displacement according to the modified Meyers-McKeever classification [14, 15].

Several studies presented to show the optimal approach for tibia eminence fractures [12–14]. Screws, K-wires, or staples have all been used intra-articularly with satisfying results [11, 12]. However, complications may delay recovery. Known complications are non-unions after the loss of reduction, extension lag due to remaining intra-articular hardware, lesions of the physis, pain, residual laxity, or irritation and pain from retained hardware [14]. Frequently, the surgeon has to remove these devices because of discomfort. Moreover, these techniques may affect the physis or violate it; thus the risk of growth disturbances may present [12–14].

Arthroscopy has become a pervasive and prevalent technique used in the treatment of tibia eminence avulsion fracture. Among the fixation systems applied in the arthroscopic therapy of avulsion fracture, suture fixation is the most popular maneuver

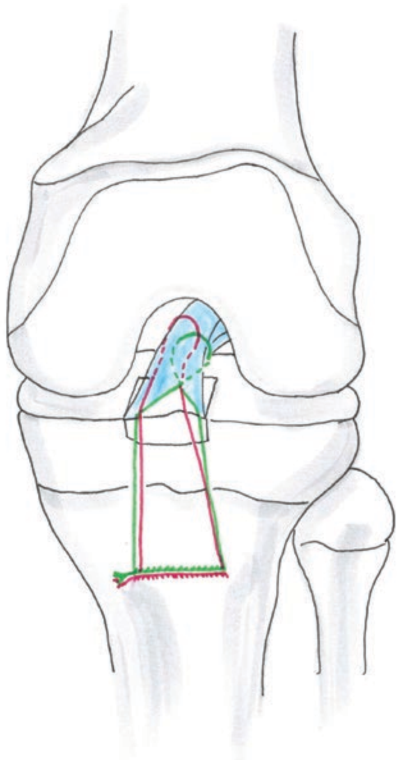

Fig. 10.8 Suture fixation is the most popular maneuver chosen by the majority of surgeons for the treatment of tibia eminence fractures

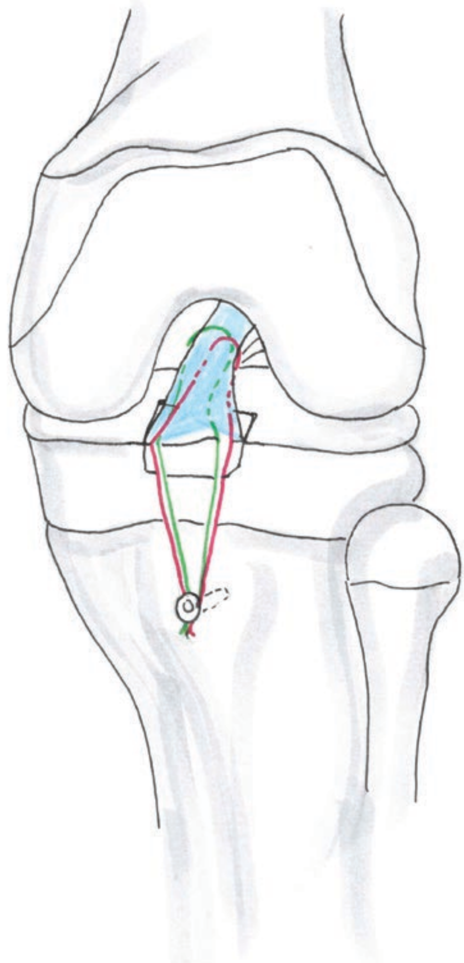

Fig. 10.9 Reduced risk of physeal injury by having the suture fixation, no hardware is passing through physis

chosen by the majority of surgeons because of the advantage of its applicability in all types of fractures, including comminuted fractures [11] (Fig. 10.8). Beside this, it was reported by Koukoulias et al. that tibia eminence fractures in adults could be effectively treated with arthroscopic suture fixation [11]. At pediatric population, violation to the physis could be an issue. Physeal-sparing arthroscopic procedure with non-absorbable sutures tied over an extra-articular tibia screw may overcome this risk of injury. Hirschmann et al. first described this procedure. The main advantage of this technique is a reduced risk of physeal injury by having the suture fixation. There is not any hardware passing through the physis [12] (Fig. 10.9). No intra-articular hardware removal is necessary. However, in two out of six patients involved in Hirschmann's series, the tibial screw was symptomatic and had to be removed [12]. Beside this philosophy, tibial screw fixation is not mandatory. Trans-osseous suture fixation could be performed. Drilling one more hole is enough to make trans-osseous suturing.

Suture properties are other factor that is important for the clinical outcome. Although absorbable sutures have a similar biomechanical performance to non-absorbable ones, they are rarely used in this context. In a biomechanical cadaver study, Schneppendahl et al. compared Vicryl and PDS against FiberWire. Vicryl had almost the same biomechanical properties as FiberWire [13]. Whereas FiberWire yielded a superior ultimate failure load, Vicryl competed with comparable results under cyclic testing conditions. In their conclusion, they favored Vicryl as a possible alternative to

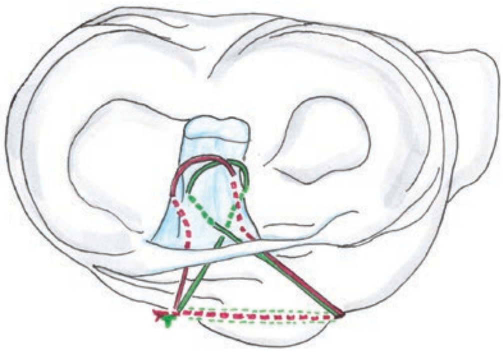

Fig. 10.10 If sutures are tight over the bone, there will not be a need for hardware removal

non-absorbable sutures but denied the same competence for PDS. Despite the inferior performance of PDS, Delcogliano et al. previously compared PDS sutures to non-absorbable Ethibond sutures for the treatment of adult tibia eminence fractures in a clinical study [14].

Finally, a well-designed study presented by Brunner et al. concluded that extraphyseal tibia eminence repair with absorbable sutures and a distal bone bridge fixation results in similar rates of radiographic and clinical healing at 3 months after surgery as non-absorbable sutures are tied around a screw while avoiding the need for hardware removal [15] (Fig. 10.10). The minimal invasive technique to fix an eminence fracture without any permanent sutures or hardware is advantageous for children.

10.3 Using Sutures as Cables on Butterfly Fragments of Diaphysis Fractures

Fixation of butterfly fragments can be challenging when fragment is small and cortical in origin. Long bones like clavicle, tibia, femur, and olecranon have a higher incidence of butterfly fragment formation during diaphysis fractures [16, 17]. During plate and screw fixation, smaller fragments may not be effectively fixed with screws and necessitate suture fixation. Although cerclage wiring and cable fixation have previously been proven to be effective, hardware irritation constitutes a major problem in fractures with poor soft tissue coverage. Looped knots like "Nice knot" can present an excellent alternative to cerclage wiring for these fragments (Fig. 10.11) [6]. Decreased hardware amount and bulkiness lower the risks of skin irritation and infection.

10.4 Tension Bands by Sutures in Olecranon

Application of tension band technique is very effective in comminuted fractures of the patella, olecranon, and medial malleolus [16, 17]. However, using K-wires is associated with certain complications such as infection, hardware irritation, malunion, and non-union especially in elder population. Proximal ends of metal wires can cause prominence and protrusion eventually leading to skin breakdown [18]. This may necessitate revision surgery or removal of wires after consolidation of fracture.

Use of braided polyester sutures to perform a tension band suture instead of tension band wiring was found to cause minimal tissue reactivity when used clinically [18]. Braided polyester sutures are found to be superior mechanically to other absorbable and non-absorbable sutures in vitro with high stiffness and high ultimate tensile strength [19]. Using suture materials generally considered easier to handle and using a needle allow more accurate placement through soft tissues, and additionally adjustment is easier when misplacement of suture is present. All these factors can decrease operating and tourniquet time. Previous cadaveric studies showed that polyester is an acceptable alternative to wire in tension band after testing in patellar fractures [20]. When subjected to tensile strains, polyester was 75% as strong as wire. Gosal et al. showed that fracture union rate for tension band suture technique was not significantly different to the fracture union rate of tension band wire technique [19]. However, it was concluded that complication and reoperation time were significantly lower in suture group. Main concern about suture tension band technique is the strength of fixation especially knot settling and dynamic creep.

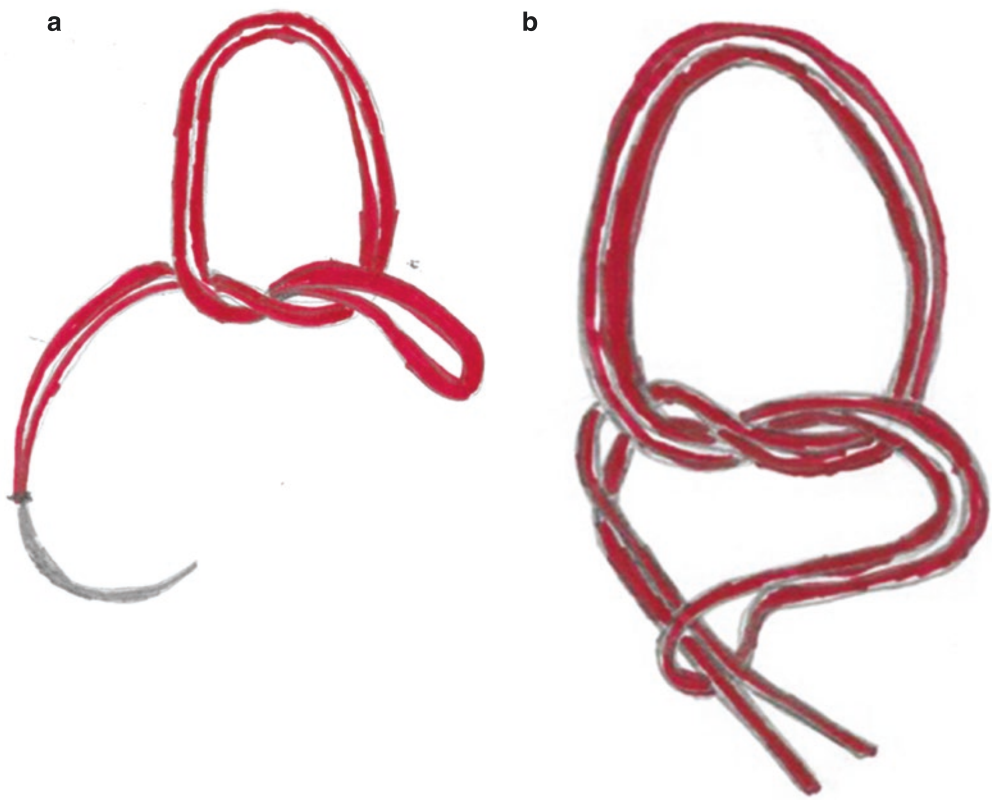

Fig. 10.11 (**a**, **b**) Nice knot involves use of a looped needle. Looped knots like "Nice knot" can present an excellent alternative to cerclage wiring

Harrell et al. demonstrated that multiple loops of Ethibond could be considered as substitute for stainless steel wire in situations where compliant repair is suitable [20].

Technique for olecranon fixation includes drilling two 2 mm holes in the distal ulnar fragment as near to the ventral ulna as possible. Two other holes are created in the proximal fragment above the triceps insertion to avoid cutting the triceps insertion. A thick non-absorbable suture (no. 6 Ethibond; Ethicon, New Jersey, USA) is passed through each distal drill hole into the intramedullary canal through the fracture site and retrieved from proximal ulna above the triceps insertion. The fracture is than reduced anatomically, and suture was tied firmly with a sliding knot. Two additional holes were drilled in distal fragment similar to conventional cerclage wiring. Another suture was passed through these holes configured in a figure of eight and tied lateral to triceps insertion to compress the fracture. The first suture acted as K-wire and second as tension band wire by converting distraction force of triceps to compression force.

10.5 Useful Knots for Fracture Reduction

When the fracture fragments are too small, thin, and osteoporotic, using knot fixation is a handy method for fixation. This technique is especially useful in tubercle fixation of proximal humerus fractures. Several knots and techniques were described for fracture reduction. Among these "Nice knot" is commonly used as cerclage for humerotomy or femorotomy, fixation of butterfly fragments, and reduction of tubercle fixation

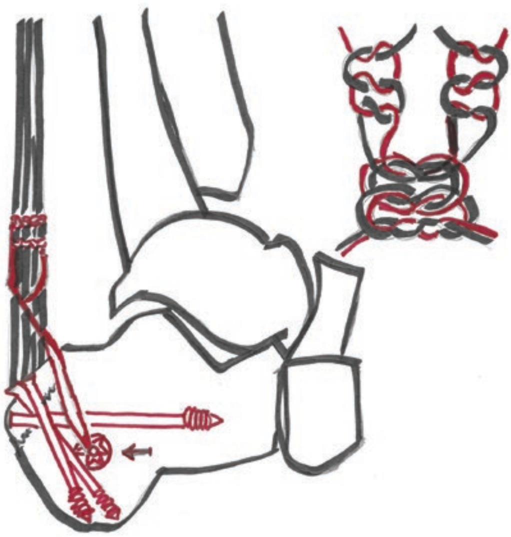

Fig. 10.12 Sutures and cannulated screws can be combined to form a strong tension band

during shoulder arthroplasty [6]. Nice knot involves use of a looped needle (Fig. 10.11a, b). Generally braided polyester non-absorbable suture materials are used. During fixation looped suture is passed around the tissues to be fixed. A square knot is made with loop on one hand and needled limb on the other hand. Then the needle is cut, and both free ends of the needled limb are passed through the loop. The knot can be dressed by making the loop smaller. After reduction is complete and knot is to be secured by pulling two free limbs apart and further tightening is performed. Finally three surgeon's knots were tied using two free limbs. This precludes the possibility that the free limbs slide back out of the loop.

Another technique was described by Miyamoto et al. which is commonly used for reducing calcaneal tuberosity fractures [21]. Biomechanical studies showed that cancellous screws alone could resist 250 N of tensile strength [22]. However using side-locking loop suture (SLLS) technique and anti-slip knot with braided polyethylene and polyester suture threads can increase tensile strength up to 600 N. Technique involves using a cannulated screw together with sutures. First two USP no:2 braided polyethylene and polyester suture heads are applied to the distal part of the Achilles tendon. By pulling the threads manually, reduction is achieved. A horizontal 4.0 cannulated screw is inserted to the calcaneus. By using a suture retriever of any kind, two lateral limbs are retrieved medially and two medial limbs retrieved laterally. These are all introduced into subcutaneous tissue around calcaneus (Fig. 10.12). Finally each suture threads are tied at the ventral side of the Achilles tendon using an anti-slip knot [22].

Conclusion

Proper combination of high-strength sutures and correct knots provides satisfactory stabilization in fracture fragments. Surgeons should know how to use knots in fracture reduction especially in comminuted, osteoporotic, and fragile fragments where metallic implants may easily end up with failure.

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Part III

Arthroscopic Knot Tying

11 Arthroscopic Instruments

M. Ugur Ozbaydar, Kerem Bilsel, and Mehmet Kapicioglu

Arthroscopic knot tying occasionally requires a series of elemental instruments, both disposable and reusable, along with preferred suture material. It is imperative that the surgeon assures the said components are obtainable and at hand prior to conducting any appropriate procedure depending upon arthroscopic knot tying. There are important tools for arthroscopic knot tying such as sutures, cannulas, suture retrievers and knot pushers [1].

11.1 Sutures

The market offers a great variety of sutures for the arthroscopic surgeon, which presents different aspects of material quality such as strength, surface texture, resistance to fraying, and durability. An optimal suture is expected to ensure safe fixation with a least possible bulky knot, to have excellent resistance to mechanical abrasion, to demonstrate minimal resistance on the advancement of the knot and finally to yield excellent resistance to knot retreat or loosening. An effective utilization of most knot pushers requires a suture of at least 27 in. (68.5 cm) in length. On the other hand a dual-lumen single-hole knot pusher requires a minimum suture length of 36 in. (91.4 cm) [2].

It is mainly the Arthroscopic surgeon's preference to decide upon the use of absorbable monofilament sutures such as polydioxanone (e.g., PDS and PDS II; Ethicon, Somerville, NJ) and polyglyconate (e.g., Maxon; Davis and Geck) or non-absorbable suture such as braided polyester (e.g., Ethibond Excel; Ethicon Somerville, NJ) and polyethylene terephthalate (e.g., Ticron; Tyco, Manfield, MA) and ultra-high molecular weight braided polyethylene sutures [1, 2].

However situation-specific factors such as the nature of reconstruction and the particular tissue being approximated will effect the surgeon's preference. Historical perspective refers to the use of monofilament suture providing a fairly easier pass with available arthroscopic suturing instruments. This has yet been found more difficult to tie securely, probably due to differences in surface characteristics of the two different suture types [1–5]. Nonabsorbable sutures give permanent fixation, however absorbable sutures gradually lose their mechanical strength as they are degraded by hydrolysis [6].

A brand new variety of high-strength braided sutures embodying ultra–high-molecular-weight polyethylene (UHMWPE) such as FiberWire (Arthrex, Naples, FL), Orthocord (DePuy-Mitek,

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Raynham, Mass), Hi-Fi (ConMed Linvatec, Largo, FL), Ultrabraid (Smith & Nephew, Andover, Mass), Force Fiber (Stryker Endoscopy, San Jose, Calif), MagnumWire (ArthroCare, Sunnyvale, Calif) and MaxBraid PE (Biomet, Warsaw, IN) have been introduced and have demonstrated advanced mechanical features when compared with traditional suture materials [2].

In addition, these new breed of sutures have also manifested different knot security qualities predominantly due to differences in surface features commanding the need for additional half hitches to lock these knots. One recent study suggests that a totality of four locking half-hitches supporting a sliding arthroscopic knot has not been found sufficient to securely rule out knot slippage with these high-strength sutures [2, 7–11]. As a matter of fact, no recommendation with regards to the adequate number locking half-hitches has been mentioned by the authors. Literature also points to some other researchers suggesting that the additional two locking half-hitches to the suggested number to be utilized in order to tie up more conventional suture materials may serve knot security effectively [2, 8].

A recent study reveals that some of the new high-strength sutures present greater bulk when compared with the same knots tied with more conventional sutures [2, 7]. When using more recent high-strength sutures, it is imperative that selecting a knot with a lower profile for use may be of extreme importance. In the process of knot tying, exertion of moderate force should be at stake particularly on tensioning the tissue loop to eliminate strangulation. Along with this issue, the surgeon should also take extra attention in that damage to gloves and even finger skin tears can be experienced when tying strenuously with these high-strength suture materials [2, 12].

11.2 Cannulas

Entanglement of soft tissue in the knot, one of the main complications in arthroscopic knot tying, can be substantially reduced through the utilization of cannulas for arthroscopic knot tying [1, 2]. The entangled soft tissue within the knot can be effectually treated by means of passing the knot through the smooth lumen of a cannula rather than through muscle fibers and other soft tissue when penetrating the joint [2]. Disposable and plastic clear cannulas that are readily accessible on the market enable the surgeon to track the knot while it is led into the joint. This procedure provides the means for the surgeon to clearly recognize and get an immaculate view of the knot seat as well as spot any unintentional twisting or tangling.

A prominent feature that differs among various cannulas is the degree of flexibility of the cannula itself. Flexible cannulas can be distorted to some extent to make way for the passage of an instrument that would contrarily necessitate a larger diameter cannula. This flexibility brings about the use of smaller cannulas in several cases while at the same time enabling the transition of full-sized instruments (Fig. 11.1).

Fig. 11.1 Different types of cannulas. (*DePuy-Mitek, Raynham, MA.Arthrex, Naples, FL*)

Several manufacturers on the market produce and carry cannulas with threads or blunt spikes on their outer barrel, which help prevent the possibility of the cannula to snap out of the portal [2]. This format also effectively ties up the cannula to the joint wall through the passage of instruments in the course of prolonged or complicated procedures where swelling of the soft tissue can impinge upon portal placement. This fixation between the cannula and joint wall also brings up several other useful assets. For instance as the cannula is withdrawn from the operative field through an exertion of an outward pull, the joint wall is equally withdrawn from the operative field which opens up space for clear visual appearance on the part of the surgeon [2]. This can be considered as a huge gain when visualization is insignificant in any other way (Fig. 11.2).

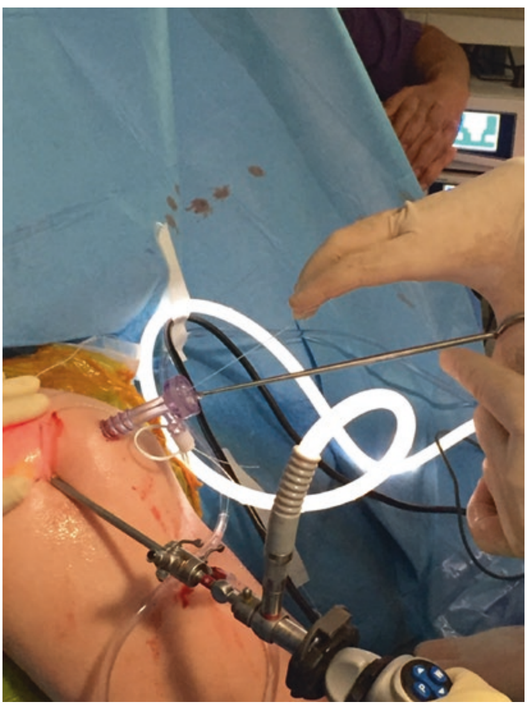

Fig. 11.2 Application and use of a plastic cannula during shoulder arthroscopy

11.3 Suture Retrievers

There are a number of instruments available for the surgeon to manipulate and retrieve the sutures arthroscopically (Fig. 11.3).

One of the common ways available is using a mere, nonspecific arthroscopic grasper with teeth. However this alternative may end up fraying and thus devitalizing the suture under question. A variety of graspers modelled particularly for suture or rotator cuff manipulation, which have seamless, atraumatic jaws allowing for damage and slide-free manipulation when the instrument is pulled out of the joint [1, 2]. Any possible trauma to the tissue that can be caused by the sawing effect of the suture sliding through the target tissue may thus be eliminated by this groundwork for suture movement within the jaws of the instrument.

11.4 Knot Pushers

The arthroscopic surgeon can make use of a number of different knot pusher alternatives available from Arthrex (Naples, FL), Linvatec (Largo, FL), Mitek (Westwood, MA), and Arthrotek (Warsaw, IN) such as single-hole, double-hole slotted, mechanical spreading, and dual-lumen single-hole [1, 2]. However, single-hole knot pushers can be considered as the most frequently preferred

Fig. 11.3 Suture retriever

type of all due to the fact that they can quite smoothly push a knot down with ease through employment on the post limb, or pull a loop down by employment on the wrapping limb (Fig. 11.4).

Right alongside, double-hole knot pushers can be utilized in the framework of these functions as well, however their added size and bulk render no convenience and therefore can complicate passage of individual knot loops. On the other hand, double-hole knot pushers excel in rectifying twists of the suture limbs right before knot tying. Both suture limbs are threaded through the knot pusher and the pusher is moved along to the target tissue intra-articularly (Fig. 11.5).

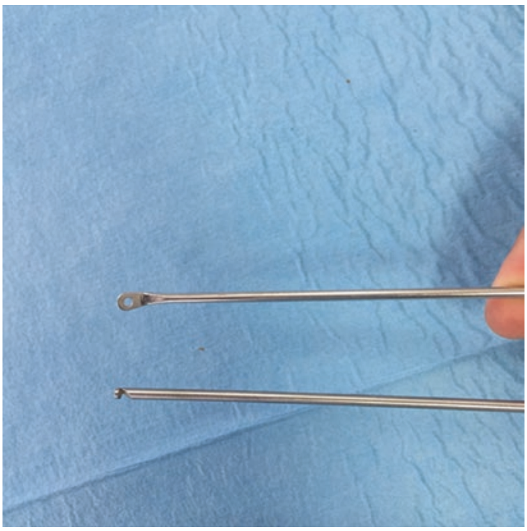

Fig. 11.4 Knot pusher

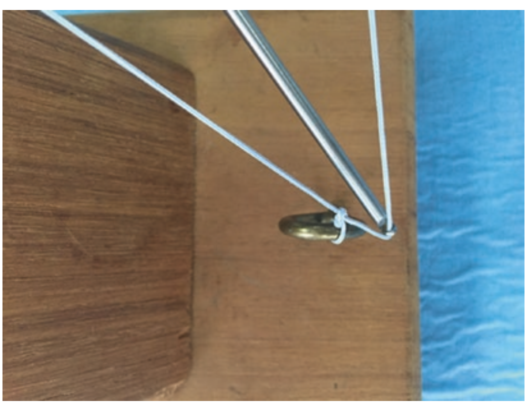

Fig. 11.5 Utilization of knot pusher

Slotted knot pushers act analogously to single-hole knot pushers, yet allow the knot pusher to be implemented and pulled out of the suture strand with no obligation to withdraw the knot pusher from the joint.

Provided the knot pusher is inadvertently separated from the intended suture limb at the time of the tying process, this function may arise like an obligation at that point. Aside from this, the half-done loop of the knot pusher tip may equally lead to soft tissue entanglement. The dual-lumen single-hole knot pusher such as sixth Finger device (Arthrex) has been patterned to absorb tension in that part of the knot already passed when additional throws have been tied and moved along (Fig. 11.6).

Studies conducted have pointed that this knot pusher type has been considerably effective in establishing loop security during arthroscopic knot tying procedure [2, 13]. Yet since it is disposable, this knot requires usage of longer sutures with the size of 36 compared to 27 in. [2]. At the same time it necessitates an advanced level of technical proficiency. In the case where the surgeon should conduct a non-sliding knot tie, the dual-lumen single-hole knot pusher may turn up as the most useful instrument. Since these non-sliding knots do not have a sliding element to hold temporary tension in the initial (tissue) loop on

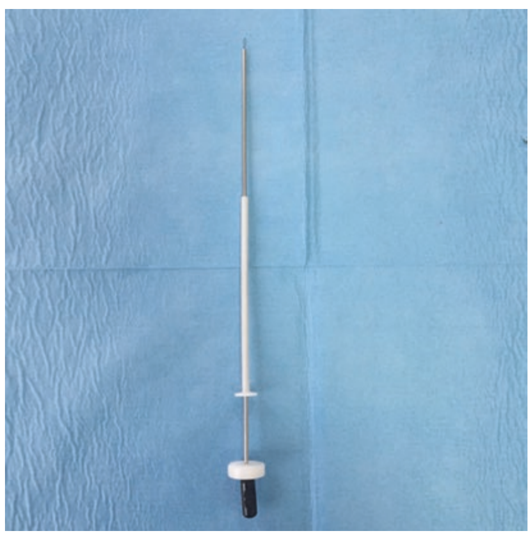

Fig. 11.6 Sixth Finger device (Arthrex, Naples, FL)

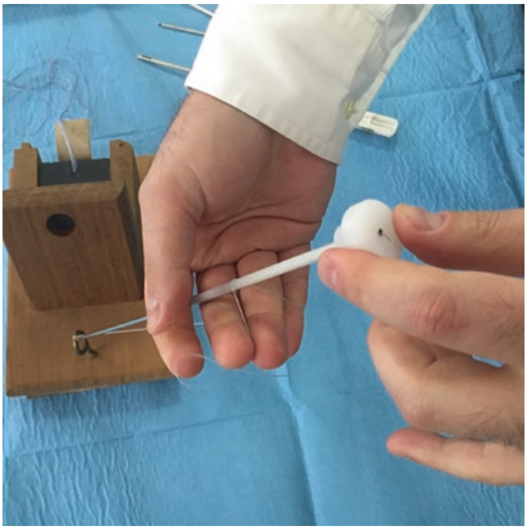

Fig. 11.7 Application for tying arthroscopic knot with sixth Finger device (Arthrex, Naples, FL)

the passage of additional securing throws, the dual-lumen single-hole knot pusher plays a prominent role in enabling this tension. It also eventually provides a solid loop security, even with mere half hitch–based non-sliding knots (Fig. 11.7).

In short, a single-hole knot pusher is a suitable alternative for a primary knot pusher due to its thorough overall utility in passaging and tensioning of knot loops. It can be concluded that a double-hole knot pusher can be considered as the most instantaneous instrument in the detection and correction of suture twisting preceding the tying process and also as an indispensable component complementing a single-hole knot pusher. Apart from this, a dual-lumen single-hole knot pusher is utilized essentially on tying non-sliding knots.

11.5 Suture Passage

Ideal suture passage allows for exact location of sutures to secure tissue fixation. Several techniques have been introduced to facilitate the passage of suture. Although many different suture-passing devices are available on the market, it is significant for the arthroscopic surgeon

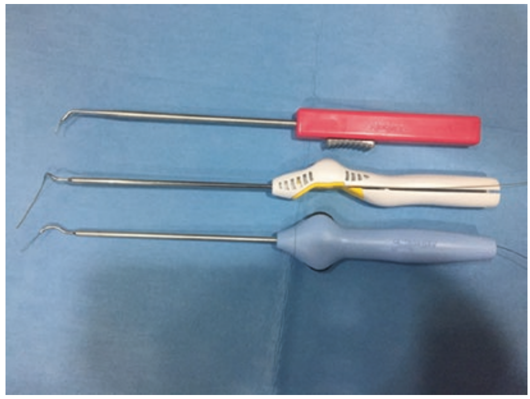

Fig. 11.8 Suture lassos are the basic instruments of arthroscopic shoulder surgery for suture passage from the soft tissue

to feel confident with different suture-passing techniques for a stable arthroscopic repair [14]. Convenience, cost-effectiveness, and tissue quality are main factors in use of any suture-passing device [15].

Suture relay has been the basic instrument for shoulder arthroscopy. Cannulated large-bore needle instruments, which have various twists and shapes, are passed through the soft tissue for a stable repair and fixation (Fig. 11.8). Before the arthroscopic operation, it is better to make some practice with several devices and use what works best in your hands on models and cadaveric specimen. Suture relay devices are particularly useful for difficult-to-reach or more delicate tissues such as the labrum, however it can be used also for the rotator cuff and biceps pathologies.

With these devices, the sharp cannulated needle is passed through the tissue; a suture lasso is deployed through the needle into the joint and retrieved with the desired suture to be passed through an accessory working portal. An easy technique to avoid this is to grasp the lasso and the suture in one pass, retrieving them through the same working portal (Fig. 11.9). The process is repeated as necessary until all sutures have been passed.

Tissue-penetrating instruments such as the Birdbeak (Arthrex, Naples, FL) are effective in

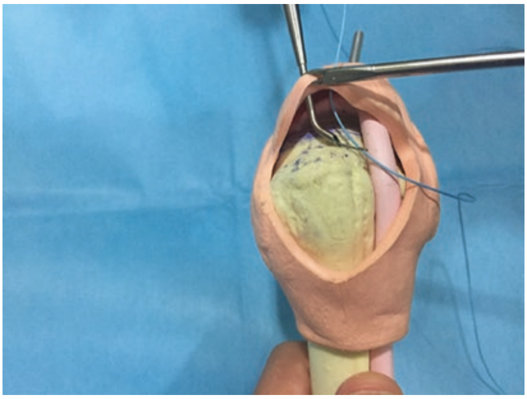

Fig. 11.9 Suture passage can be done in one pass with a special suture lasso

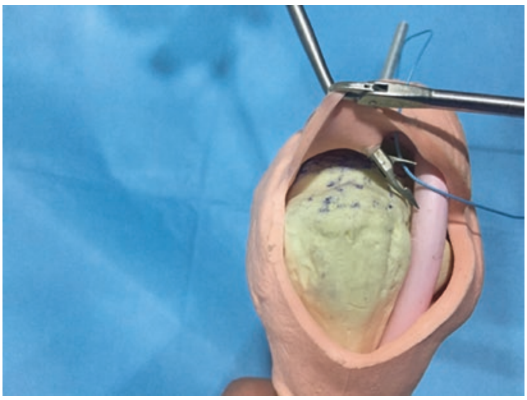

Fig. 11.10 Tissue-penetrating devices with various angles are extremely convenient and can be used in antegrade or retrograde fashion to pass suture

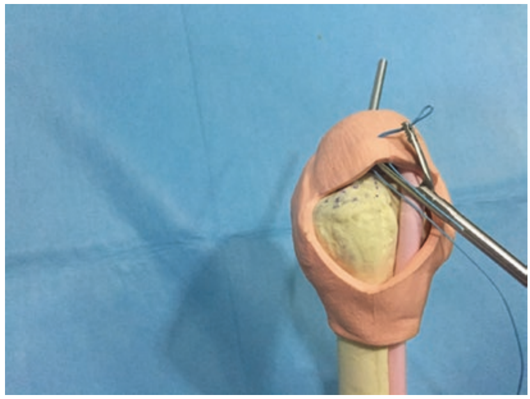

Fig. 11.11 Scorpion (Arthrex, Naples, FL) One-step suture passers were designed to minimize the number of steps involve

larger spaces with more thicker tissue (Fig. 11.10). These devices have sharp ends and are used to grasp suture in an antegrade or retrograde fashion directly through the soft tissue. Care must be taken with these instruments to avoid damage to the tissue through which the device is passing or the neighbouring cartilage and other important structures of the joint.

One- step suture punch devices use a needle to shuttle suture through tissue when the device is deployed (Fig. 11.11). Some of these devices allow for a one-step suture passage and retrieval on the opposite side of the tissue with the same instrument. Others require a suture grasper or hook to retrieve the suture. Although several variations on this design are available, suture is passed directly through the tissue and retrieved through the same portal.

Conclusion

There are many instruments designed to be used in arthroscopic procedures, surgeons should choose among those according to their needs. It is very important to make some practice with several devices and use what works best in your hands on models prior to the real procedures.

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12 Soft Tissue Handling in Arthroscopic Surgery

Didier Guignand

Even the best suture and knot combination would fail if the soft tissues are not handled properly. In this chapter, some basic manipulations to provide a tension-free soft tissue approximation will be discussed.

12.1 Basic Soft Tissue Manipulations in Arthroscopic Surgeries

Arthroscopic surgery allows minimally invasive surgical procedure. All arthroscopy incisions should penetrate only the skin and no deeper to avoid injury to neurovascular structures. Portals are created with inside-out technique or outside-inside technique with a spinal needle in order to avoid soft tissue damage and inadequate portal location.

In joint, soft tissues like bursae and fat should be debrided to define the lesion pattern accurately. This debridement is performed with a shaver or an electrocoagulation probe. This is especially true for the shoulder arthroscopy where a soft tissue ablation device is used to clear all the soft tissue on the undersurface of the acromion extending posteriorly. Then, the soft tissue is removed from the rotator cuff insertion site on the greater tuberosity exposing the cortical bone and removed lateral to the rotator cuff footprint in order to visualize the insertion site for the lateral row anchor(s). Finally, a limited debridement of degenerative tendon edge is performed using an arthroscopic shaver. It is advisable to carry out these steps at the same time not to waste any time.

After debridement, specialized instruments will be necessary to assist with management of sutures to facilitate a secure repair [1]. Soft tissue manipulations must be performed with tissue graspers which should not perforate or damage the tissue. Graspers may also lock, allowing the surgeon to work with the tissue in a hands-free manner. Instead of graspers, traction suture can be used, which would avoid repeated handling of the soft tissues.

12.2 Using Traction Sutures for Soft Tissue Reduction (Figs. 12.1, 12.2, 12.3, and 12.4)

The use of traction sutures within the free tendon edge helps to facilitate tendon mobilization techniques and suture passage. After removing soft tissue, suture traction can be performed. There are many benefits. First, iterative manipulations with graspers are avoided and thus the risk of iatrogenic soft tissue lesion decreases. We can use the traction sutures to reduce the tendon on the footprint and/or have a better understanding of the tear patterns. Then, like subscapular lesion, it is easier and less dangerous to perform the release with suture traction. Bringing the tendon in is more

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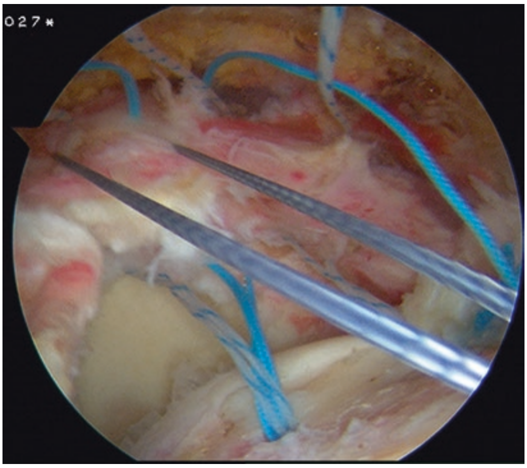

Fig. 12.1 Suture traction for lateralization of the supraspinatus tendon

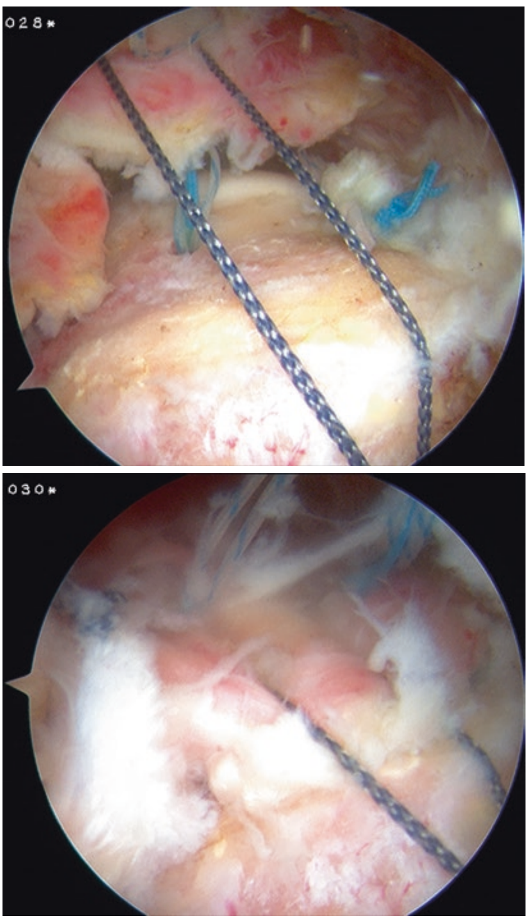

Fig. 12.2 (**a**) Suture traction with lateral anchor. (**b**) Reduction of rotator cuff on the footprint

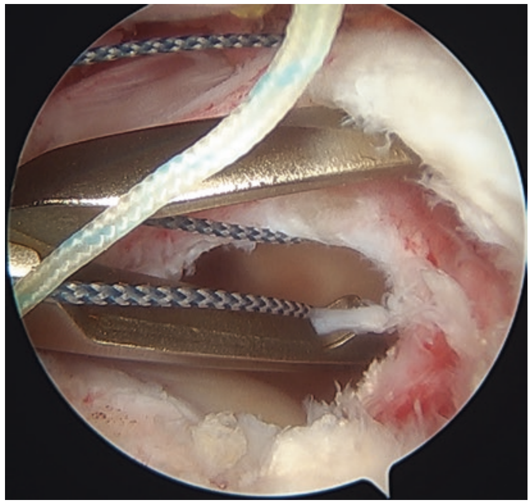

Fig. 12.3 Suture traction to reduce tendon cleavage

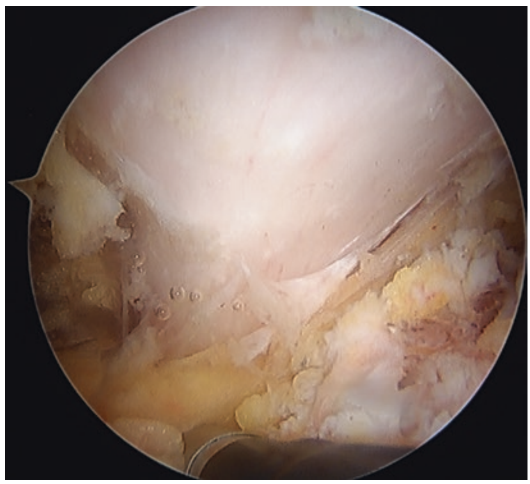

Fig. 12.4 Scapular spine. Radiofrequency probe points the fat space in which the suprascapular nerve travels

sensible than going toward it. Through manual traction suture, we can feel the tendon release and therefore, we can decide when the release is enough for the repair (Figs. 12.1 and 12.2). Furthermore, suture traction can be done through a portal already used for arthroscopic instruments and so avoid their multiplicity. According to the choice of the portal, suture traction allows to open the workspace adapted to what is needed (release, debridement, anchor positioning).

This subtlety is also very helpful to reduce tendon cleavage (Fig. 12.3). We can temporarily reduce bursal or articular surface of the tendon to perform suture passage.

12.3 Importance of Tension-Free Release in Repairs (Figs. 12.5, 12.6, 12.7, and 12.8)

Tendon release is an essential step in rotator cuff repair. It allows reduce mechanical stresses on the suture. According to Burkhart et al. [2], less mechanical stresses could limit postoperative pains ("no strain, no pain"). This release concerns bursal and articular space (capsulotomy).

The distance between the nerves of the subscapularis muscle and glenohumeral joint are averaging 36 mm in neutral rotation and between 16 and 18 mm when the limb is in external rotation [3]. This should incite extreme caution during the dissection of the subscapularis bursal surface to avoid denervation. According to Lafosse et al. [4], there may be adhesions between the retracted subscapularis and brachial plexus that may justify achieving neurolysis. At the articular surface, releasing the cuff imposes a capsulotomy.

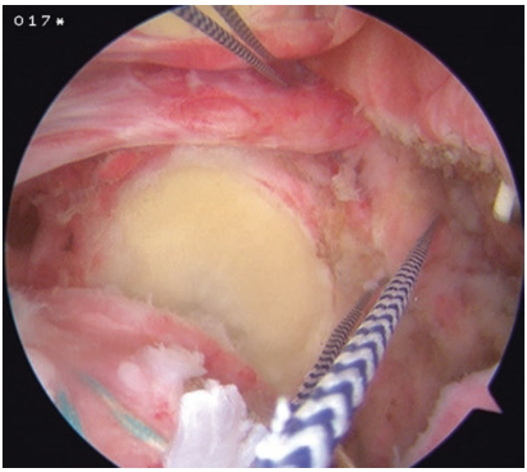

Fig. 12.5 Suture traction through supra and infraspinatus tendons. The posterior interval is between the two tendons, at the level of the spine of the scapula

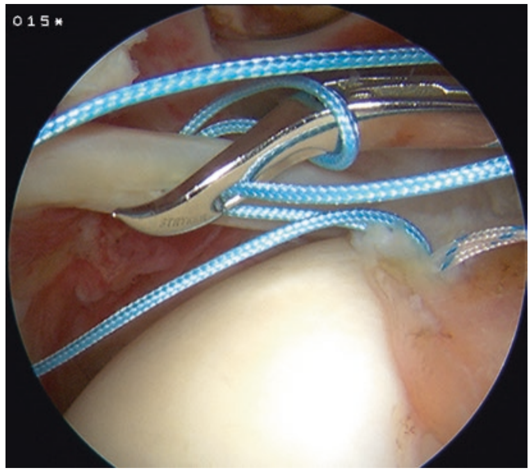

Fig. 12.7 Biceps tenodesis with lasso-loop technique

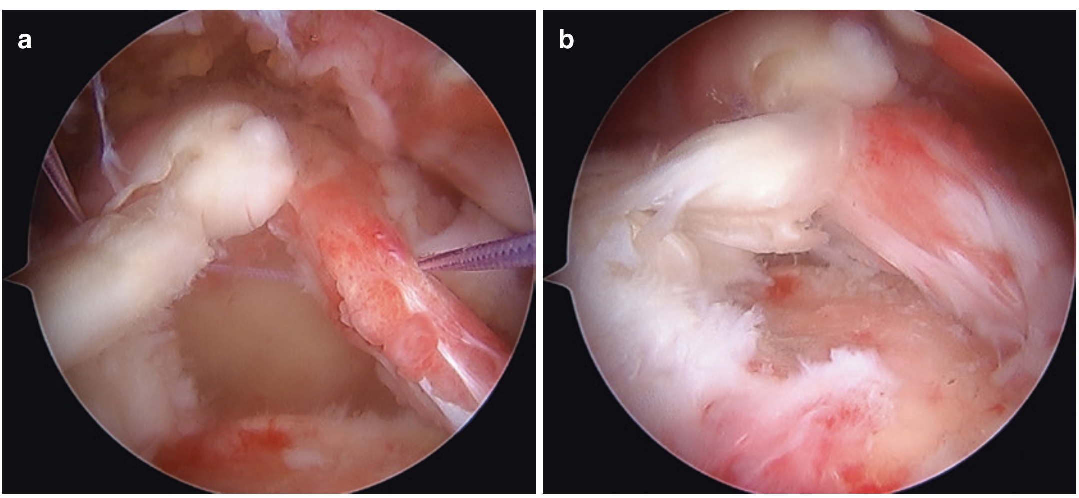

Fig. 12.6 (**a**) Margin convergence in U-shaped massive rotator cuff tear. (**b**) After performing margin convergence

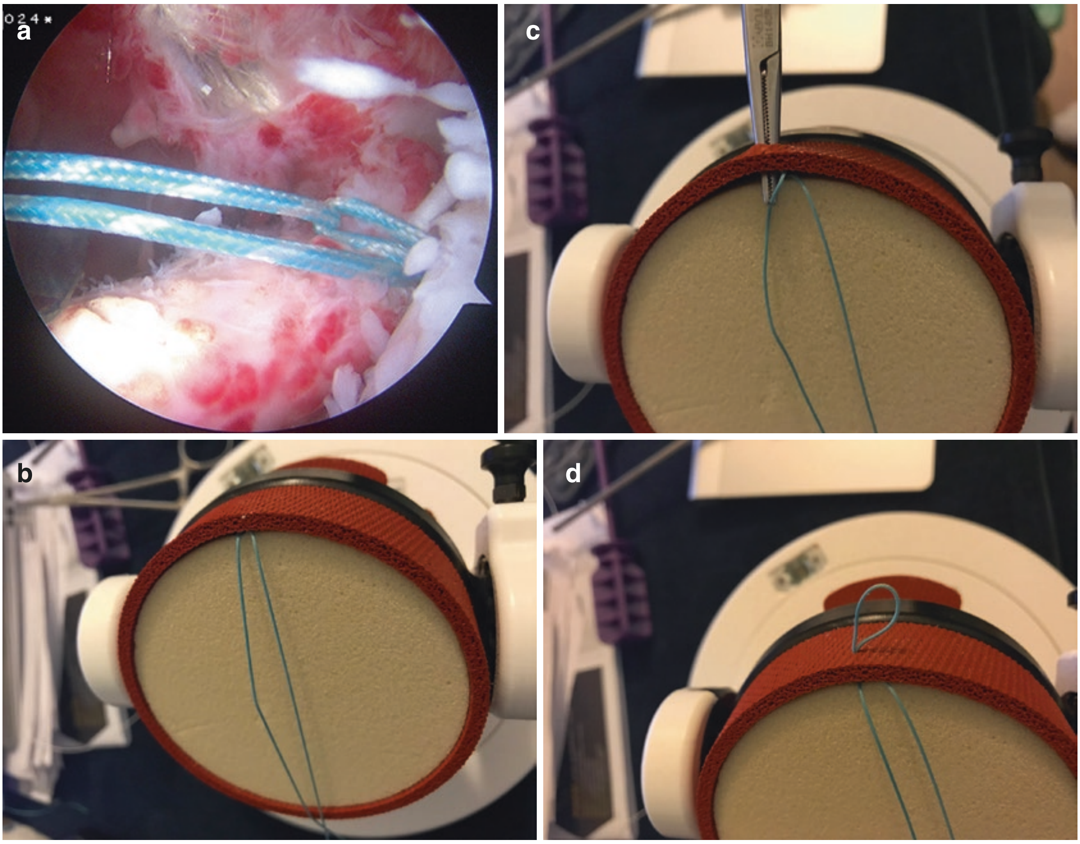

Fig. 12.8 (**a**) Lasso loop for reduction on cuff. (**b**–**h**) Step-by-step preparation of lasso loop

After releasing the superficial surface and deep face, the free tendon edge is seized with grasper and mobilized. If the cuff tear is reducible without tension, no additional release is necessary. The release of the rotator interval to the base of the coracoid was described by Cordasco and Bigliani [5] in open repair and was applied to arthroscopic procedure by Tauro [6]. This arthroscopic release is performed from the medial side of the biceps tendon to the coracoid. The release of the anterior interval allows an advancement of the anterior portion of the supraspinatus of 1–2 cm [7].

In general, tears of the supraspinatus (with or without infraspinatus lesion) reduce to the tuberosity in a posteromedial-to-anterolateral direction, rather than directly medially to laterally. In L-shaped and reverse L-shaped tears, the release of the rotator interval is generally sufficient to bring the supraspinatus to the height of greater tuberosity. In the U-shaped tears, it may be necessary to release the coracohumeral ligament to open the anterior or posterior interval slides between the supraspinatus and the infraspinatus. For this slide to be performed, the individual muscle bellies of the supraspinatus and infraspinatus are defined by skeletonization of the scapular spine (Fig. 12.4). Note that although the two muscle bellies are well defined, there is crossover between the fibers of the two tendons more laterally. A traction suture is then placed in each tendon and arthroscopic scissors are used to divide the supraspinatus and the infraspinatus back to the base of the scapular spine (Fig. 12.5). The opening of this space must not exceed the fat space in which the suprascapular nerve is travelling.

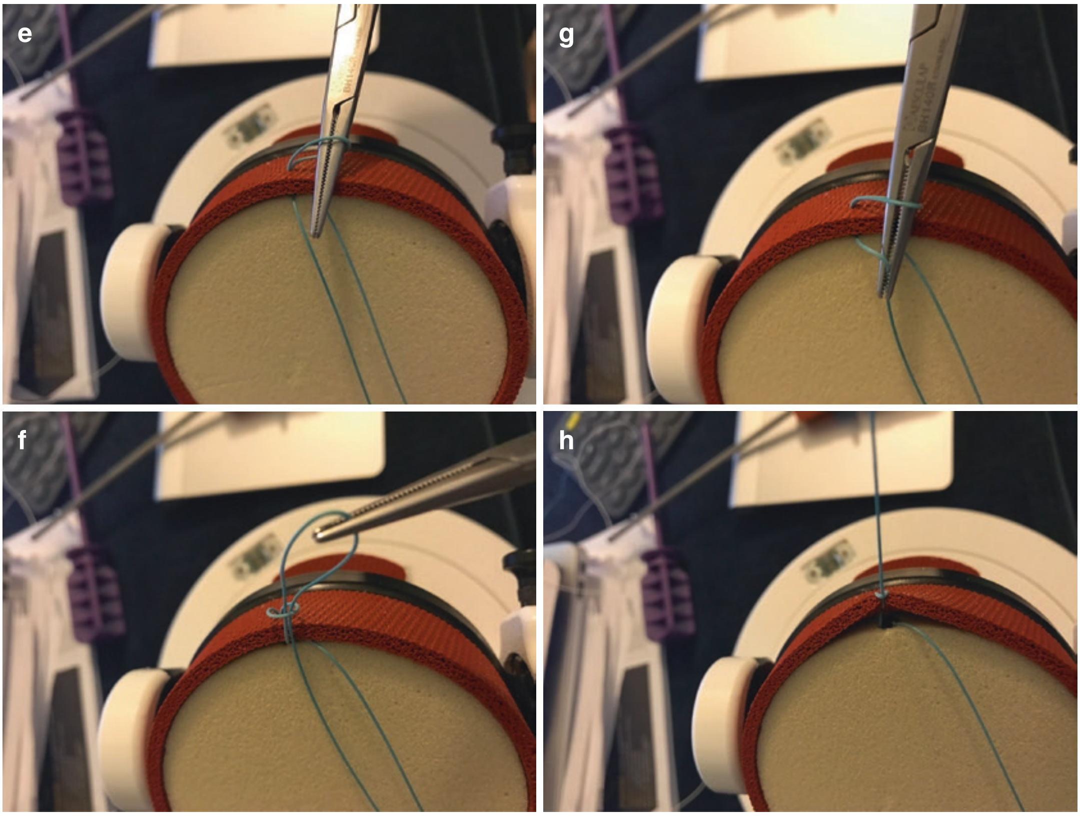

Fig. 12.8 (continued)

The release of anterior and posterior interval ("double interval procedure") allows full release of the supraspinatus tendon and progresses up the reinsertion area. Burkhart recommends placing suture traction on the edge of the supraspinatus and infraspinatus to facilitate dissection and visualization of fatty space [8]. After releasing the supraspinatus, if mobilization is insufficient to achieve the greater tuberosity, suture can appeal to margin convergence [2, 8]. It is a means to enhance the security of fixation by decreasing the mechanical strain at the margins of the tear. In a U-shaped massive rotator cuff tear, a partial side-to-side repair creates margin convergence of the tear toward the greater tuberosity (Fig. 12.6). This increases the cross-sectional area and decreases the length of the tear, thereby decreasing strain.

The strain reduction should also contribute to pain reduction. A less painful shoulder would naturally be a more functional shoulder. After release and mobilization, tears may not be fully reducible over the anatomic cuff footprint. Partial repairs may be warranted in these cases.

12.4 Reduction of Soft Tissues by Using Half Hitches or Knots (Correct Selection of Post Limb)

After passing sutures, the reduction of soft tissues is performed with knots or knotless suture anchor. There are many types of arthroscopic knots. The surgeon must be able to tie one of each type of sliding and non-sliding knots. More information about each type of knots will be given further down.

Non sliding knots consist of a series of half hitches in which the loop limb is tied around the post. They must be used when the suture material doesn't slide freely through the suture anchor. The post and loop limbs can be alternated, and the direction of throws of the suture can also be varied to increase knot security [9]. Each throw of the knot must be guided to the tissue so as to ensure that a tight knot is produced. Examples of non-sliding knots are the Revo knot and alternating half hitches. The Revo knot consists of two identical half hitches followed by a reversed half hitch on the same post. The post is switched and a reversed half hitch is thrown. The post is switched again and a reversed half hitch is thrown. This is the only version that has been shown to have the highest load to failure among half hitch configurations.

The selection of post limb depends on what we want to achieve:

- If we want to achieve a specific reduction of the tendon, it is preferable to do the knot on the side of the anchor, by choosing the limb on the anchor side (the limb that is not passing through the tendon) as the post limb.
- If we want to achieve an effect of plication, like arthroscopic Bankart repair (fixation of the avulsed labrum), you must choose the limb passing through the tissue (labrum) as the post limb.

Sliding knots consist of a knot prepared by loop limb on the shortened post limb (post limb is generally set to 1/3 or 1/2 of the loop limb prior to the preparation of the knot). When the post is pulled or the knot is pushed, the knot slides down the post to the tissue. Tension must be maintained on the post limb until half hitches are thrown to provide knot security. Furthermore, tying three half hitches with alternating posts after a self-locking knot to prevent knot failure is recommended. Burkhart et al. did a study in order to evaluate the configuration of sliding knots that would have adequate strength for rotator cuff repair [10]. They demonstrated that reversing posts while tying half hitches to secure sliding knots greatly increased the load to failure of the knot.

To avoid the pitfalls in achieving the knot, some tips are welcome. You'd better:

- Take and bring outside through the same portal the two strands of the same wire.
- Have no other wire in this portal.
- If you do not prefer cannulas, prior to knot tying, use your knot pusher on the two strands and follow them till the target tissue. This maneuver will help to avoid twists and soft tissue strangulation within the suture limbs.
- Always keep an eye on the half hitches while you are advancing them to the target tissue, because they may be trapped within the cannula.
- Do not forget to alternate the post and the loop limb to prevent knot failure and increase security.

12.5 Lasso Loop for Reduction (Figs. 12.9 and 12.10)

The lasso-loop stitch has been described by Lafosse et al. [11] in order to improve tissue grip. As he notes in his original article, passage of the suture through the tendon occurs at the start of the chain of reattachment of the rotator cuff. This step determines the quality of the rotator cuff repair. Gerber et al. [12] concluded that modified Mason-Allen stitch is a secure way of

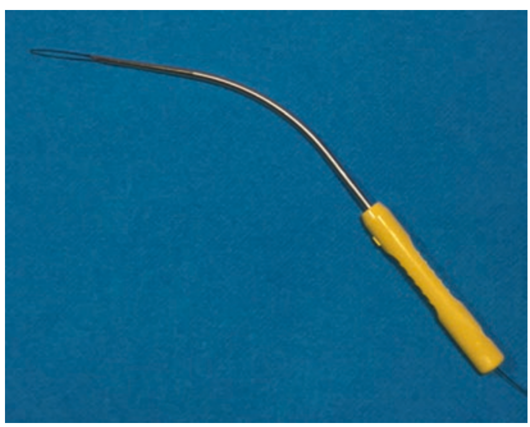

Fig. 12.9 Suture Lasso®

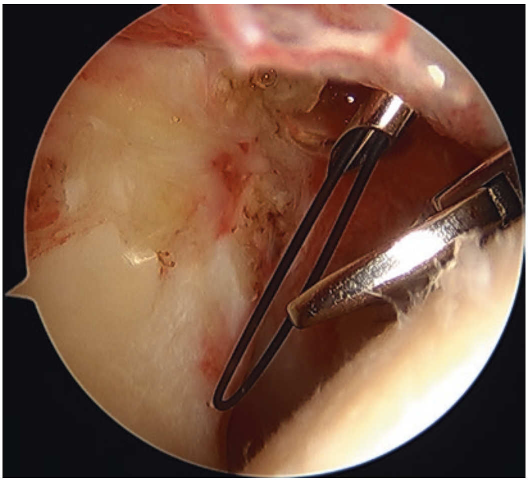

Fig. 12.10 The relay is captured and the wire is passed through the relay

achieving suture purchase on cuff tendons, however this technique is difficult to be performed in arthroscopic procedures. The lasso-loop stitch is easier to perform and can be used in tendon traction, rotator cuff repair, biceps tenodesis and Bankart repair (Fig. 12.7).

The first step is to pass one limb of the suture of the anchor through the free edge of the tendon by taking the limb in the middle. The limb is not pulled through completely. At this stage, a loop is created. The end of the suture, at the same limb used to make the loop, is passed through the loop with a grasper or a suture passer. The limb is passed through the loop, and the end of the limb is brought extra-articular. Then, the two limbs are taken and brought outside through the same portal. Depending on the choice of the puller limb, the tendon will behave differently. To reduce the tendon by using a lever arm mechanism, the end of the limb that passes through the tendon must be pulled. (Fig. 12.8) If the end of the limb that doesn't pass the tendon is pulled, the stitch is placed close to the anchor. Thus, the lasso-loop configuration requires half-stitch locking knots to secure the suture. It should be noted that in mattress lasso-loop stitch, only one side of the limb passes directly through the tendon and the other side is passed according to lasso-loop technique.

12.6 Soft Tissue Suture Passing Techniques and Tips for Minimum Tissue Damage

There are a number of different techniques available for passing suture through the rotator cuff. Surgeons need to be comfortable with several different methods of suture passing and have them available at the time of surgery. Suture passages can be performed with direct and indirect techniques. Direct suture passages are further subdivided into antegrade and retrograde. Direct passage occurs when the suture is passed directly in the tendon, whereas indirect passage requires a suture shuttle.

To manage the best possible type of suture, different tissue penetrators are required. The simplest is the cannulated needle, for indirect retrograde passages like the suture Lasso® (Fig. 12.9), and then sharp-end suture passers with various angles of curvature like BirdBeak® and CleverHook® for direct retrograde passages. At last, suture passers which grasped and passed the suture like Scorpion® for direct antegrade passages.

Suture lassos are easy to use and allow precise positioning of the suture limbs on the tendon. With the curved needle, we decide on the width of the tissue to be load. The scope is usually moved to the lateral working portal so that the surgeon has a view of the rotator cuff tear on both its bursal and articular surfaces.

The retrieval device is introduced from the posterior portal, the Neviaser portal or through an additional portal determined by need. The cuff is transfixed at the determined distance and the relay can be captured to the cannula. (Fig. 12.10) Once the wire is passed through the relay, it must be placed in the parking area. The surgical approach used for placing anchor is particularly suited.

The sutures are passed one by one, anterior to posterior, this prevents them from becoming tangled. In delaminated cuff, the use of this device can reduce the lower layer with the wire catch and pass with the needle at the same time, unlike the use of forceps.

The use of the cannula is highly recommended here to prevent the risk of entangling the wires and to avoid soft tissue interposition in the suture.

The hook is specifically designed for suture passing and retrieving during rotator cuff repair. The suture can be retrieved by piercing the superior portion of the rotator cuff with the sharp distal tip of the instrument, rotating through the tissue, and then retrieving the suture using a twisting retrograde motion.

To save time, the wire must be submitted in advance where the cuff is expected to be transfixed.

The hook is maneuvered with small, circular movements of the wrist that augment the curvature of the instrument, allowing it to delicately pass through the depth of the rotator cuff. The ideal direction of the device to perforate the tendon is as perpendicular as possible to the direction of the fibers.

The use of the cannula is less useful than when using the suture lasso. Suture can be passed by grasping the suture and advancing the distal tip of the hook in an antegrade fashion through the rotator cuff. Care must be used with these instruments to avoid damage to the tissue through which the device is passing, the articular cartilage or other structures within the joint. As previously said, the sutures are passed one by one, anterior to posterior, to prevent them from becoming tangled.

These tissue-penetrating devices are particularly useful in arthroscopic instability and SLAP repairs, in order to pass through the capsulolabral tissue but also in biceps tenodesis according to lasso-loop technique, for example. (Fig. 12.11) In rotator cuff repair, the use of these devices depends on the surgeon's habits, but the use of all these devices must be thoroughly mastered by all surgeons.

Finally, they will be particularly useful in the arthroscopic reduction and stabilization of tuberosity fractures. Indeed, a forceps cannot cross the distal bone fragments to pass the suture through the supraspinatus tendon.

Sometimes, obtaining ideal angle for suture passage can be difficult. If the work place allows, we can use suture punch devices. They are larger than suture relay or tissue penetrators. Generally suture punch devices are used through a cannula placed in the lateral portal.

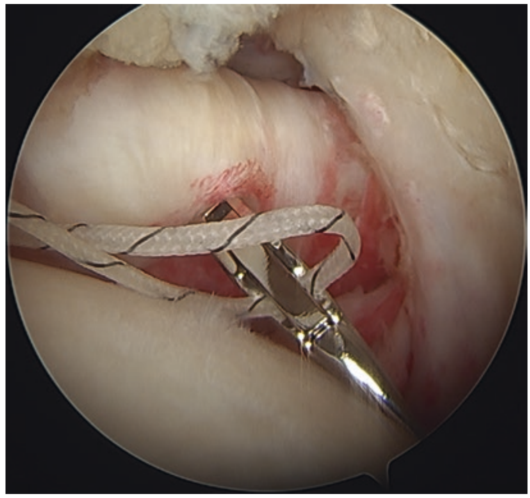

Fig. 12.11 Retrograde suture passage by a CleverHook®

They use a needle to shuttle suture through tissue when the device is deployed. Then, the suture can be retrieved by a suture grasper or by the same instrument, which allows both a one-step suture passage and retrieval on the opposite side of the tissue.

However, performing the grasping and retrieving steps through a different portal to avoid pulling the suture out of the tissue is recommended. This device facilitates the passage of sutures including the massive retracted rotator cuff tears where the positioning of a suture relay would sometimes be difficult.

Moreover, they minimize the number of steps involved in suture passing and is a real time saver. Unlike suture relay, the suture passage is constrained by the size of the forceps; they also are not the best for delaminated tears.

Thus, one needs to be familiar with more than one suture passing technique.

12.7 Positioning of Sutures for Maximum Tissue Grab

Care is taken to assess for tendon delamination and potential differential retraction of tendon layers, especially posteriorly. Sutures are passed approximately 1–1.5 cm medially to the lateral edge of the tear in order to avoid over-reduction of the rotator cuff and to position the sutures in a sufficient tissue.

Conclusion

Even the best suture, anchor and knot combination would fail to repair soft tissues in poor quality and/or high tension. Proper soft tissue handling techniques will help surgeons to overcome this potential problem.

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Suture Manipulation in Arthroscopic Surgery

13

Urszula Zdanowicz and Michał Drwięga

Suture manipulation is a key point in arthroscopic surgery. Sutures are mainly used in shoulder surgeries. However, during meniscal repairs, some ankle and elbow arthroscopic procedures surgeons need ability of suture manipulation. In this chapter, we will focus on suture manipulations during shoulder arthroscopies such as basic suture handling and configurations. All these maneuvers can be adapted to other procedures in different joints.

The goal of successful rotator cuff repair is to provide good initial stability, no or minimal gap formation, to restore its anatomical footprint, maintaining stability under cyclic loading as well as wide and stable contact area between the bone and reconstructed tendon to provide good healing. There might be a variety of different causes of failure such as suture failure, knot loosening, anchor pull out, and soft tissue break. A good technique with different suture configurations would minimize such risks [1, 2].

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13.1 Basics in Suture Handling During Arthroscopy

1. Always mark your sutures. Clamping the free ends can do this.
2. Group your sutures in order to prevent possible confusion.
3. Use parking portals in order to prevent a tangle (Fig. 13.1).
4. After choosing your working portal, transfer sutures to the parking portal except the suture you are going pass through the soft tissue. During instrumentation, keep only one suture at a time in the working portal.
5. While pulling a suture out of a portal, always hold the free end of the other limb. Otherwise suture can be completely pulled out of the anchor eyelet.

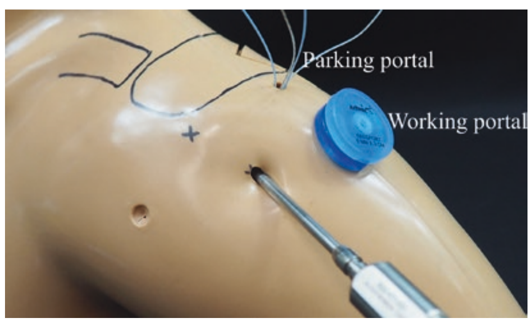

Fig. 13.1 Parking portals are used to protect suture limbs when they are not in use

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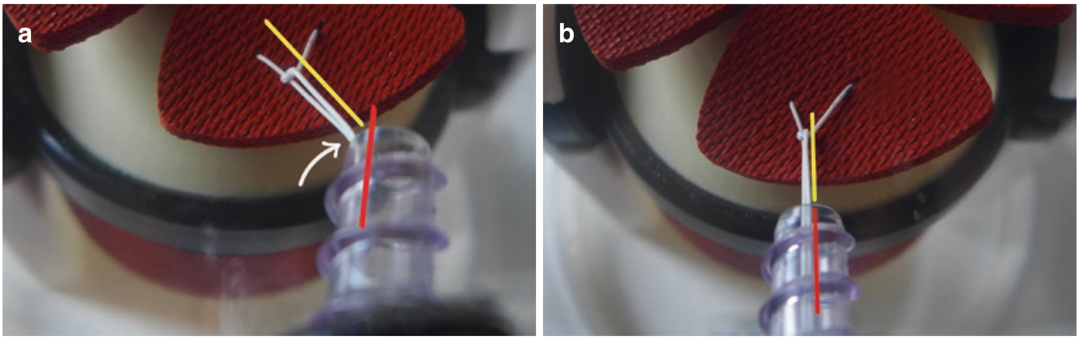


Fig. 13.2 (**a**) Working cannula (red line) is not aligned with the target tissue (yellow line); suture impinges against edge of the cannula. (**b**) Working cannula is well aligned

6. Once you complete soft tissue passage of the sutures, transfer these sutures to the parking portals until knot tying.
7. If you cannot locate a suture within the joint, you can use a knot pusher on that suture, advance the knot pusher into the joint, and find your suture.
8. Before tying the knot, choose your working portal. For knot tying, working portal should be aligned with the anchor or the target tissue. If not, during knot tying suture will impinge against the arthroscopic cannula and can be damaged (Fig. 13.2).
9. Suture limbs should be parallel before tying knots. Tying knots on twisted limbs will cause slacks within the hitches.
10. If you will perform a sliding knot, you need to set the length of the post limb as 1/3 of the loop limb. Otherwise sliding the knot will cause a limb length discrepancy and the surgeon can not complete the knot properly.

13.2 Different Types of Suture Configuration

First, attention must be taken into proper suture placement within the tendon. If there is no loss of tendon length, medial sutures should be placed about 2–3 mm lateral to musculotendinous junction. It allows for proper restoration of tendon length, secure fixation within soft tissue [3] (Fig. 13.3a, b), and equal tension within the sutured tendon. For suture passing through the tendon, different instruments are available on the market. Surgeon should be familiar with several techniques to use on different situations.

13.3 Single Row

As single row repairs have lower in vitro mechanical properties [4] compared to double row, they can be used in partial thickness, superficial (bursal) injuries, or in retracted cuff injuries without sufficient mobility to perform double-row repair [3]. With single row technique, one must distinguish between simple (Fig. 13.4a–n) and horizontal mattress configurations (Fig. 13.5a–v).

A different type of single row repair is a modified Masson-Allen technique, described by Scheibel et al. [5] for suture anchor rotator cuff repair. This technique is a combination of horizontal mattress and simple stitch through the same anchor [2] (Fig. 13.6a–o). Baums et al. [2] compared single row Mason-Allen technique with a combination of double-row technique with use of Mason-Allen technique and proved that double-row technique had significantly higher tensile strength and resistance

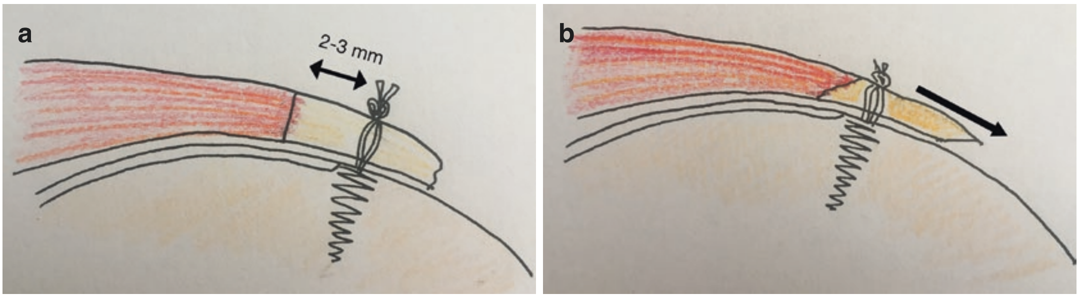


Fig. 13.3 (**a**) Proper suture placement: medial sutures should be placed about 2–3 mm lateral to musculotendinous junction. This allows for achieving equal tension within whole sutured tendon. Antergrading suture passage facilitates proper suture placement. (**b**) Incorrect, oblique suture placement within rotator cuff may cause uneven tension in the tendon, where superficial part is pulled much further laterally than deeper layers; this may cause clinical failure. Be careful with retrograde suture passage. Additionally, placing sutures too far medially (within muscle part) can cause pulling through and cutting the tissue, also resulting in suture failure

during cycling loading. This technique is rarely used nowadays, however may be a part of a more complex repair.

There are newer single row techniques providing better compression over the repair zone such as SpeedFix repair (with inverted mattress FiberTape, Arthrex, Naples, FL, and BioComposite SwiveLock C anchor, Arthrex, Naples, FL).

13.4 Double-Row Technique

Historically, first-generation double-row technique consisted of medial and lateral simple sutures without any linking between two rows [3, 6]. There have been a variety of different suture configurations forming double-row suturing: two mattress sutures on medial side and two simple sutures on lateral side and two mattress sutures on medial side and Mason-Allen stitches on lateral side [2] and many others. In general, results of those repairs are similar.

The new generation double-row technique is different, with a self-reinforcing structure consisting of medial and lateral rows linked together with a suture bridge (Fig. 13.7a–ai) (also known as transosseous-equivalent technique). Suture bridge technique might be improved by adding multiple anchors and sutures medially and laterally giving a final Diamondback appearance on the repair zone (Fig. 13.8). This construction provides maximal compression under loading, and that makes this technique biomechanically superior to the others (Fig. 13.9a, b).

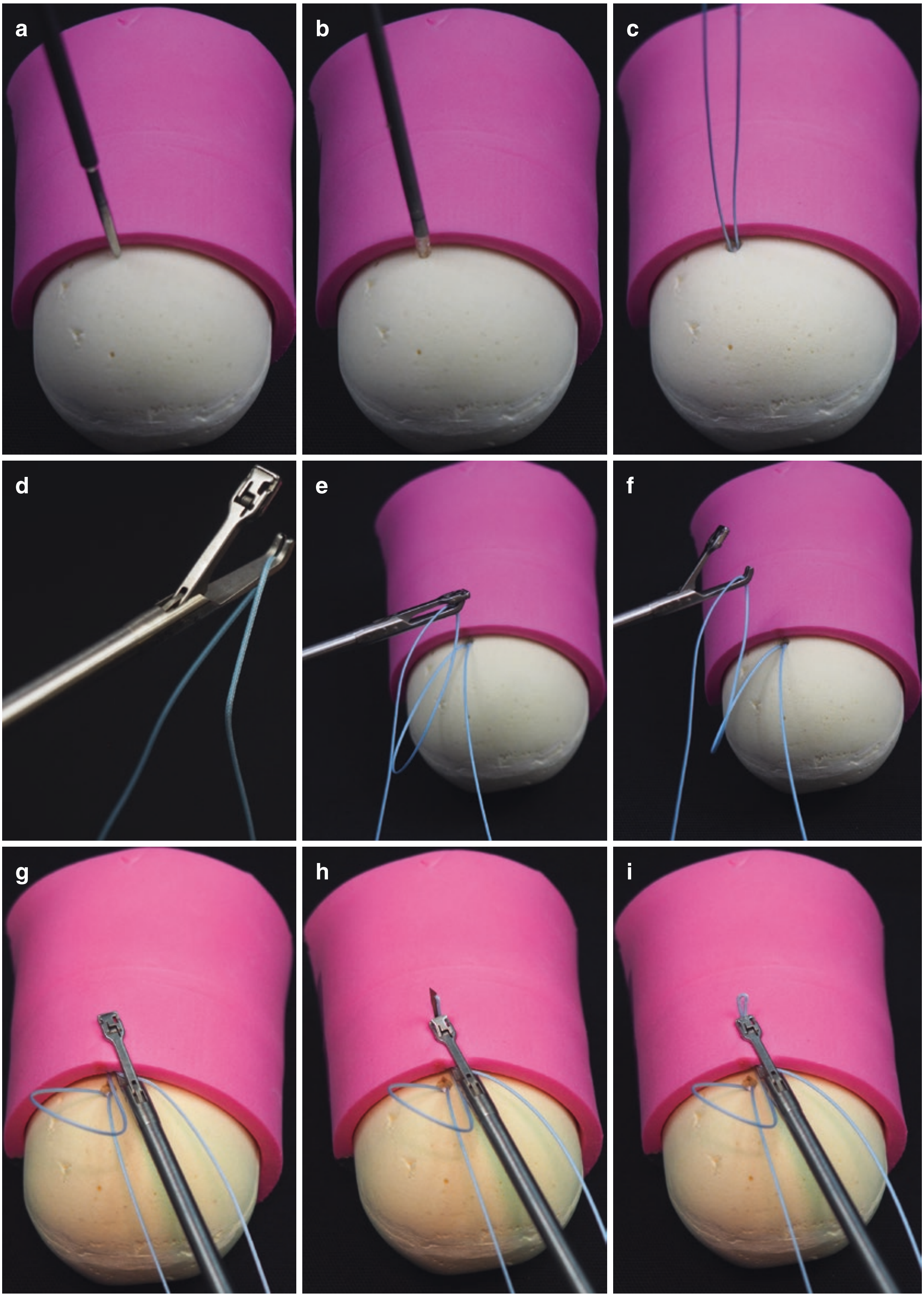
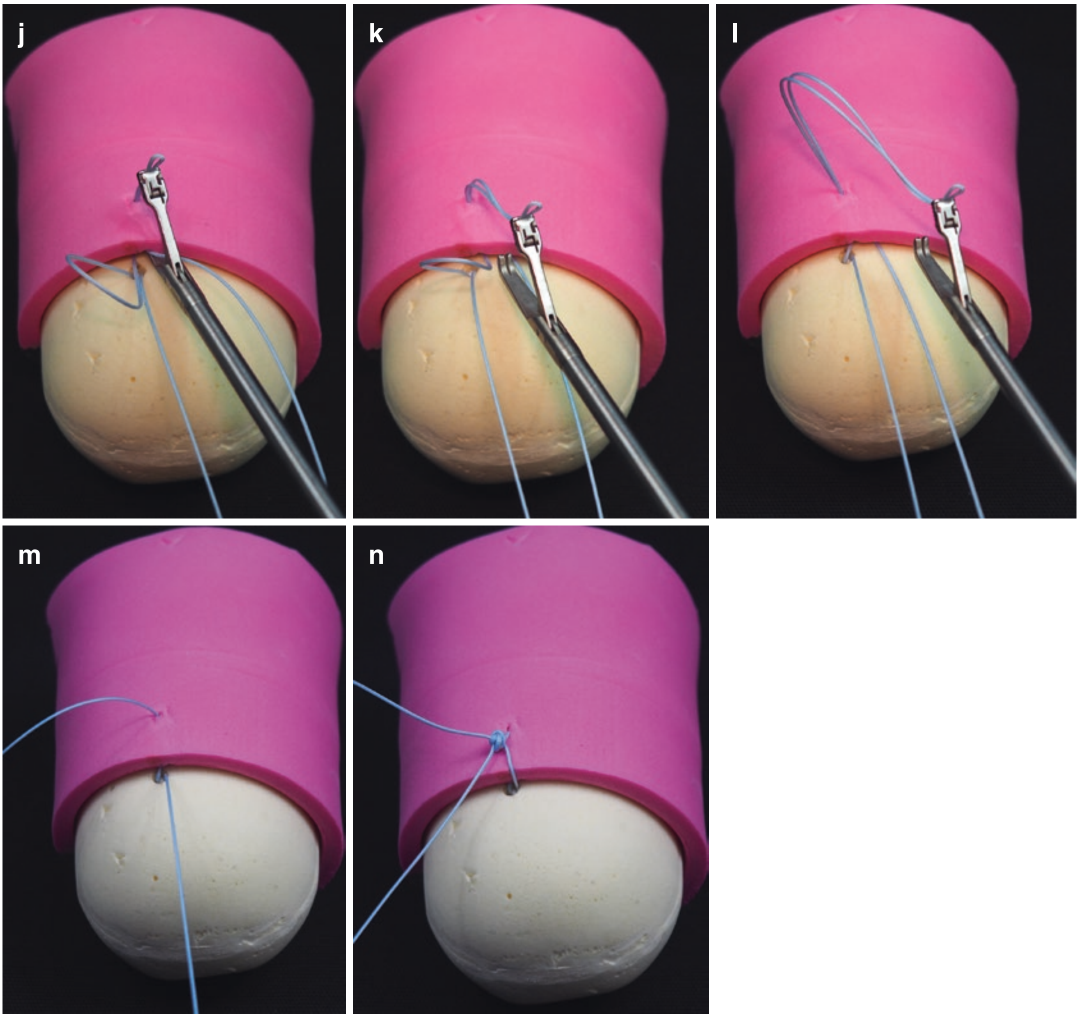


Fig. 13.4 (**a**–**n**) Step-by-step single suture (single row) technique



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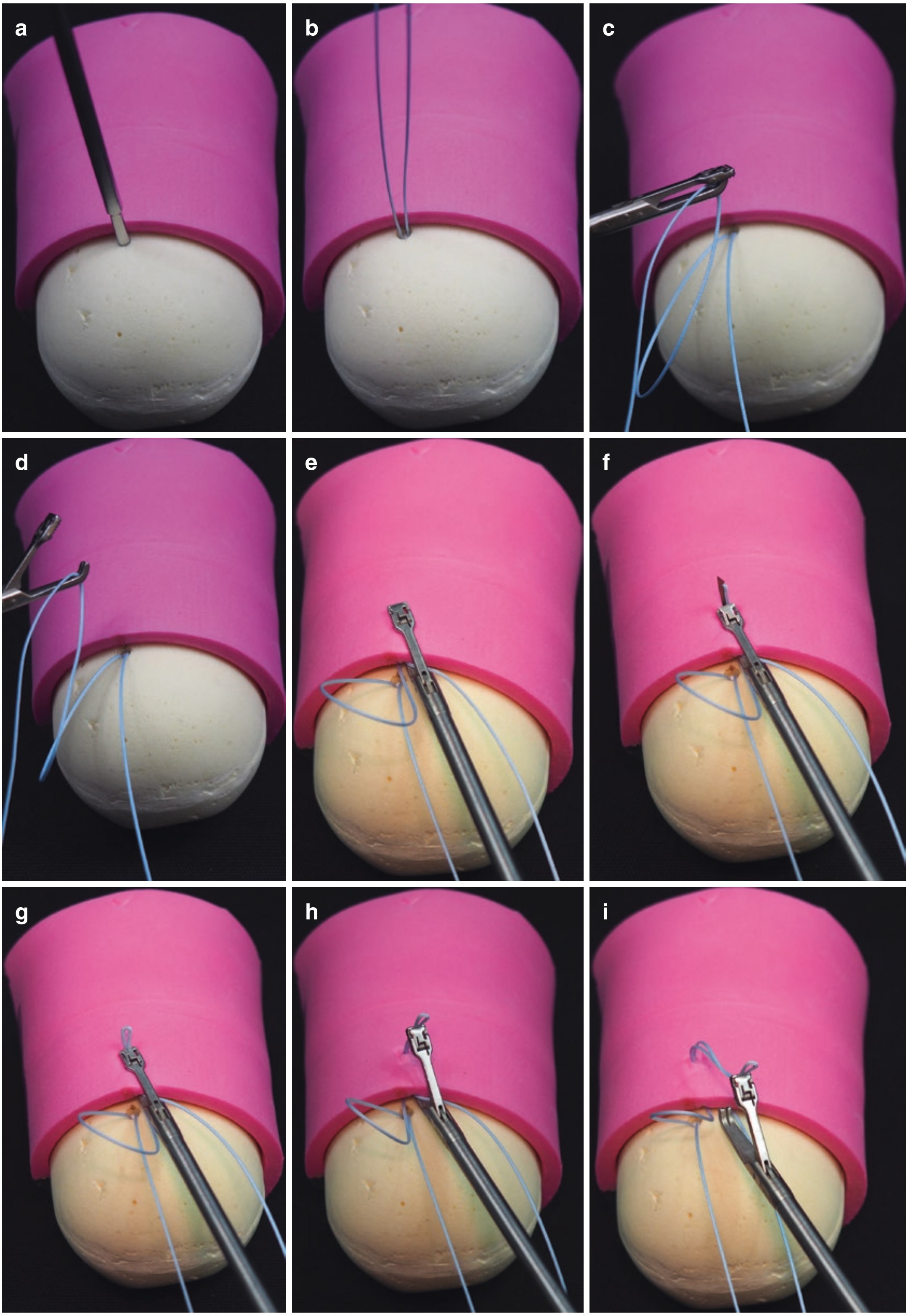
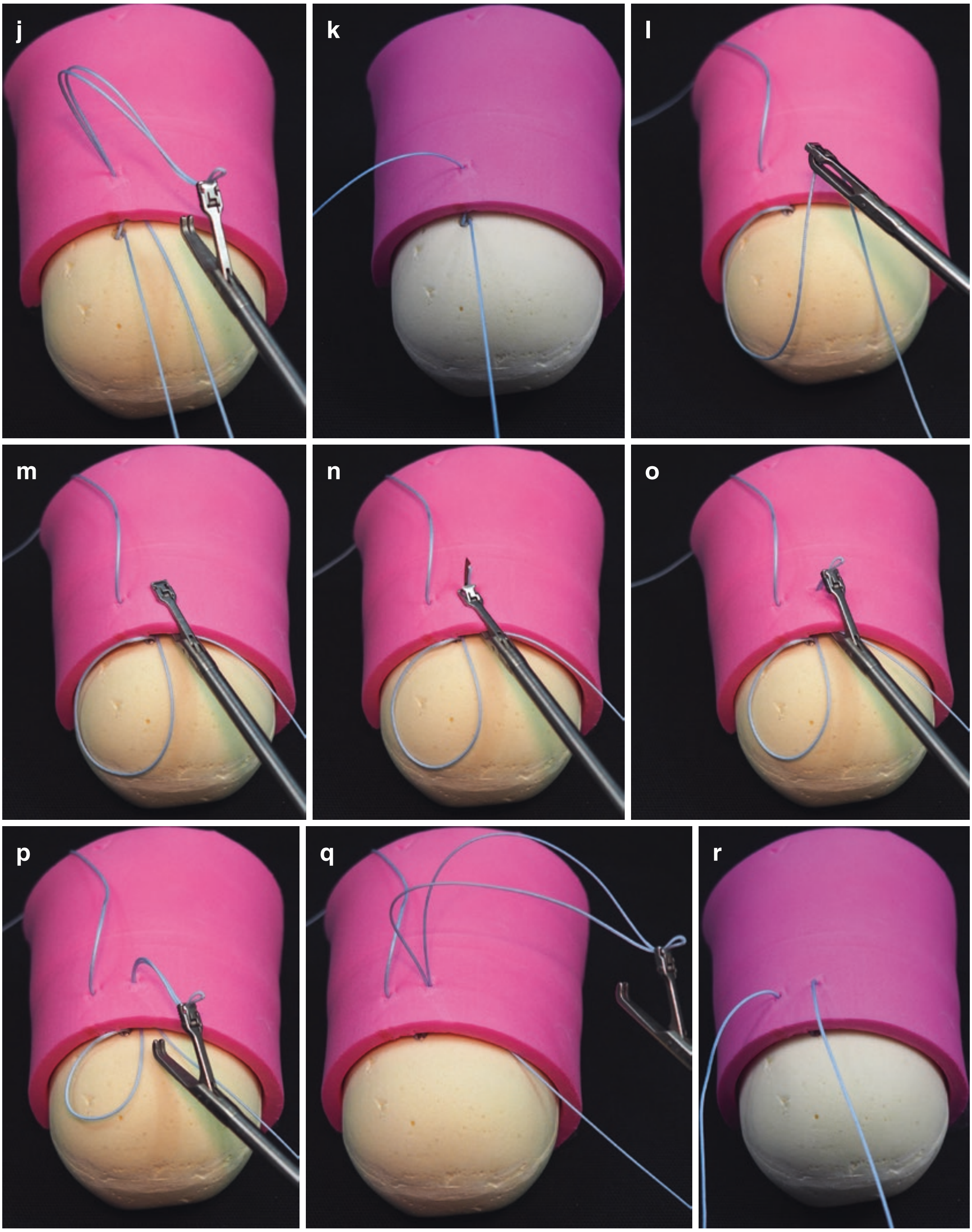


Fig. 13.5 (**a**–**z**) Step-by-step horizontal mattress stich



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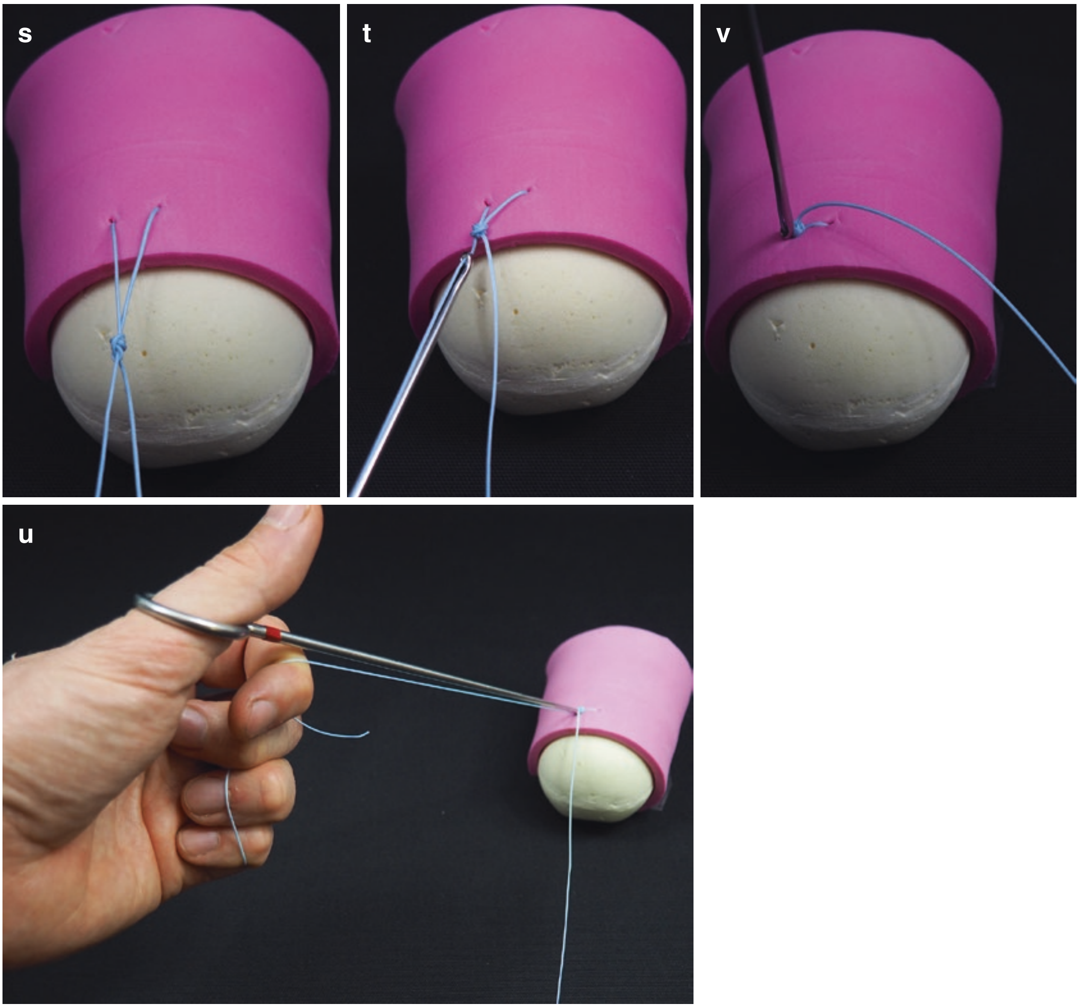

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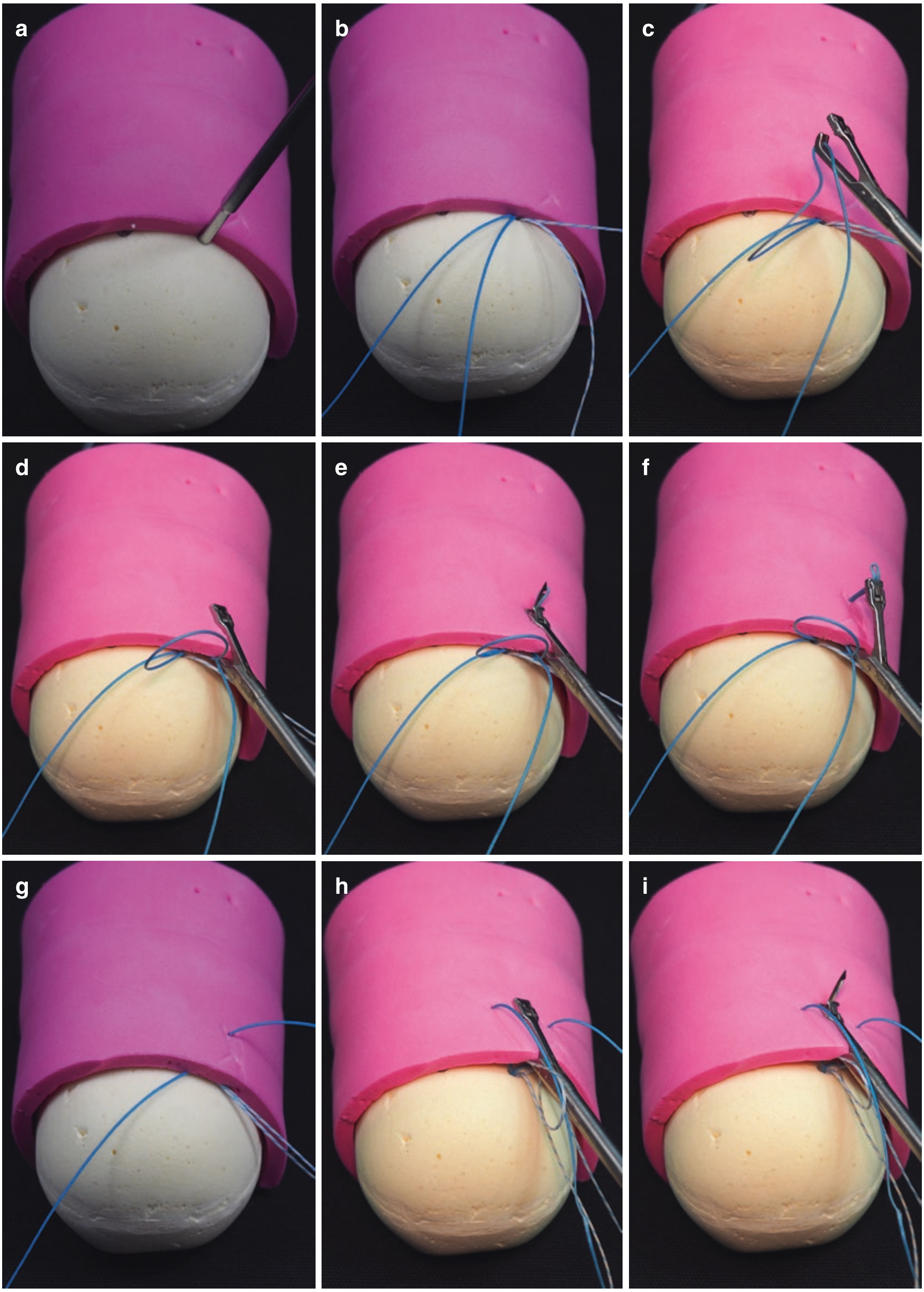
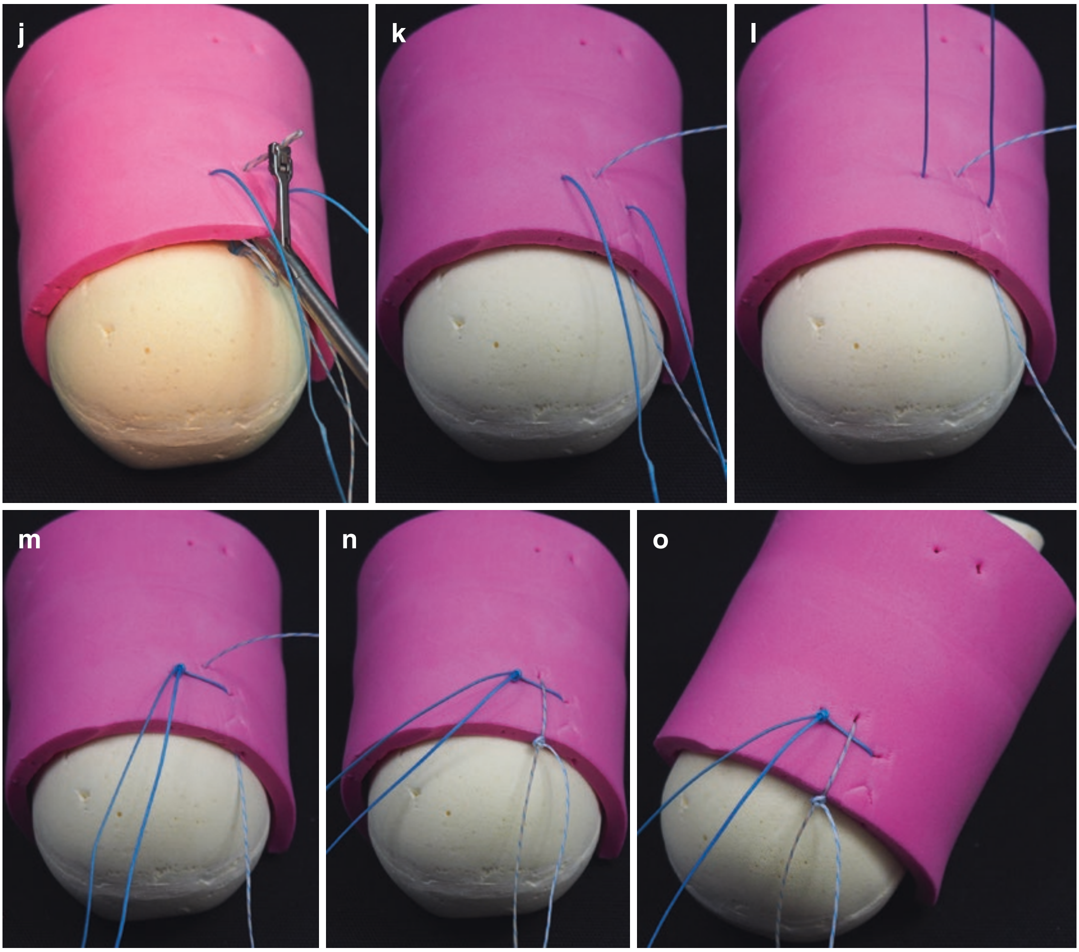


Fig. 13.6 (**a**–**o**) Step-by-step arthroscopic (modified) Mason-Allen technique



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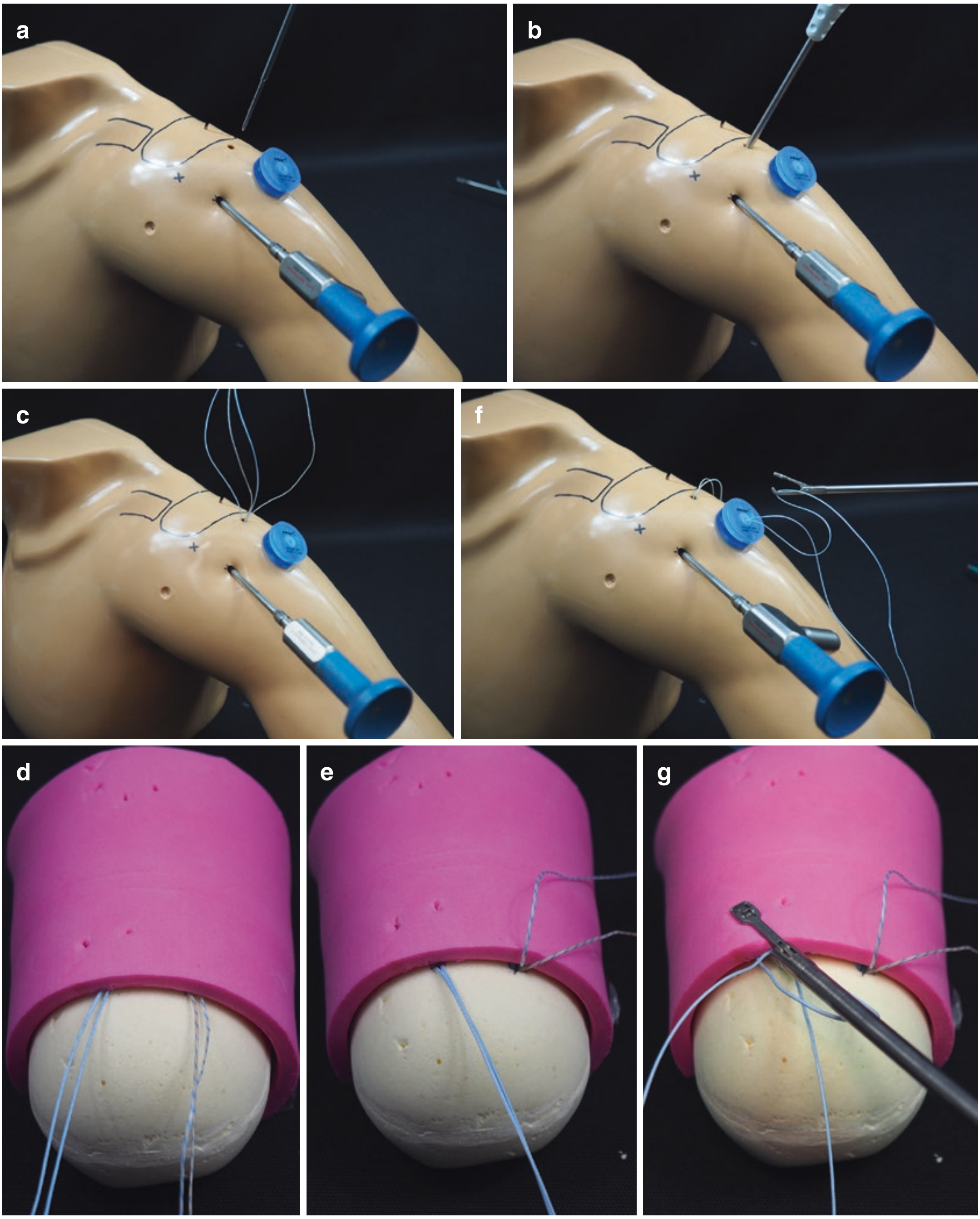
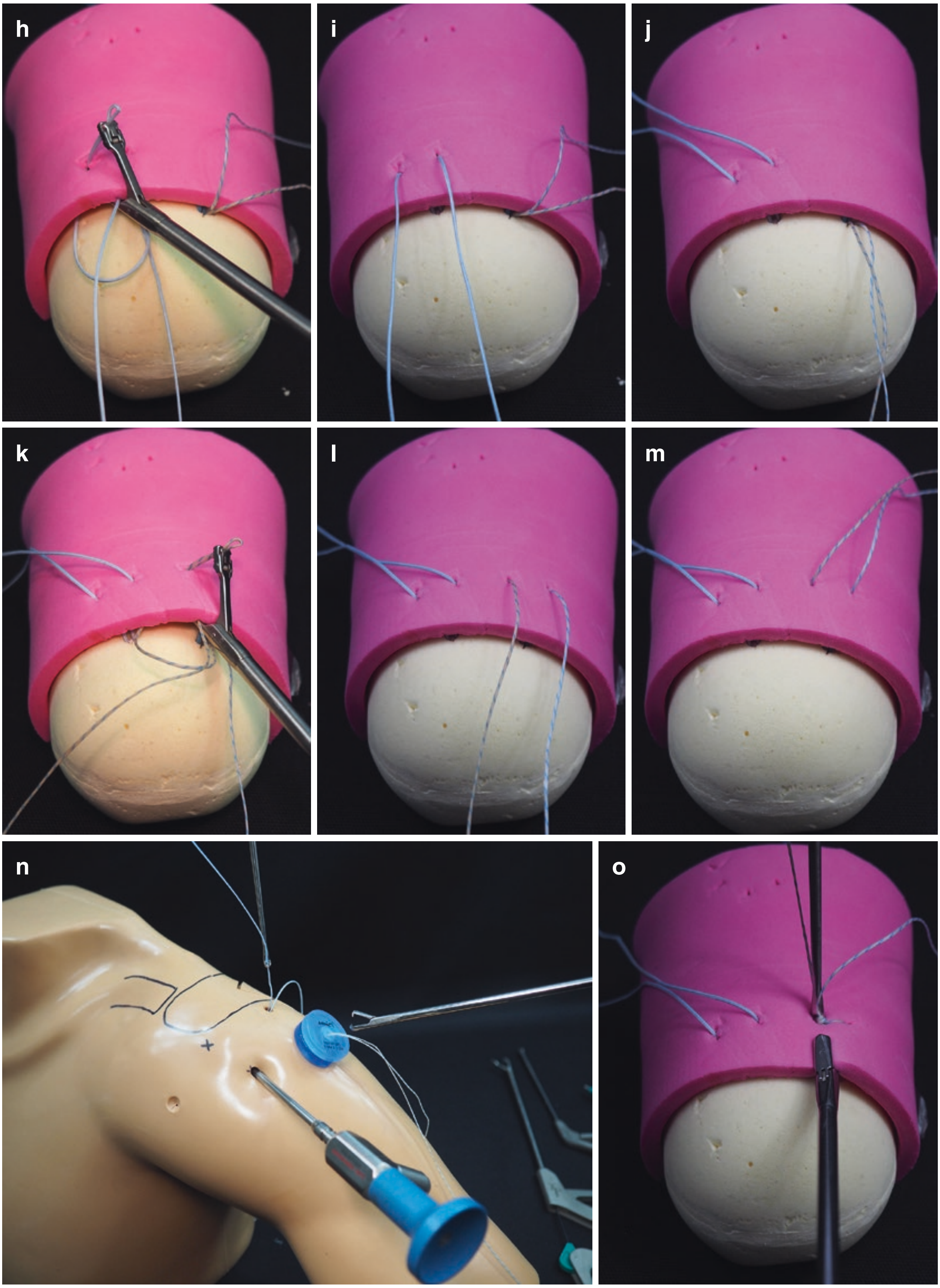


Fig. 13.7 (**a**–**ai**) Step-by-step suture bridge technique



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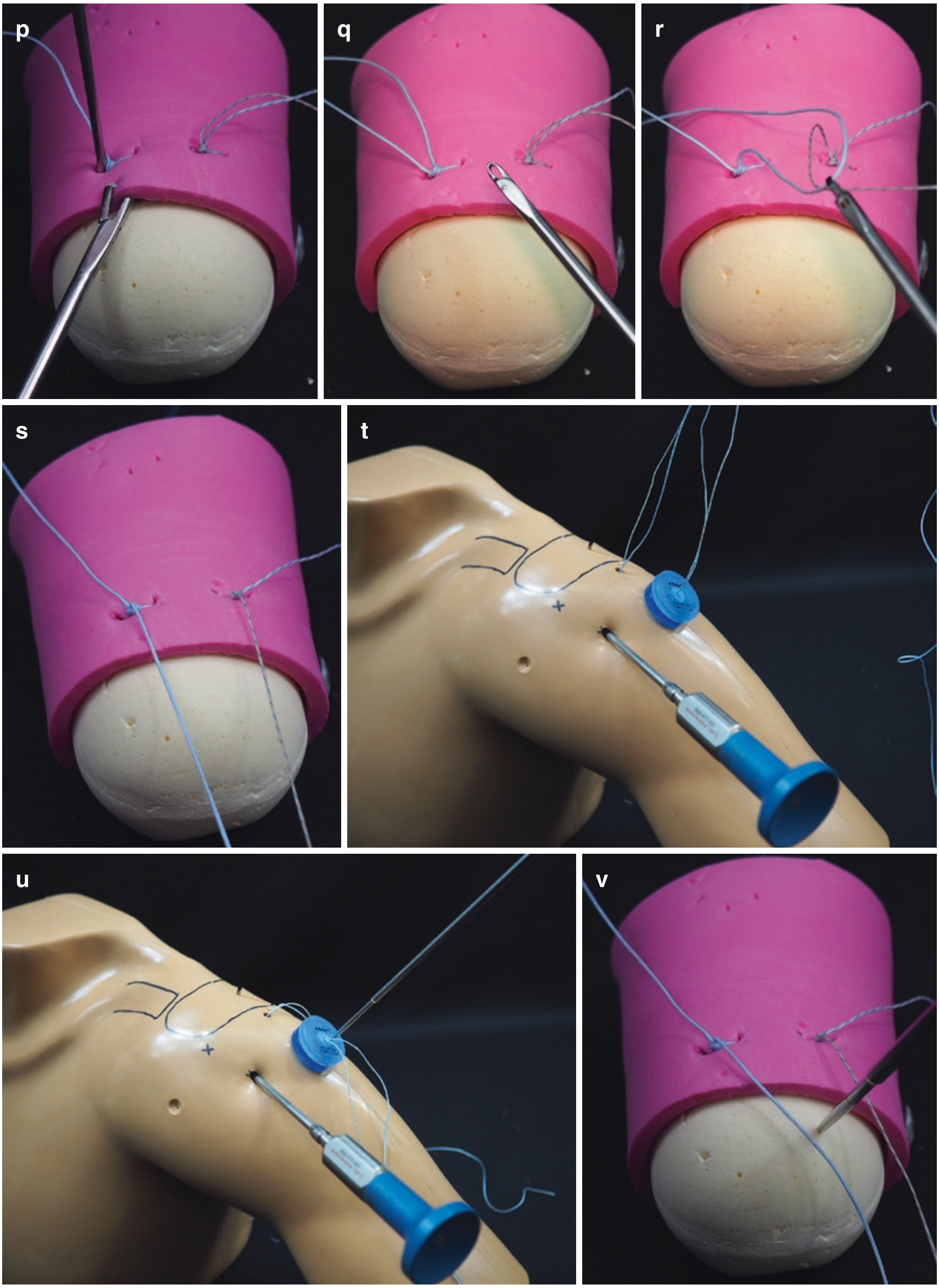

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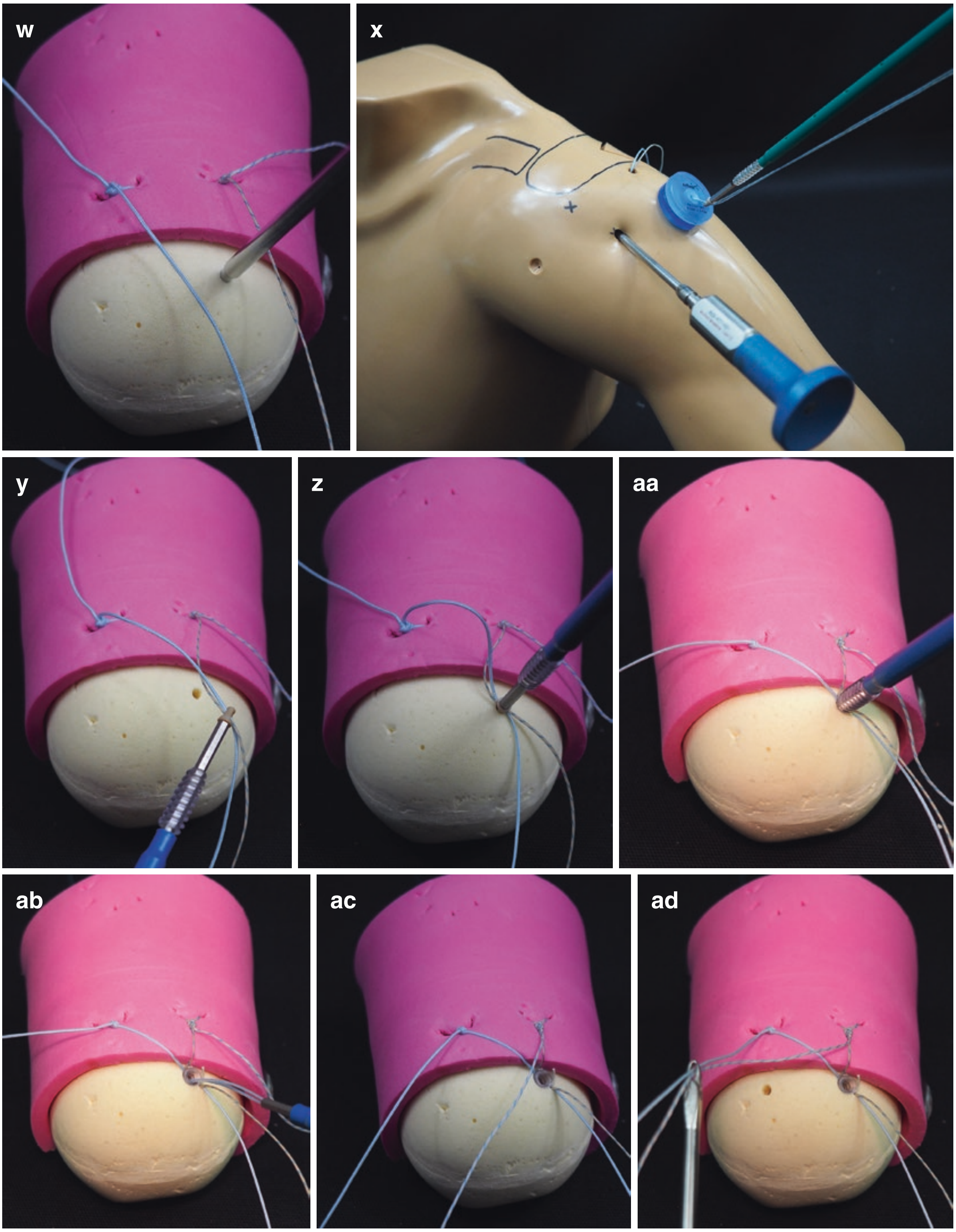

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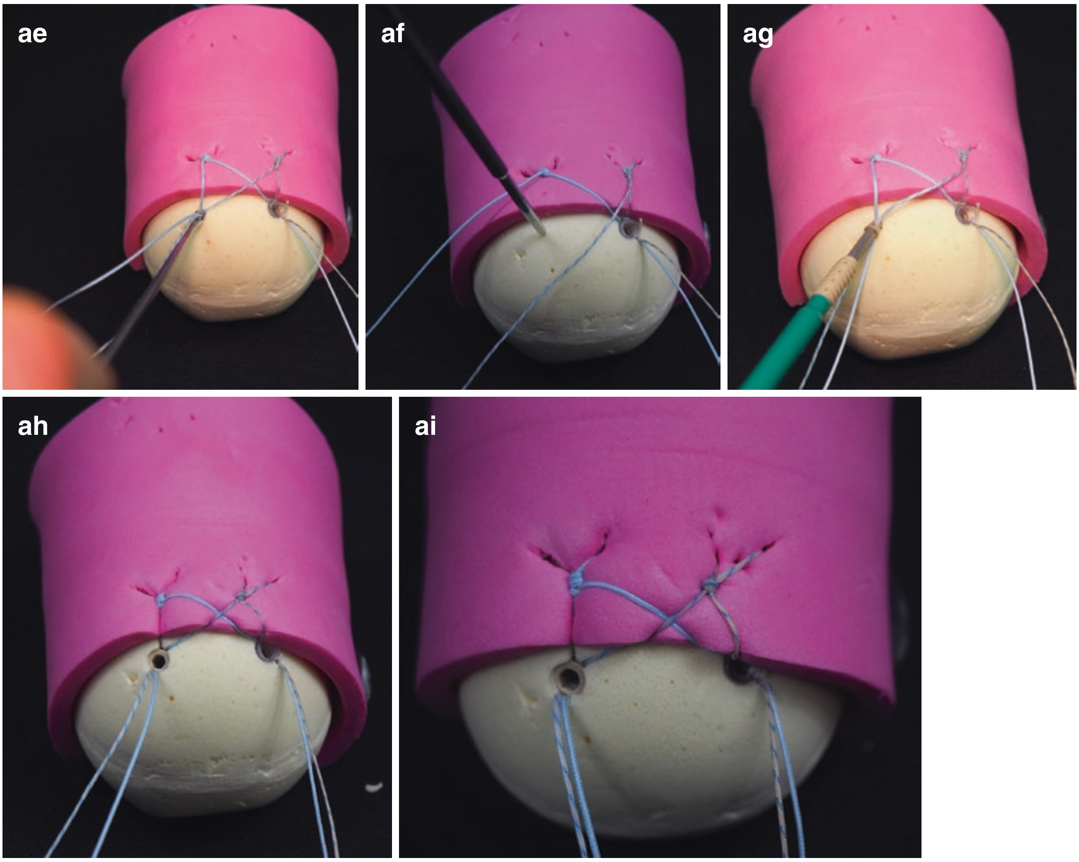

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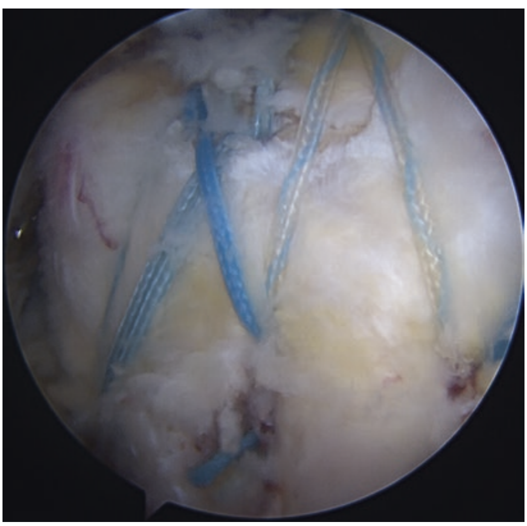

Fig. 13.8 Arthroscopic view of Diamondback SutureBridge technique

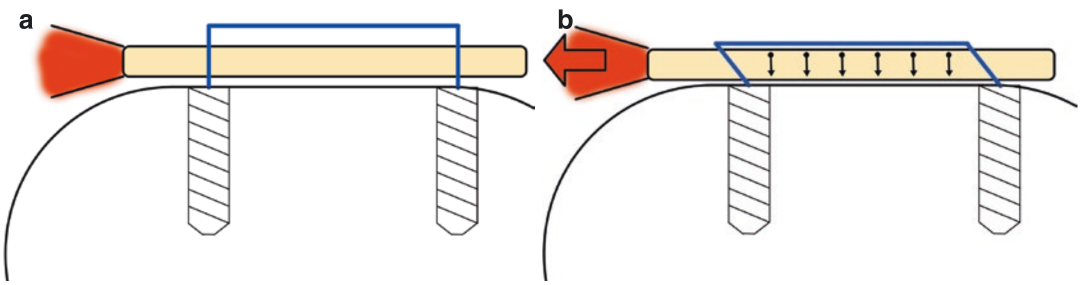

Fig. 13.9 Schematic drawing of suture bridge showing how pulling of the tendon results in higher compression forces on the reconstructed rotator cuff footprint. Mechanism that makes this type of suture configuration superior to other techniques

Conclusion

Suture manipulation is an important skill in arthroscopic repairs. Surgeons should be capable of basic manipulation techniques before entering the operating room.

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Half Hitches

14

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Half hitch is named as "work horse of knot tying" by some authors [1]. Half hitches may be stacked on each other to create a non-sliding knot or may also be used to secure both locking and non-locking sliding knots. Half hitches can be formed in two different configurations: a loop limp tied under the post limb (underhand half hitch) and a loop limb tied over the post limb (overhand limb).

In arthroscopic surgery, the aim of knot tying is to prepare half hitches outside the joint, advance them through the cannula using instruments, and transfer them over the tissue. Adequate tension and secure configuration should be maintained.

14.1 Underhand Half Hitch, Basic Technique (Fig. 14.1)

1. Before beginning to prepare your half hitch, transfer the two limbs that will be tied to the same cannula. Do not keep other suture limbs in the same cannula. Do not forget to check the orientation of the limbs within the cannula and on the target tissue, they should be parallel. Twists on the limbs will prevent proper half hitch orientation and cause slacks (Fig. 14.1a).
2. Knot pusher is placed on the post limb. Place the working limb beneath the post and form a loop (Fig. 14.1b).
3. Pass the free end of the working limb through the loop (Fig. 14.1c).
4. Underhand half hitch is ready on the post (Fig. 14.1d).

14.2 Underhand Half Hitch, Alternative Technique (Fig. 14.2)

1. Hold the loop limb with the dominant hand and post limb with the non-dominant hand (Fig. 14.2a).
2. Loop limb should be over the index finger and thumb of the dominant hand while holding the end of the loop limb in the remaining fingers. Cross the loop limb perpendicular to the post limb (Fig. 14.2b).
3. Curl the dominant index finger around the post limb, and catch the loop limb with the dorsum of the distal phalanx of the dominant index finger (Fig. 14.2c).

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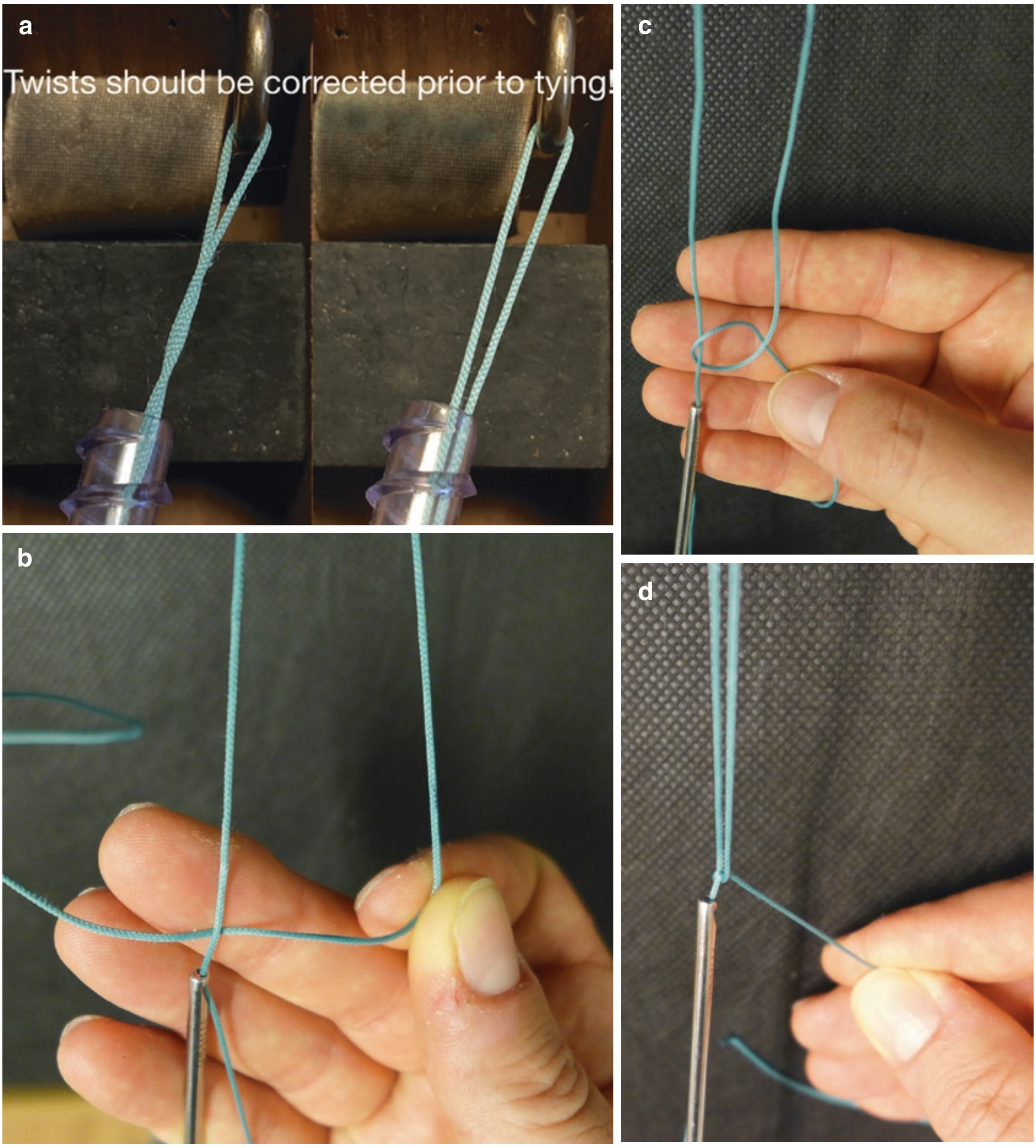

Fig. 14.1 Underhand half hitch by basic technique

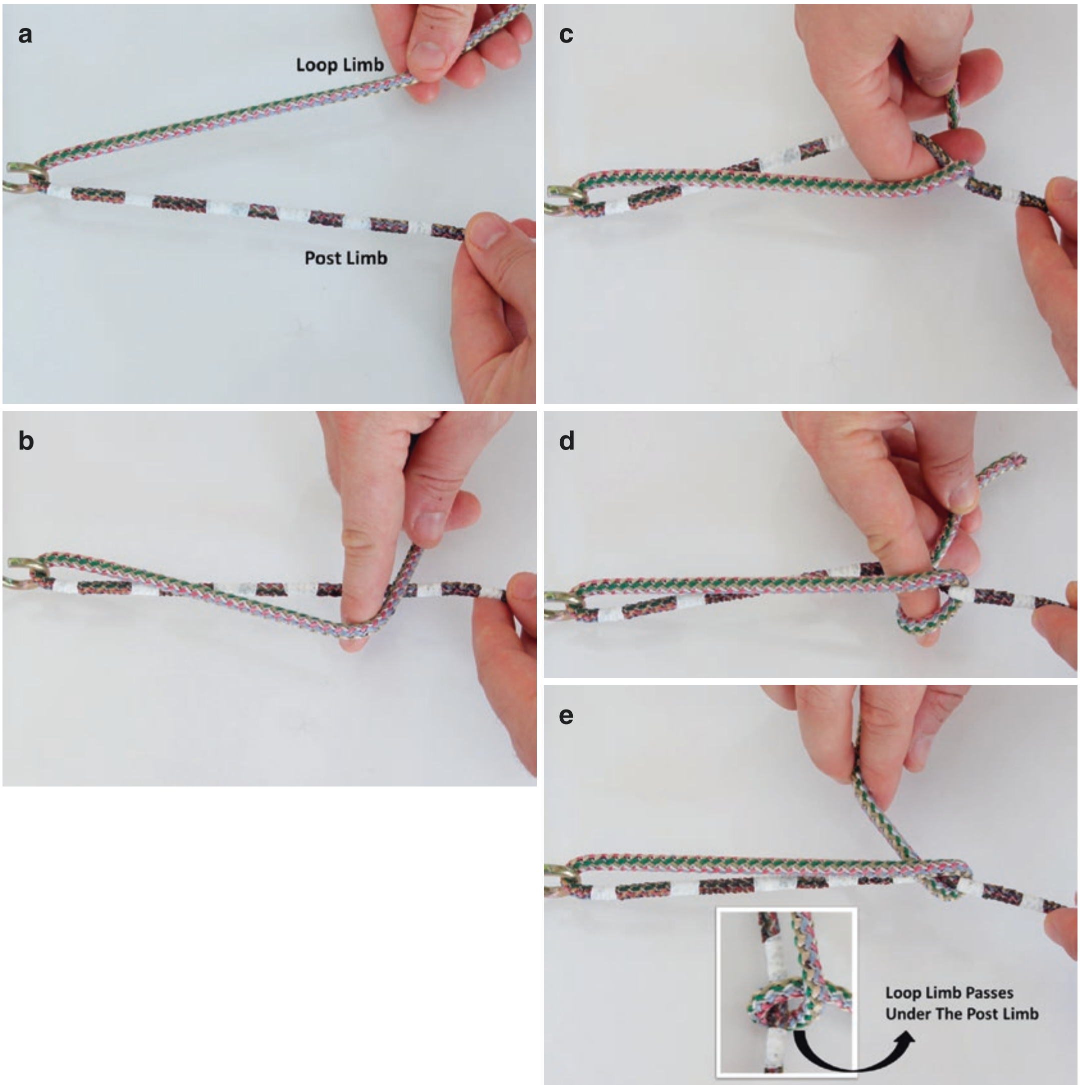

Fig. 14.2 Underhand half hitch by alternative technique

4. Extend the index finger of the dominant hand (Fig. 14.2d) to draw the distal aspect of the loop limb through the circle made by the post and the proximal aspect of the loop limb (Fig. 14.2e).

14.3 Overhand Half Hitch, Basic Technique (Fig. 14.3)

1. Knot pusher is placed on the post limb. Place the working limb above the post and form a loop (Fig. 14.3a).

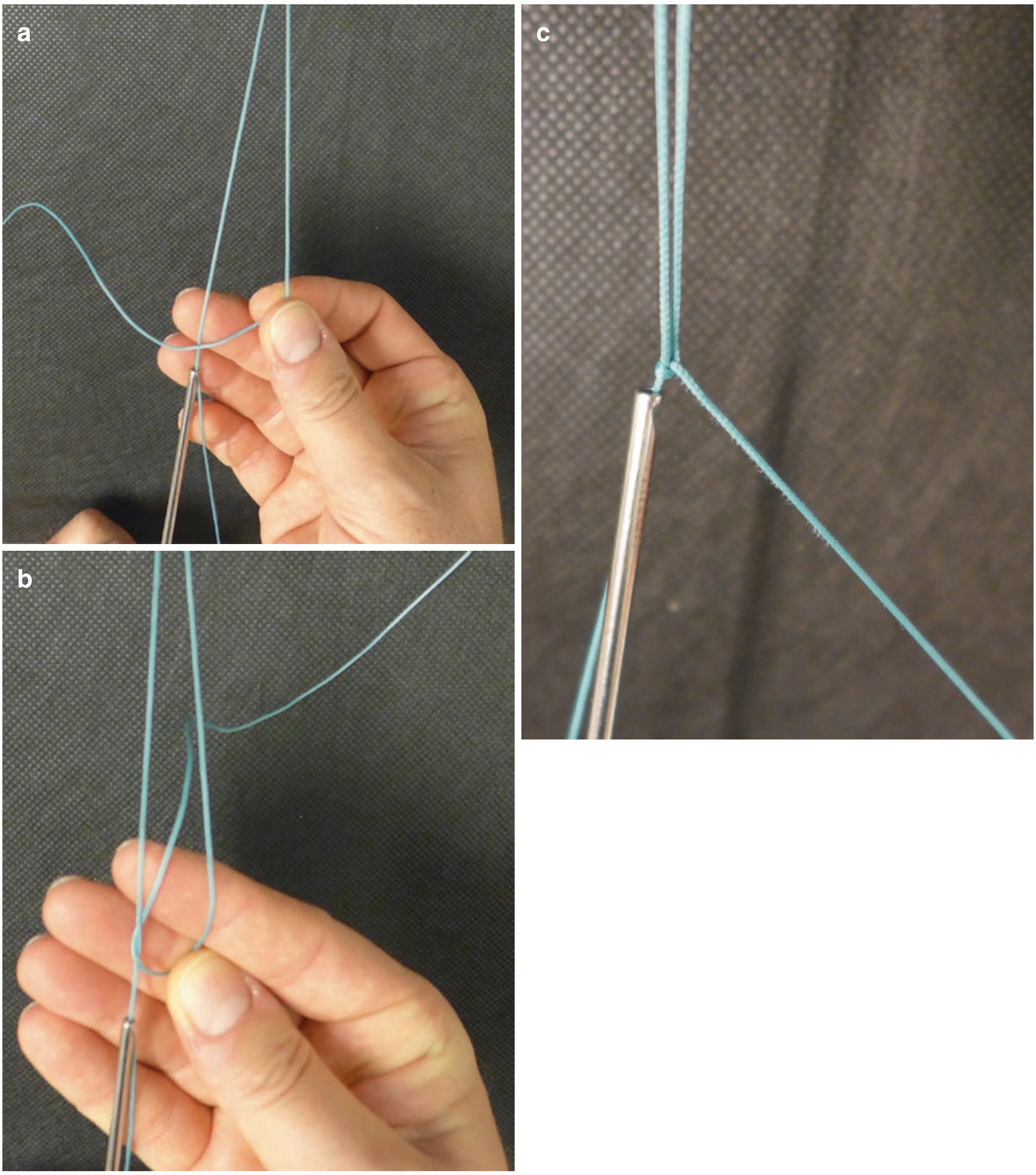

Fig. 14.3 Overhand half hitch by basic technique

2. Pass the free end of the working limb through the loop (Fig. 14.3b).
3. Overhand half hitch is ready on the post (Fig. 14.3c).

14.4 Overhand Half Hitch, Alternative Technique (Fig. 14.4)

1. Hold the loop limb with the dominant hand and post limb with the non-dominant hand (Fig. 14.4a).
2. Ulnarly deviate and supinate the dominant wrist to drape proximal part of the loop limb across the long and ring fingers, and hold the distal aspect of the loop limb with thumb and index fingers (Fig. 14.4b).
3. Cross the post limb perpendicular to the loop limb by curling the dominant long finger around the post limb (Fig. 14.4c), and catch the loop limb with the dorsum of the distal phalanx of the dominant long finger (Fig. 14.4d).
4. Extend the long finger of the dominant hand (Fig. 14.4e) to draw the distal aspect of the

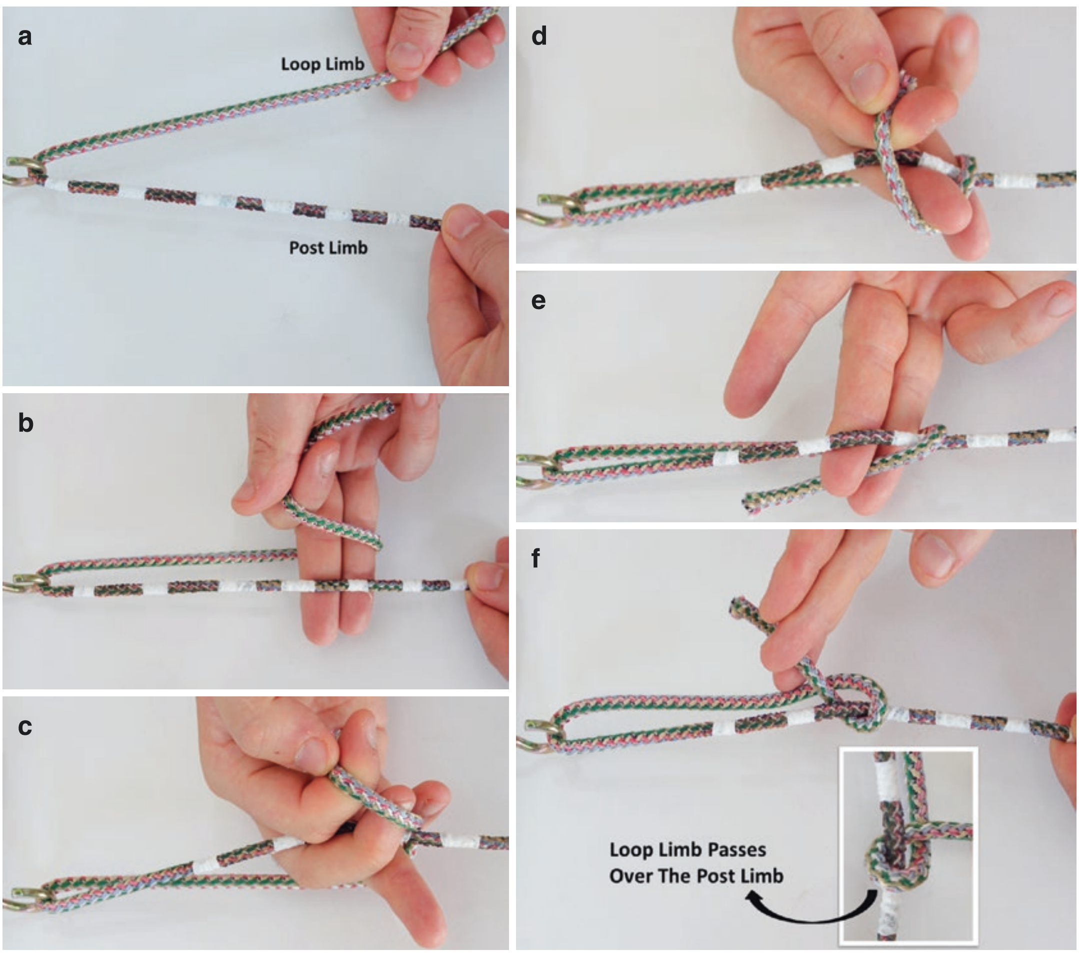

Fig. 14.4 Overhand half hitch by alternative technique

loop limb through the circle made by the post and the proximal aspect of the loop limb (Fig. 14.4f).

14.5 Advancing a Half Hitch on Post (Fig. 14.5)

1. Place the knot pusher on the post limb (Fig. 14.5a). Use your thumb to manipulate the instrument. Other fingers are used to pull and apply tension on the post limb. Attach a clamp on the free end of the post limb.
2. By the aid of the knot pusher, surgeon can push (Fig. 14.5b) the half hitch.
3. Maintain the tension on the post limb while pushing your half hitch by the knot pusher. A gentle traction should also be done on the loop limb; otherwise, the knot pusher can easily pass through the loop of the half hitch (Fig. 14.5c). In arthroscopic surgery, surgeon should be carefully advance the half hitches, if an half hitch is missed as shown in Fig. 14.5c, limbs will be tangled within the cannula.
4. Half hitches on the same post will reduce the tissue gradually. While pushing the half

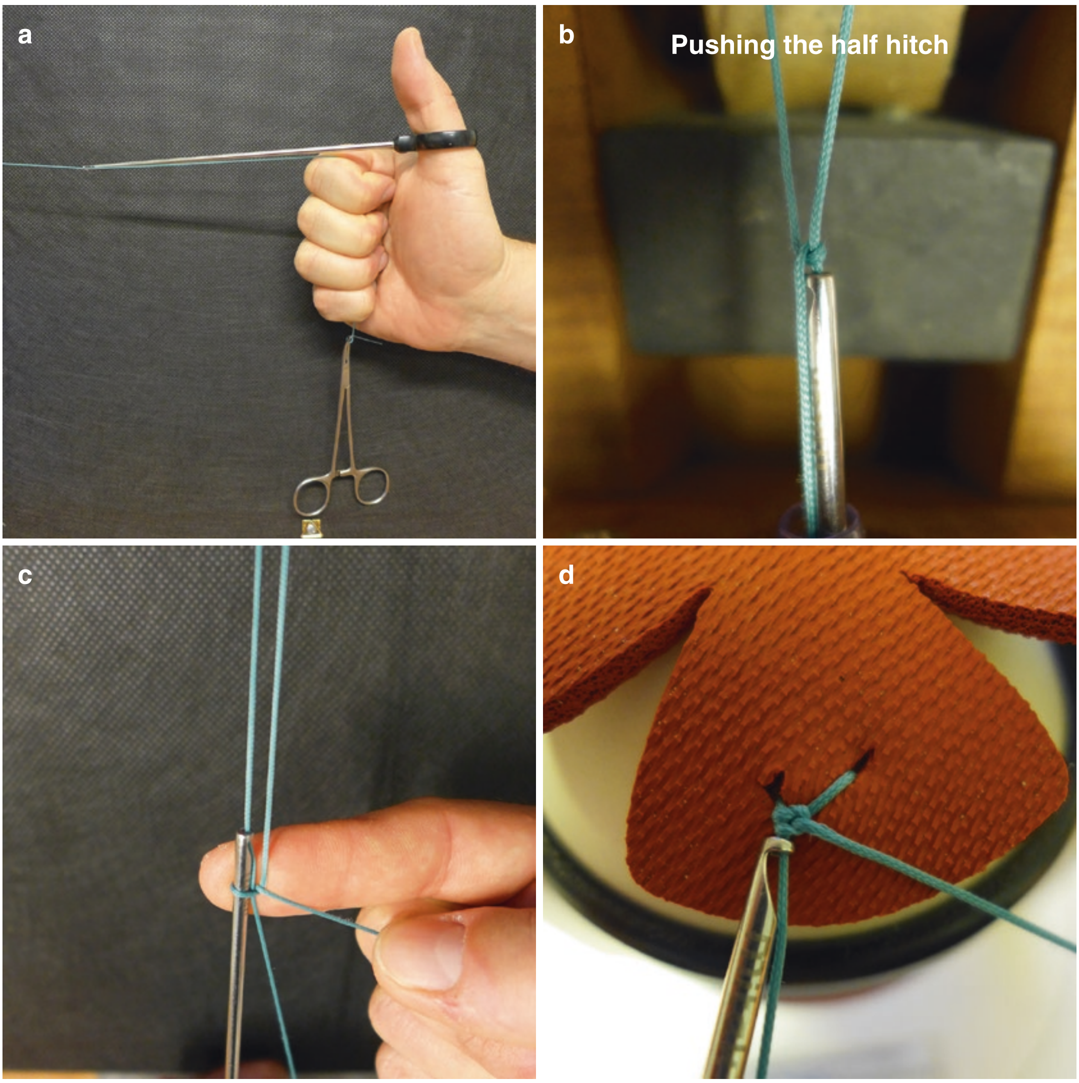

Fig. 14.5 Advancing a half hitch on post

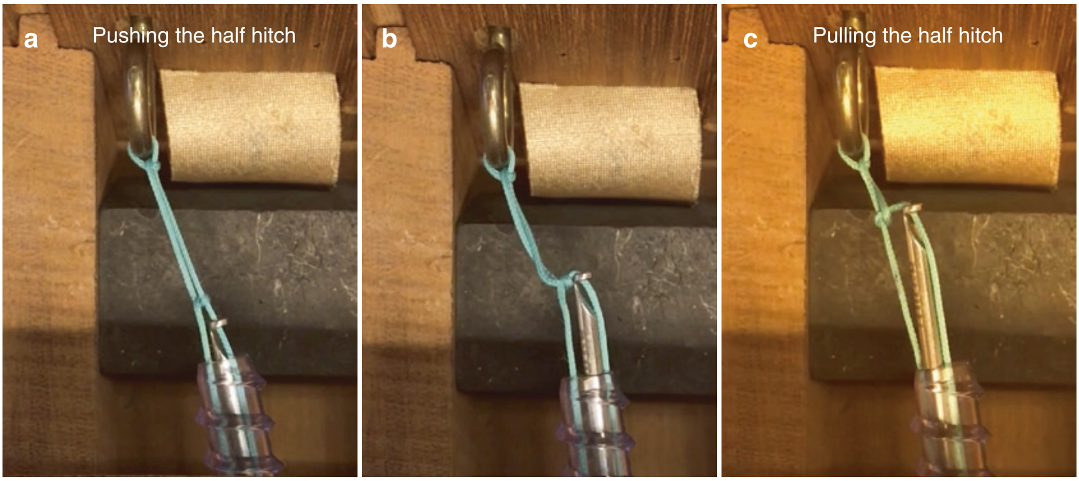

Fig. 14.6 Switching the post limb

hitches one by one, surgeon can handle slacks by gently tensioning both limbs (Fig. 14.5d).

5. Further tensioning is achieved by resting your knot pusher on the half hitches over the tissue and pulling your post limb (Fig. 14.5d).

14.6 How to Switch the Post

Switching the post is an essential step in arthroscopic knot tying. Once the desired tissue reduction is provided by half hitches on the same post, switching the post is needed to secure the knot. In order to switch the post, the half hitch should be flipped.

1. Push the half hitch till you cleared out the cannula, then relieve tension on both limbs, advance the tip of the knot pusher in front of the half hitch, gently pull the loop limb, and flip the half hitch. Now as you begin to pull the loop limb, then it will become the “new” post limb (Fig. 14.6).

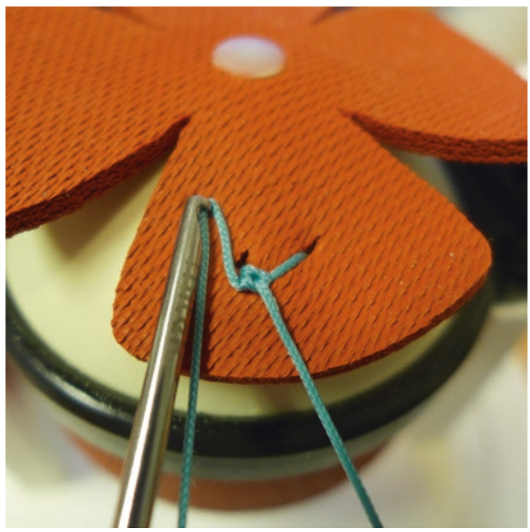

Fig. 14.7 Past pointing the knot on the tissue

2. Further tensioning is achieved by past pointing the knot on the tissue (Fig. 14.7).
3. Although not suggested by the author, half hitch can also be flipped on the tissue by just shifting the tension from post limb to loop

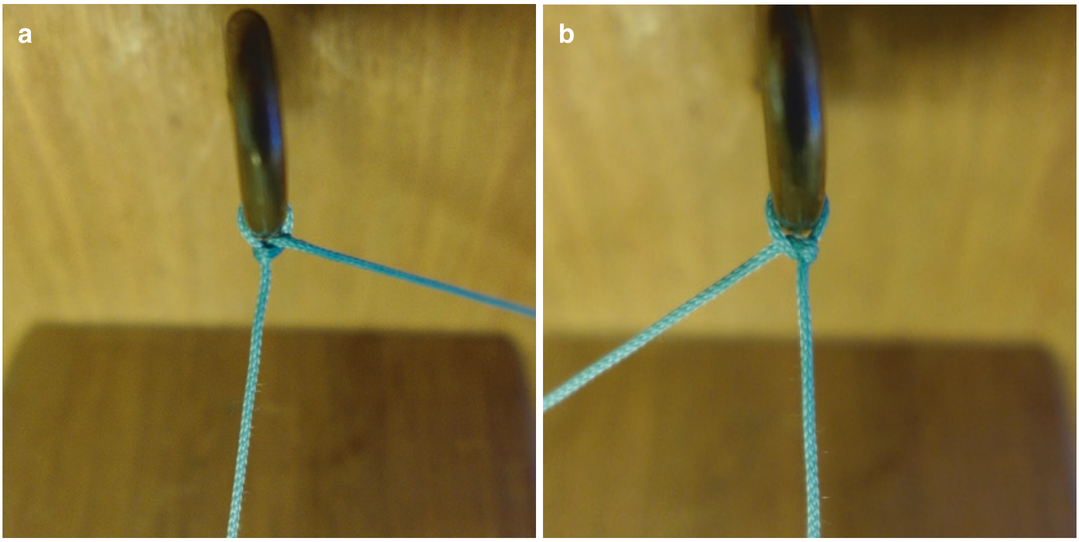

Fig. 14.8 (**a**) Overhand half hitch is firmly placed on tissue. Left is the post limb on tension. (**b**) Former loop limp is pulled. Half hitch is flipped on tissue and becomes an underhand half hitch on the new post

limb. Relieving tension on the post and pulling the loop limb will flip the half hitch on the tissue with a sensible click (Fig. 14.8). But this maneuver can damage the suture.

14.7 Knot Configuration Symbols (Fig. 14.9)

Half hitches can be tied in the same direction (two serial underhand half hitches), can be tied in opposite directions (an underhand half hitch followed by an overhand one), or can also be tied on opposite posts. Tera and Aberg [2] introduced standardized symbols for knots; Trimbos [3] modified it in 1984. Since then, there were slight variations among authors in use of such symbols. However, the most widely accepted symbolization nomenclature seems to be the one Loutzenheiser et al. [4] and Burkhart et al. [5] used: "S" refers to single sliding throw (half-hitch). "=" refers to identical throw around same post. "x" refers to nonidentical throw, (loop reversed) around the same post. "//" refers to post switching between throws (Table 14.1).

14.8 Optimal Configuration of the Half Hitches

Half hitches will act in two different ways:

1. The reduction tool (Fig. 14.10): Half hitches on the same post will reduce the tissue. The number of consecutive half hitches will increase the internal friction and help the initial loop security of the configuration until definitive locking maneuvers.
2. The locking tool (Fig. 14.10): Once desired reduction and tension is achieved by the previous half hitches on the same post (the reduction tool), surgeon can lock the configuration by changing the post.

The most secure locking configuration for a series of half hitches should at least have three reversed half hitches on alternating posts (//xS//xS//xS) as described by Loutzenheiser [4]. This is also suggested to secure all arthroscopic sliding knots. The surgeon should aim the optimal half hitch configuration with a minimum number of half hitches to reduce the tissue and

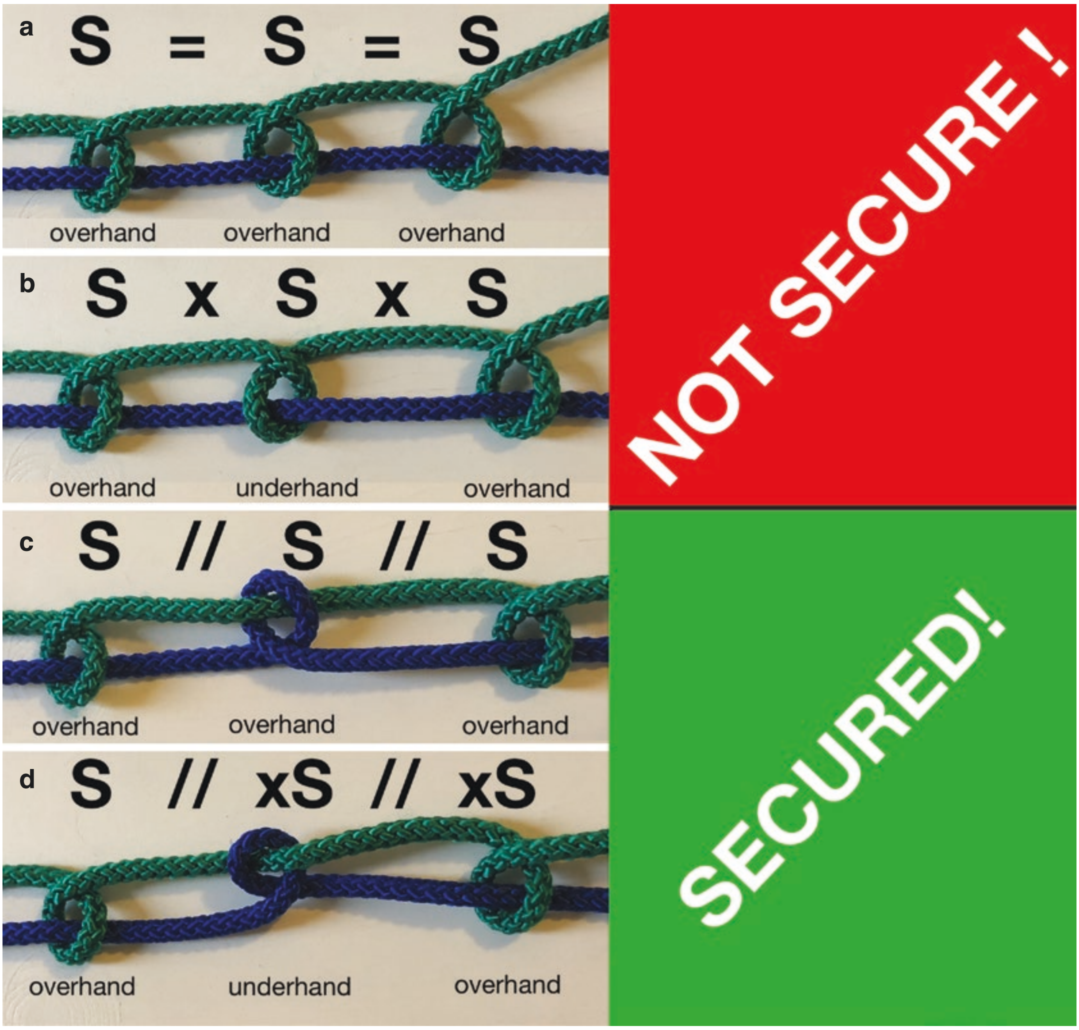

Fig. 14.9 (**a**) Left to right, overhand half hitches on the same post. This configuration is not secure, it can be used to reduce the tissue. (**b**) Left to right, reverse half hitches on the same post. This configuration has more internal friction compared to the configuration on figure "**a**", but not secure. (**c**) From left to right, post is changing but the half hitches are identical. This configuration is secure and locked. (**d**) From left to right, post and the half hitches are changing (RHAP=reverse half hitches on alternating posts). This configuration is also secure and locked besides it has superior biomechanical properties compared to the configuration on figure "**c**"

Table 14.1 Symbols to describe sliding knots

Symbol	Definition	Example
S	Sliding throw	Single half hitch (overhand or underhand)
=	Identical throw around same post	Serial overhand half hitches on the same post
X	Nonidentical throw around same post	Overhand half hitch followed by an underhand half hitch on the same post
//	Post switching between throws	Overhand half hitch followed by post switching and an overhand half hitch

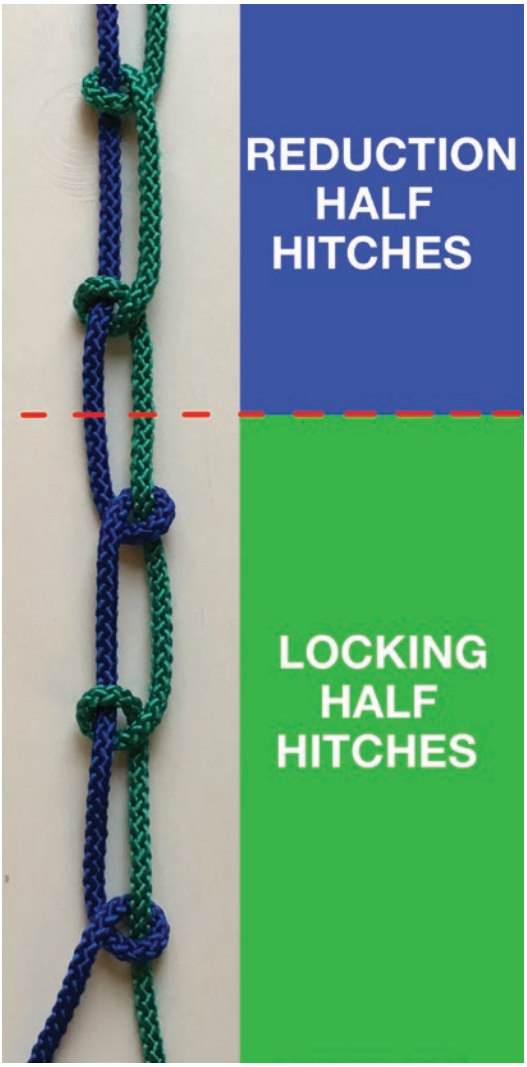

Fig. 14.10 From up to down, first and second half hitches on the blue post will be used to reduce the tissue. Third, fourth and fifth half hitches on the alternating posts will lock the knot

lock the system, because excessive number of half hitches will be bulky and may cause tissue irritation and/or impengement.

Conclusion

As a work horse of arthroscopic knots, one should know how to tie an underhand and an overhand half hitch. If a surgeon can tie and advance half hitches, provide the security by switching the posts; he would not need to know any other knot.

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Non-sliding (Static) Knots

15

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Knot tying is a basic but critical skill of surgeons. Historically, non-sliding knots have been used for open surgeries, while sliding knots are more popular in an arthroscopic setting (i.e., rotator cuff repair). Typical indications for either sliding or non-sliding knots are rotator cuff, labral, superior labrum anterior to posterior (SLAP), or meniscal repairs. Despite superior biomechanical properties of non-sliding knots, surgeons often prefer sliding knots for arthroscopic procedures, which are easier to perform [1–9]. To tie a non-sliding knot, one has to cross the suture ends and switch the post with a consecutive release of tension on the suture limbs, which may lead to slippage of the first throws [6, 10–12]. This becomes especially important when tying an arthroscopic knot where the sutures have to be tied via a knot pusher without any tactile feedback and where knot security often can only be assessed visually. Even though sliding knots are easier to perform, surgeons should be able to tie a static knot properly. For instance, when using suture anchors without an eyelet, it is not possible to tie a sliding knot. Likewise, when using suture anchors with an eyelet, suture passage through the eyelet or soft tissue may be difficult, and the use of a static knot is advantageous. Furthermore, sliding knots can potentially damage the soft tissue during advancement. Therefore, it is recommended to use non-sliding knots especially when repairing degenerative soft tissue [6, 13, 14].

In summary, non-sliding knots are recommended when it is difficult to slide or advance suture through the soft tissue or anchor and when repairing degenerative tissue to avoid further damage.

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15.1 Advantages and Disadvantages of Non-sliding Knots

An ideal knot should provide sufficient knot and loop security and be easy to place with the lowest necessary force during knot advancement. Static knots provide improved biomechanical properties in terms of load to failure and displacement, especially when using braided sutures. This results in higher knot and loop security compared to sliding knots [1, 2, 4–6, 9, 11, 15, 16]. The Revo knot has a reported load to failure of 280 Newton (N) when using braided sutures. When compared with sliding knots, only the Samsung Medical Center (SMC) and the Tennessee slider knots have comparable failure strengths (275 N and 254 N, respec-

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tively) [1]. However, these numbers vary between studies depending on the suture material and biomechanical testing protocol [2]. As such, clinical failure has been widely accepted, reported, and defined as residual displacement of 3 mm after soft tissue repair. The load at 3 mm of displacement is significantly higher for a square knot (78 N) and modified Revo knot (96 N) compared to the SMC knot (71 N) and non-flipping sliding knots (67 N) [16]. These biomechanical properties are reflected by the failure mechanism. While sliding knots usually fail by slippage, static knots fail due to suture breakage [1].

As mentioned, non-sliding knots are preferred in cases of poor tissue quality or difficulty with suture passage through the anchor or soft tissue since low force is necessary to advance the half hitches [6, 10, 14]. In addition, non-sliding knots are usually less bulky compared to sliding knots with the same number of throws [3, 9, 10, 17]. A bulky knot can cause irritation to overlying soft tissue and pain. This is particularly relevant following labral and SLAP repairs above the glenoid equator and following supraspinatus tendon repair in patients with diminutive subacromial space. In these cases a less bulky non-sliding knot or knotless anchor may be advantageous. On the other hand, non-sliding knots take longer and are more difficult to tie [6, 14]. However, it has been shown that the Revo knot, a type of non-sliding knot, is easy to learn, especially with less rigid braided sutures [18]. Due to the necessity to switch the post during static knot tying with consecutive tension release in the suture limbs, a backsliding of the knot and loosening of the loop can occur. Therefore, the margin of error is very small when tying an arthroscopic non-sliding knot [10].

15.1.1 How to Provide Loop Security in Non-sliding Knots

An ideal knot should be easy to advance and should not slip once the knot has seated. In this context, knot and loop security are two important issues to consider when performing any soft tissue repair [5, 6]. Knot security refers to the ability of a knot to resist suture slippage, whereas loop security is defined as the tightness of the initial loop as the knot is tied [4, 6, 7]. Poor loop security causes insufficient tissue approximation and results in an inferior repair [19]. It is well known from comparative biomechanical studies that static knots provide better knot and loop security [1, 2, 4–7, 9, 11, 15, 16]. Ideally, an arthroscopic knot provides an equal or at least comparable amount of security compared to openly tied knots. Loop security mostly depends on the strength of the first throws, since a loose suture loop will not become tighter once it is tied [20].

Conventionally, switching the post by crossing the sutures is the key to secure non-sliding knots [5, 12, 21]. Biomechanical studies have shown that at least one switched post is necessary to achieve good loop security [13]. However, this post switching or hand crossing results in asymmetric tension between the two suture limbs which may lead to premature knot seating or backsliding [10, 22]. To avoid this backsliding mechanism and improve loop and knot security, past-pointing (advancing the knot pusher beyond the knot while maintaining constant tension on the post limb) and post switching (alternating tension on the suture limbs to flip the knot) are two useful techniques when performing static knot tying [8, 11, 14, 23]. When tying a square knot, it is important to maintain equal tension on both suture limbs when adding the throws after the first two half hitches to achieve a square pattern. Indeed, intense suture tightening does improve loop security but cannot fully avoid suture slippage, regardless of the knot configuration [21]. When the first throws are seated, adding more throws improves loop as well as knot security [12, 17] but results in bulkier knots. It is recommended to add at least three reversing half hitches on alternating posts (RHAPs) to avoid loosening of the initial loop. This is especially true, when tying a knot with monofilament sutures [2, 3, 6, 13, 24, 25]. However, delivering half hitches incorrectly or unbalanced suture limb tensioning during half hitch formation has a negative effect on loop security [9].

In summary, it is recommended to first set two throws with the knot pusher in place followed by post switching. To further improve loop security, reversing the half hitches and past-pointing the knot with the knot pusher while maintaining equal tension on both limbs are helpful. Between different steps, quality control by direct visualization by the surgeon should be used to evaluate each throw for loosening and slack and adjust accordingly.

15.1.2 Single vs. Double-Diameter Knot Pusher Designs to Prepare Non-sliding Knots

Various knot pusher designs are available and commercially sold. Most commonly, surgeons use a standard single-diameter knot pusher. It has been proposed that a cannulated double-diameter knot pusher, such as the Surgeon's Sixth Finger (Arthrex, Naples, FL), is a helpful tool to improve loop security of arthroscopically tied non-sliding knots [20]. The biggest advantage of a single-diameter knot pusher is that it can simply be used as either a pusher or a puller. However, when tying non-sliding knots arthroscopically, one has to consider the potential risk of backsliding before the knot is seated with resultant poor loop security. This issue can be partially addressed when combining an over-pointing and past-pointing technique [26]. It has been shown in recent studies that a double-diameter knot pusher provides comparable loop security to a hand-tied knot, because it does not have to be withdrawn after the first throws. The inner tube of a double-diameter knot pusher pushes against the first throw and therefore prevents loosening of the loop while tying the second locking throw [20]. Another advantage of a double-diameter knot pusher is that when loaded outside the cannula, the surgeon can see tangling between the suture limbs and remove them before the knot is seated [14].

15.1.3 Effect of Suture Type on Non-sliding Knots

The type of suture used for soft tissue repair also influences knot and loop security. The chosen suture material should not impede knot sliding and still provide sufficient grip to the surgeon. Monofilament sutures are stiff and resist deformation. As a result, it becomes difficult to seat each knot properly [14, 18, 27]. When combined with its lower coefficient of friction, monofilament sutures have lower ultimate load and higher risk of suture slippage with significantly lower loop and knot security compared to braided sutures [2, 13, 28]. However, it has been shown that when adding more RHAPs to the knot, even monofilament sutures provide sufficient knot security while providing greater ease in suture sliding compared to braided sutures [7, 24]. However, when adding more RHAPs, the knot will be bulkier which may lead to irritation of the surrounding soft tissue. Additionally, monofilament sutures may cut through the tissue. As such, the authors recommend the use of braided sutures if high repair strength is necessary or if tissue approximation results in high tension on the soft tissue site in question.

15.2 Arthroscopic Square Knot

Square knots have generally been accepted as reliable knots for both open and arthroscopic procedures [29–31]. However, to achieve a square configuration, it is necessary to tension both suture limbs symmetrically; otherwise the knot will convert into two nonidentical half hitches (Figs. 15.1, 15.2, 15.3, and 15.4). Therefore, it is difficult to tie and secure square knots through a cannula in an arthroscopic setting [5]. It should be mentioned that the square knot is the only static knot where the knot pusher has to be placed on the loop rather than the post limb [14]. If an arthroscopic square knot is tied properly, loop as well as knot security are comparable to hand-tied knots [15].

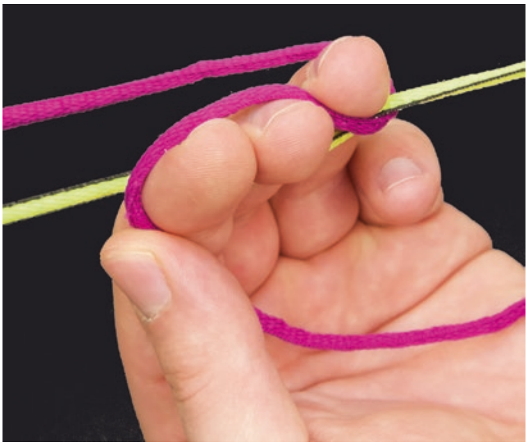

Fig. 15.1 Arthroscopic square knot. Step #1: The arthroscopic square knot begins with the first half hitch (overhand) placed over the post (yellow limb)

Fig. 15.2 Arthroscopic square knot. Step #2: After the first half hitch, the knot pusher has to be placed on the loop limb (purple) and past-point the first throw (arrow)

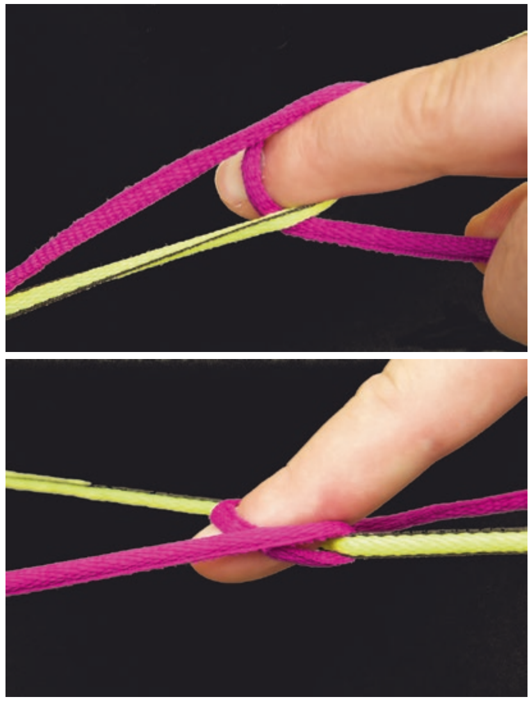

Fig. 15.3 Arthroscopic square knot. Step #3: Place an underhand throw around the post and push it into the joint

15.3 Revo Knot

The Revo knot is one of the most popular non-sliding knots and was first described by Snyder in 1997 [32]. It consists of a series of half hitches with alternating the post after the third half hitch (Figs. 15.5, 15.6, 15.7, 15.8, and 15.9) [14, 18, 33]. The Revo knot shows good biomechanical properties in terms of load to failure, loop and knot security, and suture slippage [1–3, 18]. Additionally, the knot is easy to learn and not as bulky [18].

15.4 Modified Revo Knot

Since its first description, the Revo knot has been modified several times. The modified Revo knot consists of two half hitches (underhand) followed

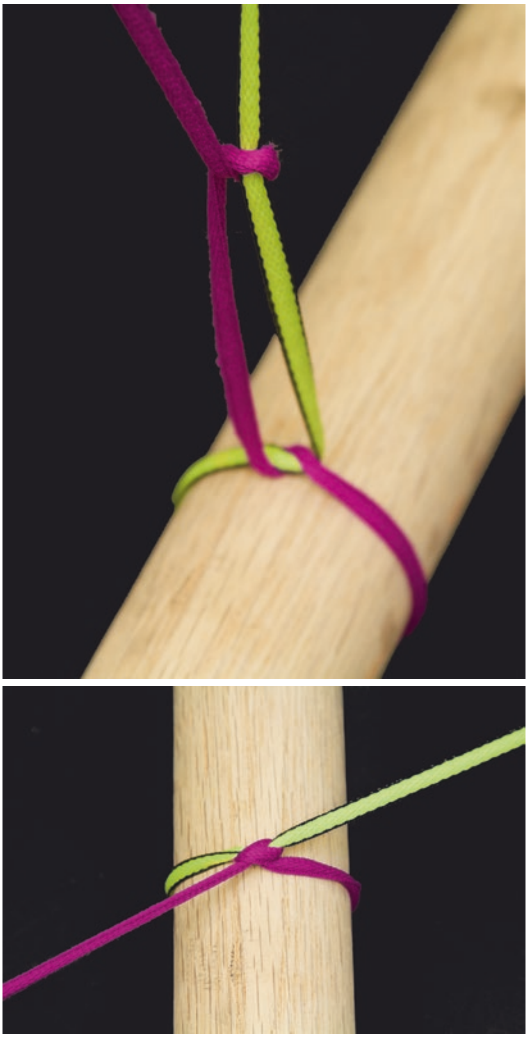

Fig. 15.4 Arthroscopic square knot. Step #4: The sutures should be tensioned by past-pointing the knot with the knot pusher placed on the post limb. Additional reversed half hitches can be placed to further secure the knot

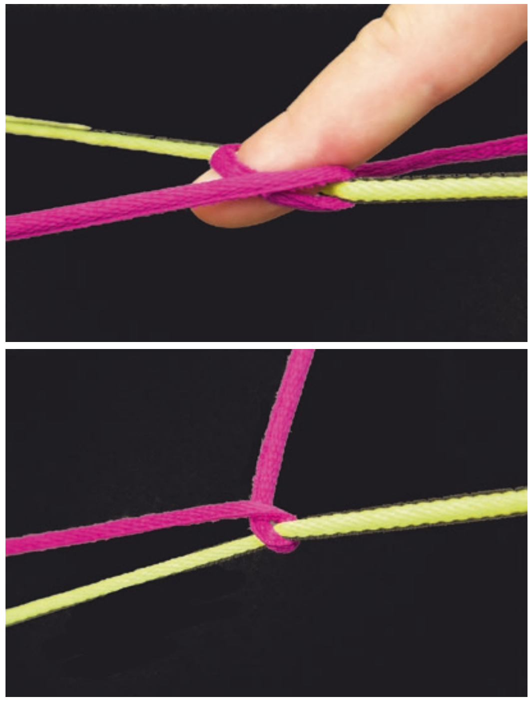

Fig. 15.5 Arthroscopic Revo knot. Step #1: The Revo knot begins with an underhand half hitch (yellow limb represents the post). The half hitch has to be advanced into the joint with a knot pusher. By tensioning both limbs in an alternating fashion, the first half hitch will be tightened down the tissue

Fig. 15.6 Arthroscopic Revo knot. Step #2: After adding another underhand half hitch around the same post, the knot becomes seated

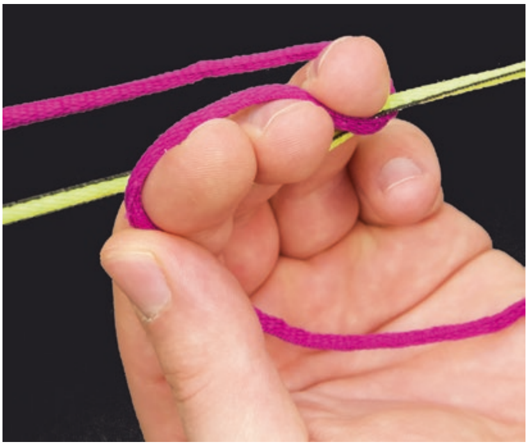

Fig. 15.7 Arthroscopic Revo knot. Step #3: Once the knot became seated, an overhand half hitch around the same post has to be added to increase the loop security

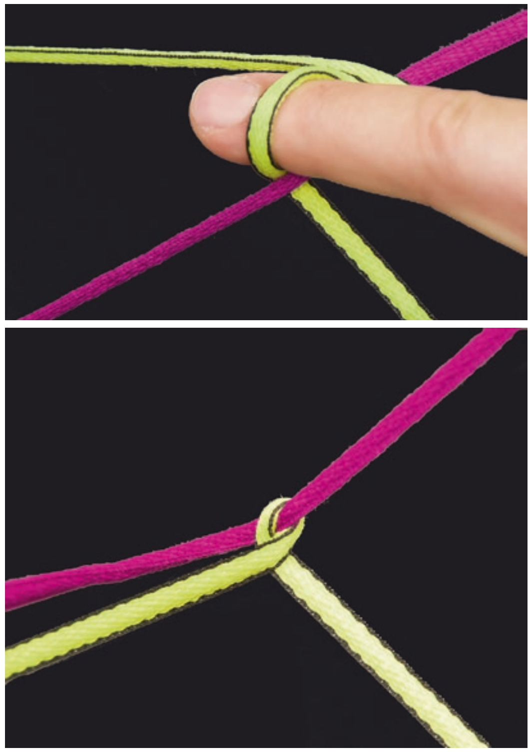

Fig. 15.8 Arthroscopic Revo knot. Step #4: After switching the post (now represented by the purple suture limb), an underhand half hitch is placed. At this step knot is locked

by a reversed half hitch (overhand) on the same post. After switching the post, two half hitches with alternating posts in between have to be thrown [5, 14]. The modified Revo knot requires only low force to advance the knot [10] and provides good loop and knot security [1, 3, 11].

15.4.1 Authors' Preferred Knot

Taking into consideration the low learning curve and superior biomechanical properties, the modified Revo knot is the preferred non-sliding knot of the authors. However, surgeons should be familiar with at least one sliding and one static knot to adapt the knot configuration according to the intraoperative findings and scenarios.

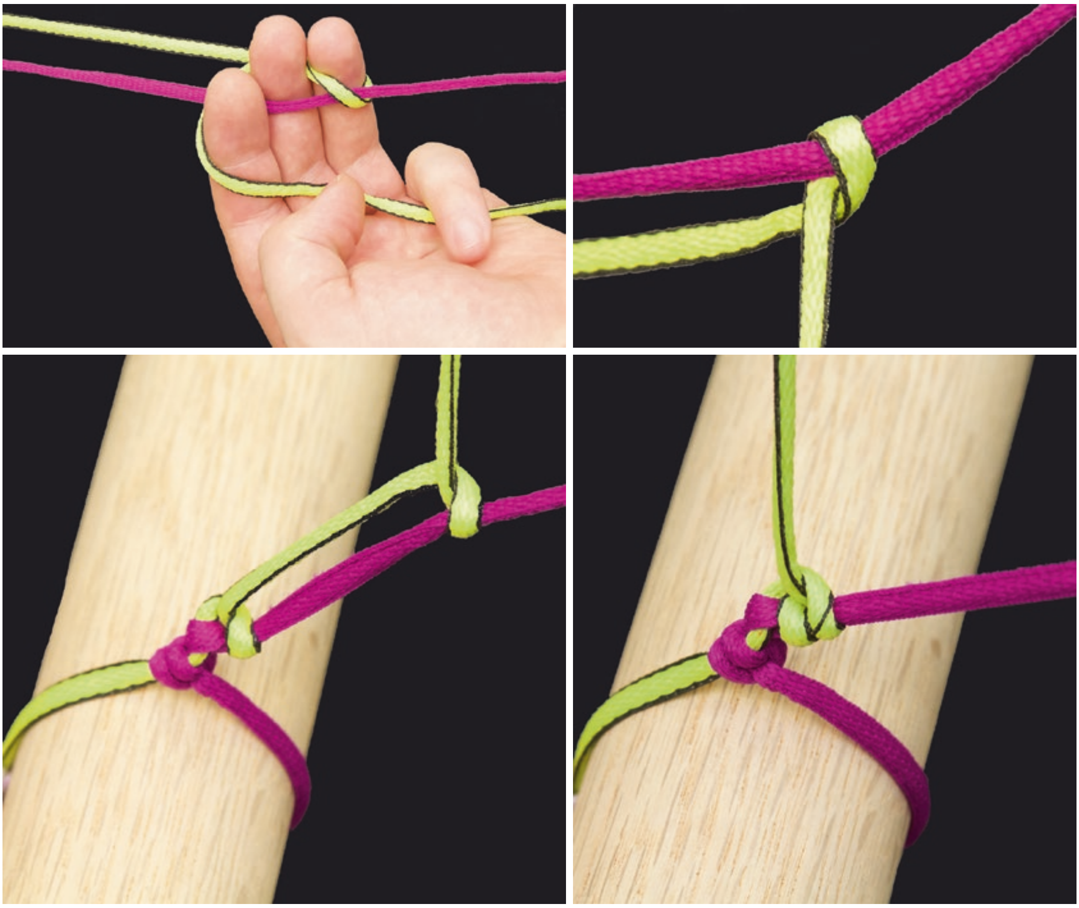

Fig. 15.9 Arthroscopic Revo knot. Step #5: A last overhand half hitch has to be thrown to secure the knot (purple represents the post limb)

Conclusion

In conclusion, arthroscopic sliding knots are easier to tie through a cannula, while non-sliding knots have superior biomechanical properties once the knot becomes secured. To achieve sufficient loop and knot security when tying static knots, the surgeon has to make sure that the first throws are seated properly without any backsliding before adding more reversed half hitches in order to avoid premature locking.

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16 Sliding Knots

Riccardo Compagnoni, Federico Cabitza,
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Knots are fundamental for the success of various orthopedic operations. The perfect knot should have a balance between slippage and locking for loop security, and it must be rapid to execute and easy to learn. The goal of surgical knot tying is the capacity of a knot to be tightened and remain tight. As a general rule, knots must be tight and must not slide back; loosening of 3 mm, or more, could be considered a failure of the suture function. An interrelated and partially dependent concept is the 'loop security', which is defined as the ability of the suture loop to maintain the initial tension and length as the knot is delivered and tightened [1, 2]. The two free ends of any given suture are called 'limbs'. A knot is made up of a series of loops passed around the 'post' limb. The limb that is not currently acting as the post is by default the "non-post" (loop/working limb). The post is not always the same limb, and, in fact, it can be changed with every throw if desired—it is simply the limb that the loops or wraps are being thrown around [3].

The arthroscopic knot is the one that must be dressed outside the body and then tightened at the level of the target tissue. Two groups of arthroscopic knots are used in surgery: non-sliding and sliding knots. Non-sliding knots are prepared and tensioned inside the joint with many half hitches at the tissue site in a stepwise manner. Some examples of non-sliding knots are the square knot and the Revo knot. Sliding knots are constructed outside the body and delivered to the tissue site through tension on the post limb that allows the knot to slide into place [4].

16.1 Sliding Knots

When performing a sliding knot, it is important that the suture could slip freely through the tissue and the eyelet of the suture anchor. If the suture does not slip freely, a non-sliding knot must be used. Some authors report that sliding knots may create a higher degree of suture damage, leading to a possible failure during or after knot tying, but at the same time can guarantee a good tensioning of the suture [1]. Performing a sliding knot is technically more difficult than non-sliding knots and requests a training before using them safely in an operative room. A lot of sliding knots have been described, but it is still a technical challenge

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for inexperienced surgeons to perform those knots in the operating room, and it is quite difficult to teach others how to make them [5, 6].

Sliding knots are divided into non-locking and locking. Non-locking knots require further half hitches after they have been delivered and tensioned on the tissue. These knots are held in place by the friction of the suture as the knot is tightened. Example of non-locking sliding knots is Duncan loop (hangman's-fisherman's knot). Locking sliding knots, with their special configuration, have the ability to lock by usually pulling the non-post/loop limb after proper positioning of the knot on the tissue. Technically, the surgeon prepares the locking knot; the knot is advanced to the target tissue and tensioned by pulling the post limb, once desired tension is achieved pulling the non-post limb will lock the knot. However, in some configurations the locking mechanism may result in a loss of initial tension on the tissue as the knot folds back on itself. Examples of locking sliding knots are taut-line (midshipman) hitch, Roeder knot, Weston knot and SMC knot [7]. Although locking sliding knots prevent reverse slippage of the initial loop, a relevant study shows that at least two or three additional half hitches are mandatory to achieve an optimal knot-holding capacity [8]. A described problem with this kind of knots is the risk of locking of the knot before reaching the 'loop security' and the need of a new knot.

16.1.1 Where and when to Use a Sliding Knot

Sliding knots can be performed in many situations during an arthroscopic procedure. Their use is possible in quite all conditions where a tissue should be fixed using a suture as in rotator cuff tear repair or Bankart repair. When knotless stabilization devices are used, a sliding knot is not possible. As in all surgical procedures, some basic principles have to be respected. First the suture limbs must be free to slide through the tissue and the eyelet of the anchor. If not, the suture can be damaged during sliding and/or the optimal knot security can not be obtained. Second, it is crucial to check to exclude the presence of tissue in the cannula or around the suture limbs, to avoid premature locking of the knot before it reaches the desired loop security. The cannula should be placed close to the final knot position, to avoid any soft tissue entrapment during the sliding of the knot. Third, suture limbs should be parallel. Any twist within the post and working limb will disrupt the final security of the knot [2]. The length of the "non-post" has to be longer (at least 2 times) than the post limb. In this way the surgeon will have two limbs with a similar length after tying and sliding the knot on the target tissue and can effectively lock the knot and perform any additional half hitches if needed. Additional half hitches should firmly placed on the knot without slack, otherwise the knot security will be compromised.

16.1.2 Suture Type on Sliding Knots

In arthroscopic surgery few suture materials are available. The choice of suture material is based upon the inherent suture characteristics and surgeon preference. The sutures may be absorbable or non-absorbable, monofilament or braided. Non-absorbable braided suture typically provides permanent fixation, and the knots tend to lay down better. It also has increased pliability and ductility and overall increased strength. In the last years, ultrahigh molecular weight polyethylene (UHMWP)-containing suture has been progressively introduced in the market. The roughened surface adds strength to knot security. This kind of suture is usually preloaded in the majority of the anchors on the market, with differences in mechanical properties. Anchors can be loaded up to three sutures each, all sliding in the same eyelet.

Absorbable monofilament sutures can be also used to tie sliding knots. It is fast and easy to use them. However, monofilament is stiffer to work with and more difficult to get knots 'tight'; it is weaker and tends to stretch with repeated cyclic loads.

16.1.3 How to Provide Loop and Knot Security in a Sliding Knot

Loop security is defined as the ability of maintaining the size and the tension of the loop during knot tying. Knot security is the ability of the knot to resist slipping when traction is applied. This is affected by three factors: friction, internal interference and slack between throws [9]. Unfortunately, it is possible to have a loose knot on a secure loop or a loose loop on a secure knot. In both cases the knots will be insufficient. To provide a good security, an optimal arthroscopic vision is crucial, in order to see how the knot fixes the tissue and if it is adequately tensioned. The choice of the suture is important, considering material properties and quality of the tissue. Many surgeons consider that a braided non-absorbable suture could be the better choice for knot security and loop security. The knot pusher should be on the post limb while seating the initial knot on the target tissue. The sliding knot should be “pushed” and firmly placed on the target tissue (knot kissing). Simultaneously pulling the post limb will help to provide desired tension and prevent loosening till locking. Locking maneuver will differ according to the type of the sliding knot used. Non-locking sliding knots need at least 3 reverse half hitches on alternating posts. It is also advised to use these half hitches to back up the locking sliding knots.

16.2 Non-locking Sliding Knots

16.2.1 Duncan Loop (Fisherman’s Knot)

Its name is a tribute to Norman Duncan who developed it independently as a fishing knot in the early 1960s. The knot was popularized as the uni-knot by Vic Dunaway, an editor at the Miami Herald, in a 1970 fishing book.

The Duncan knot works well with both braided and monofilament sutures and with practice is fairly easy to tie.

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post, and hold both limbs between the left thumb and the second finger (Fig. 16.1a).
2. Throw an overhand loop over the tip of the thumb and over the post (Fig. 16.1b).
3. Throw three more overhand loops on the post (Fig. 16.1c).
4. Move the loop that was over your thumb tip down and pass the end of the non-post limb through the loop (Fig. 16.1d).
5. Apply tension to both ends of the non-post limb to snug the knot (Fig. 16.1e).
6. Apply a push to the knot to compact it. Seat the knot by applying tension to the post and throw an underhand half hitch to lock (final security will be provided by a total of 3 RHAPs).

16.2.2 Tennessee Slider

Described by Steve Snyder, its name is a tribute to the state of one of his fellow from Tennessee (Frye, M.D.) who suggested him the use of a sliding knot. It is a basic buntline hitch with added two locking half hitches. This knot is quite difficult to tie but guarantees a good strength and a low profile and volume.

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post, and hold both limbs between the left thumb and the second finger (Fig. 16.1a).
2. Throw an overhand loop over both limbs (Fig. 16.2a).
3. Throw an overhand loop on the post and pass the non-post suture back through the knot (Fig. 16.2b).
4. Apply tension to both ends of the non-post limb to snug the knot. Pull the post limb and slide the knot to the target tissue (Fig. 16.2c).
5. Once the knot is on the desired position and properly tensioned, the post should be changed

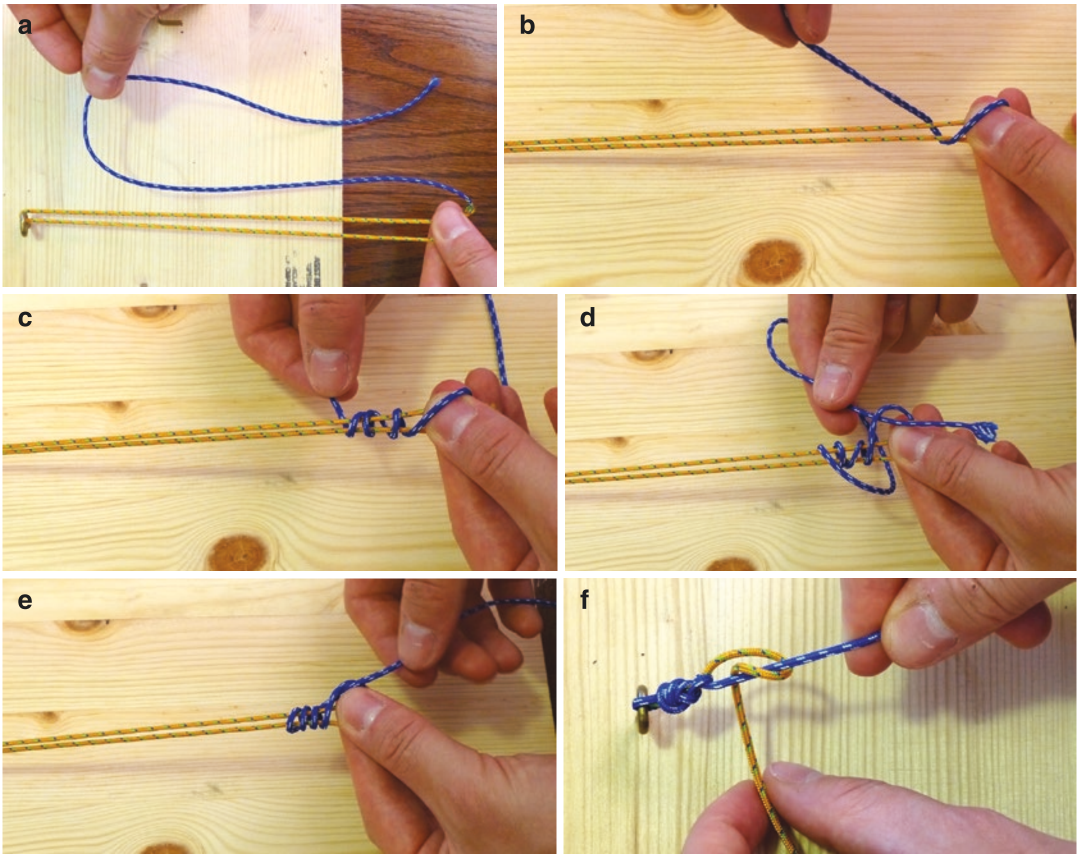

Fig. 16.1 Steps of the Duncan Loop (Fisherman's Knot)

and RHAPs will be added to lock the knot (Fig. 16.2d).

6. Some authors describe the use of two overhand loops on the post at step 3 (Fig. 16.2e).

16.2.3 Nicky's Knot

Nicky's knot is a 'ratchet' knot. It is a one-way slip knot. It has excellent initial holding capacity, maintaining tension on soft tissue while additional hitches are being tied (Fig. 16.3).

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post, and hold both limbs between the left thumb and the second finger (Fig. 16.1a).
2. Throw an overhand loop on the post (Fig. 16.3a).
3. Wrap the working limb on the post limb in proximal direction (Fig. 16.3b).
4. Slide the left thumb and second finger down so that the original loops are held under slight tension, and throw an overhand loop on the post in this new position (Fig. 16.3c, d).
5. Slide the knot to the target tissue by pulling the post limb (Fig. 16.3e). Once desired tension is achieved, 3 RHAPs are needed to lock.

16.2.4 Midshipman's (Taut Line) Hitch

It is similar to Nicky's knot. It has one more wrap in the proximal section (Fig. 16.3f). This knot is relatively easy to tie or untie under load, but, even after being heavily loaded, it is reasonably easy to release. Three half hitches on alternating posts (RHAPs) are needed to lock the knot.

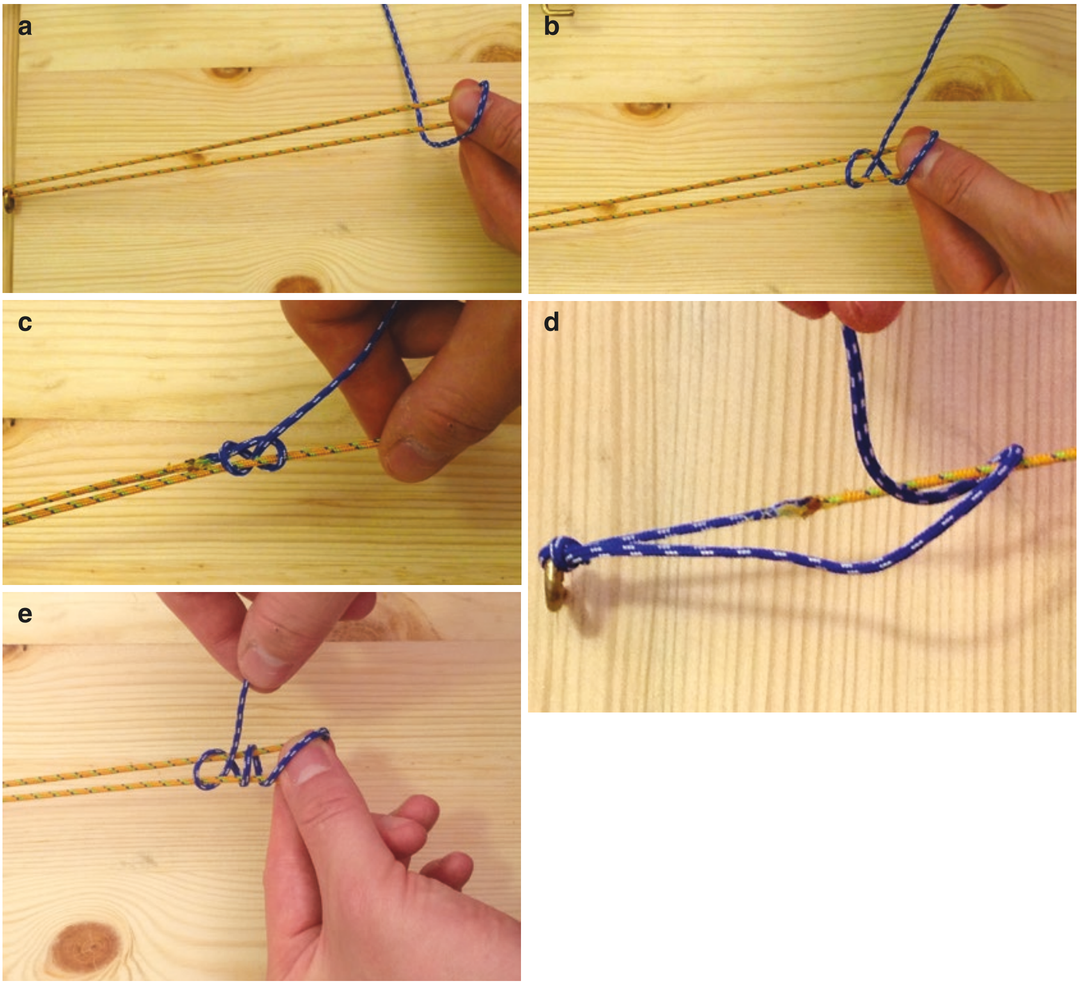

Fig. 16.2 Steps of the Tennessee Slider knot

16.3 Locking Sliding Knots

16.3.1 The Weston Knot

The Weston knot was described by Dr. Peter Weston, a gynecologist working in San Antonio in Texas, USA, in 1991. The knot was not originally designed to be used at laparoscopy but has been adopted by endoscopic surgeons as a very elegant slip knot.

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post, and hold both limbs between the left thumb and the second finger (Fig. 16.1a).
2. Throw an underhand loop on the post (Fig. 16.4a).
3. Throw an overhand loop on the post and under the non-post (Fig. 16.4b).
4. Throw an overhand loop on the non-post (Fig. 16.4c).
5. Pass the suture in the first loop on the non-post (Fig. 16.4d).
6. Slide and seat the knot by pulling the post limb (Fig. 16.4e). Once desired tension on the target tissue is achieved, knot will be locked by pulling the non-post (loop) limb.

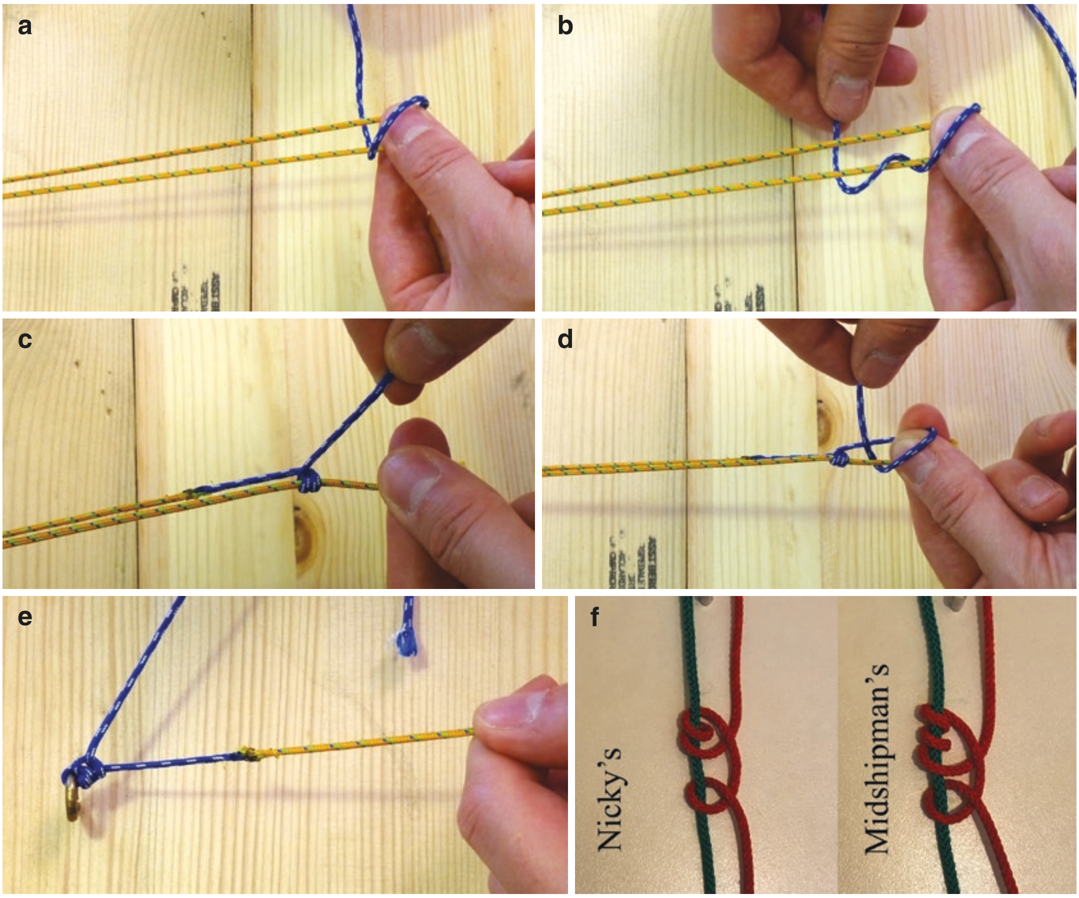

Fig. 16.3 Steps of the Nicky's Knot

16.3.2 The Giant Knot

This knot is a one-way self-locking knot. It is similar to Nicky's knot. Nicky's knot consists of three overhand half hitches, whereas the Giant knot has four overhand half hitches. Unlike Nicky's knot, this knot configuration locks pulling on the loop strand once it is pushed into place.

Steps to Tie

1. The first steps of the knot are the same of Nicky's knot (Fig. 16.1a, 16.3a, b).
2. After that slide the left thumb and second finger down so that the original loops are held under slight tension, and throw two overhand loops on the post in this new position (Fig. 16.5a).
3. After that slide and seat the knot by pulling the post limb (Fig. 16.5b). In order to lock the knot, loop limb should be pulled.

16.3.3 The Samsung Medical Center (SMC) Knot

The SMC knot is a sliding knot that was designed to slide easily then lock once in place. The developers of this knot reported that the locking mechanism of this knot obviates the need for multiple half hitches. It has a low profile and volume.

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post, and hold both limbs between the right thumb and the second finger (Fig. 16.6a).
2. Begin the knot by wrapping the loop limb over both limbs in a proximal direction (Fig. 16.6a, b).

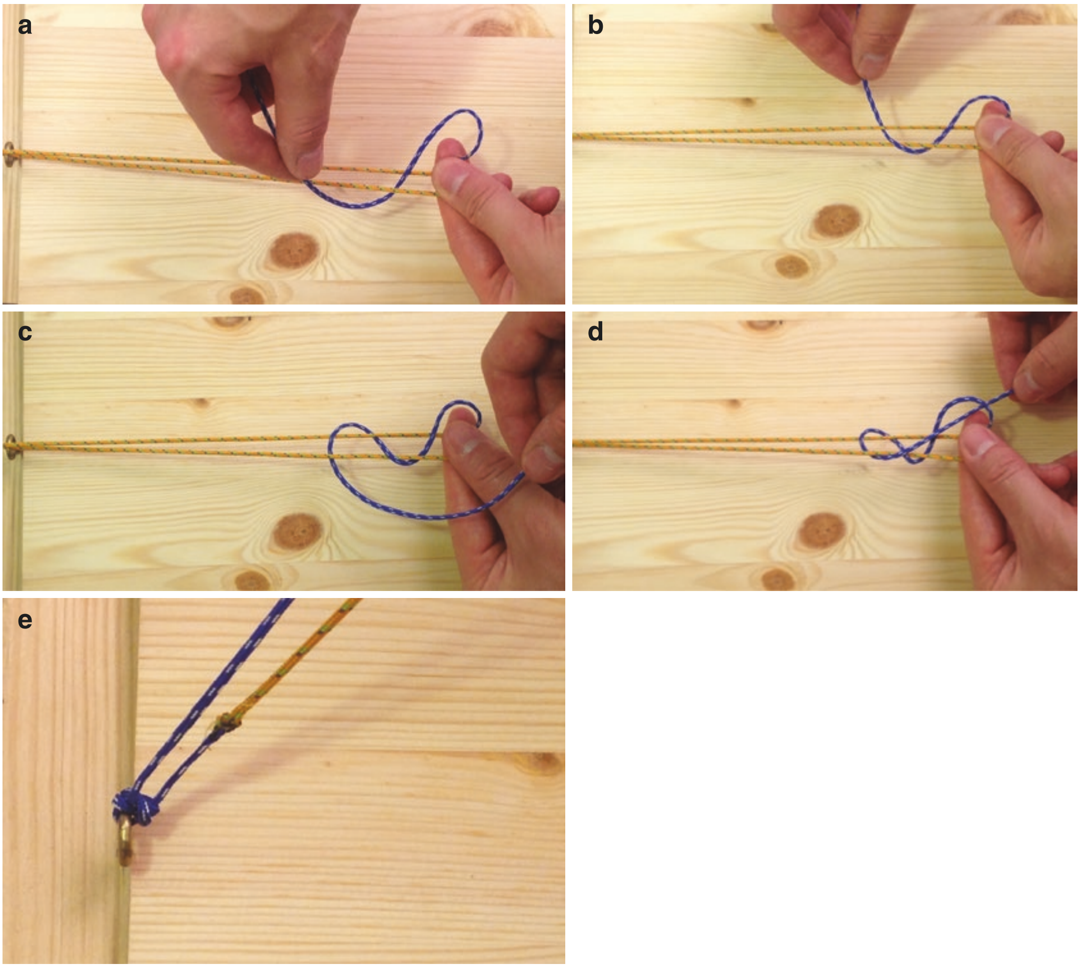

Fig. 16.4 Steps of the Weston Knot

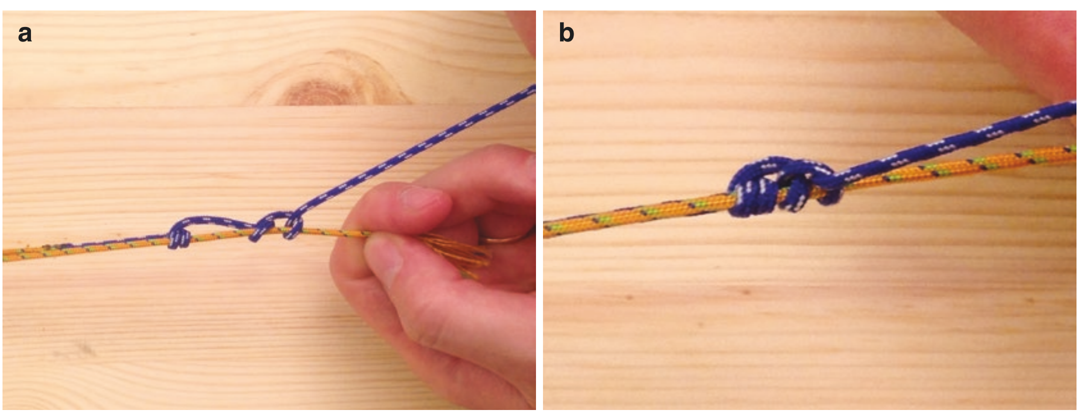

Fig. 16.5 Steps of the Giant Knot

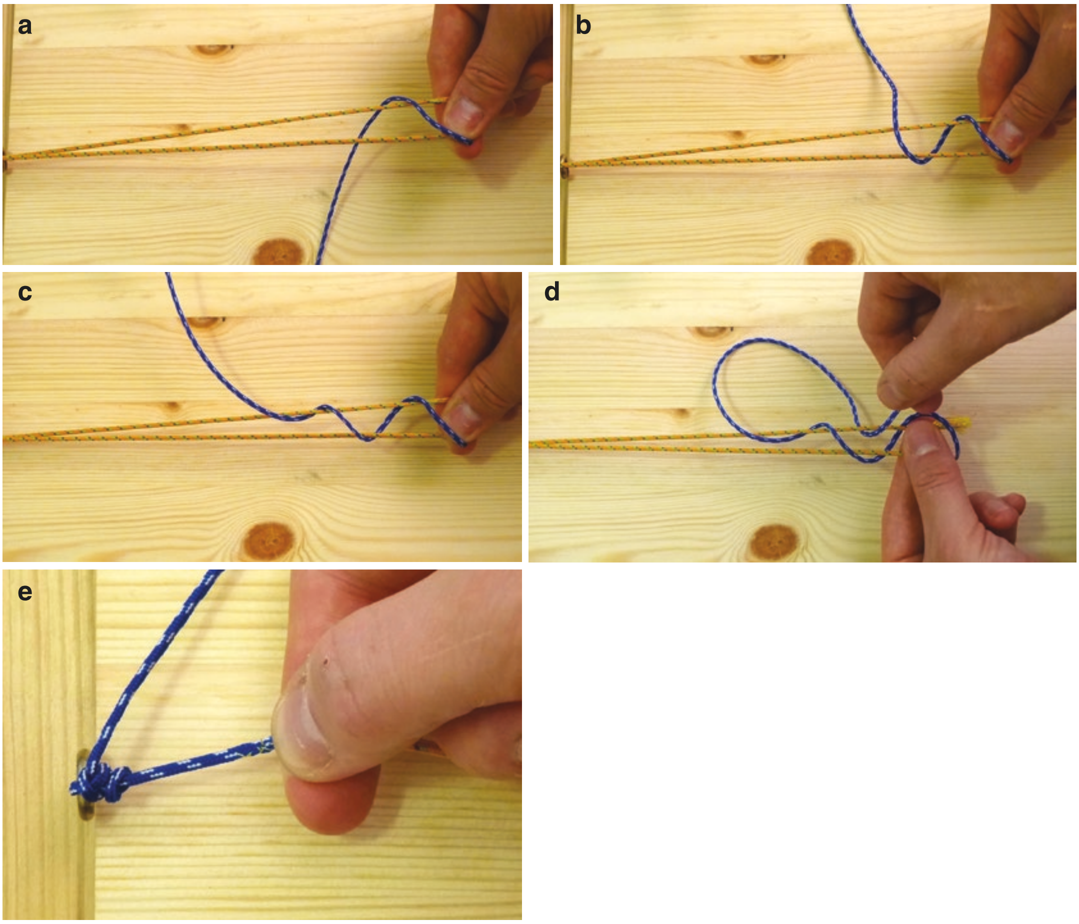

Fig. 16.6 Steps of the Samsung Medical Center (SMC) Knot

3. Wrap the loop limb on the post limb in a proximal direction (Fig. 16.6c).
4. Pass the free end of the loop limb suture under the post between the first two throws. Lightly dress the knot, but do not pull on the loop limb (Fig. 16.6d).
5. Advance the knot to the tissue by pulling on the post. The knot can then be locked by pulling on the loop limb to incorporate the locking loop into the knot and capturing the post (Fig. 16.6e).

16.3.4 The Roeder Knot

This is the first laparoscopic sliding knot described, and there are several versions of this knot. Roeder loop security depends predominantly on the number of initial turns around the standing part. Its knot security depends on the additional half hitches.

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post, and hold both limbs between the right thumb and the second finger (Fig. 16.7a).
2. Throw an overhand loop over both limbs (Fig. 16.7a).
3. Throw two overhand loops over the post (Fig. 16.7b, c).
4. Throw two overhand loops over both limbs (Fig. 16.7d).

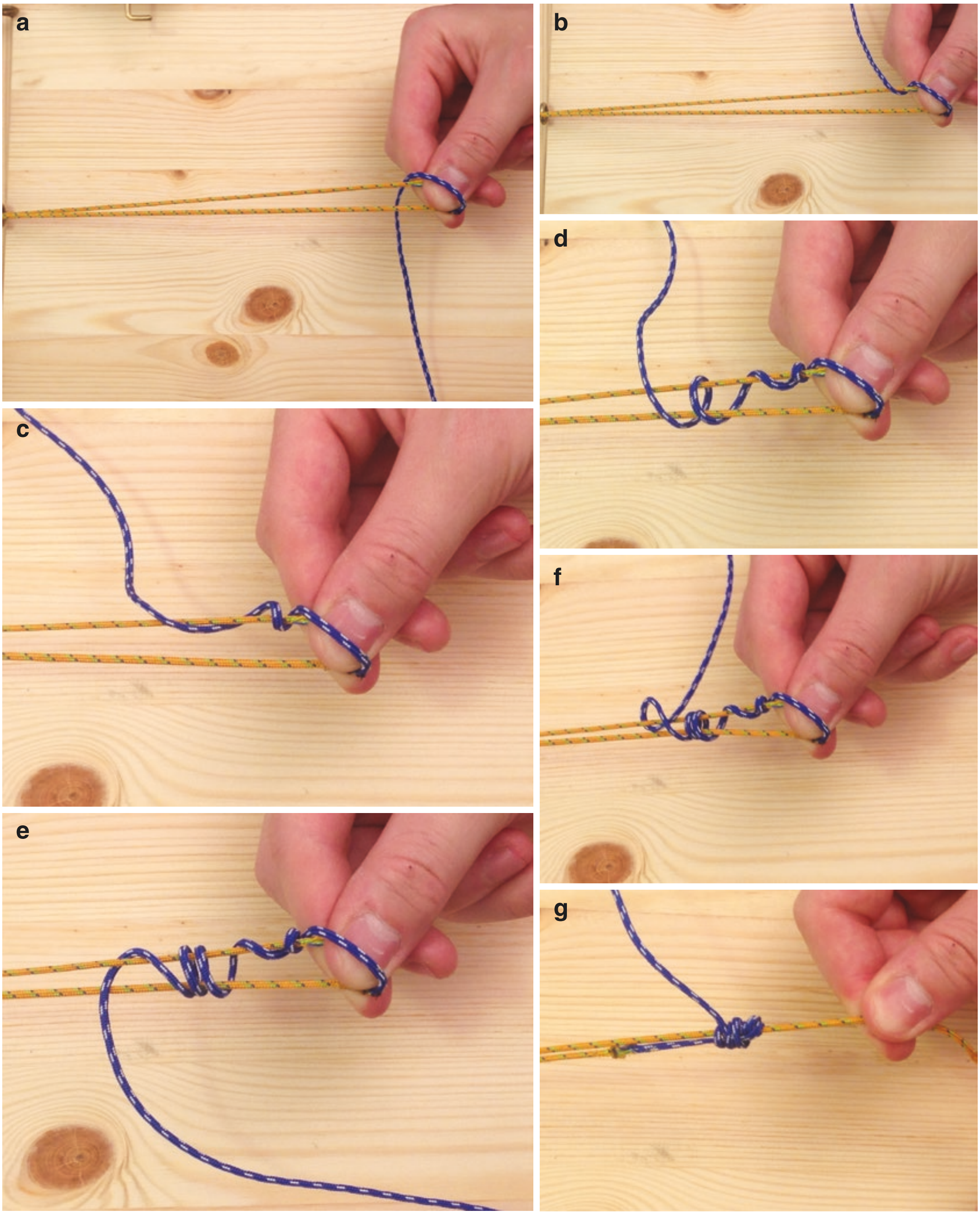

Fig. 16.7 Steps of the Roeder Knot

5. Wrap the suture on the post in a proximal direction and pass through the limbs (Fig. 16.7e).
6. Pass the free end of the loop limb under the last loop (Fig. 16.7f).
7. Advance the knot to the tissue by pulling on the post (Fig. 16.7g). Once it is fully seated, pull the loop limb to lock the knot.

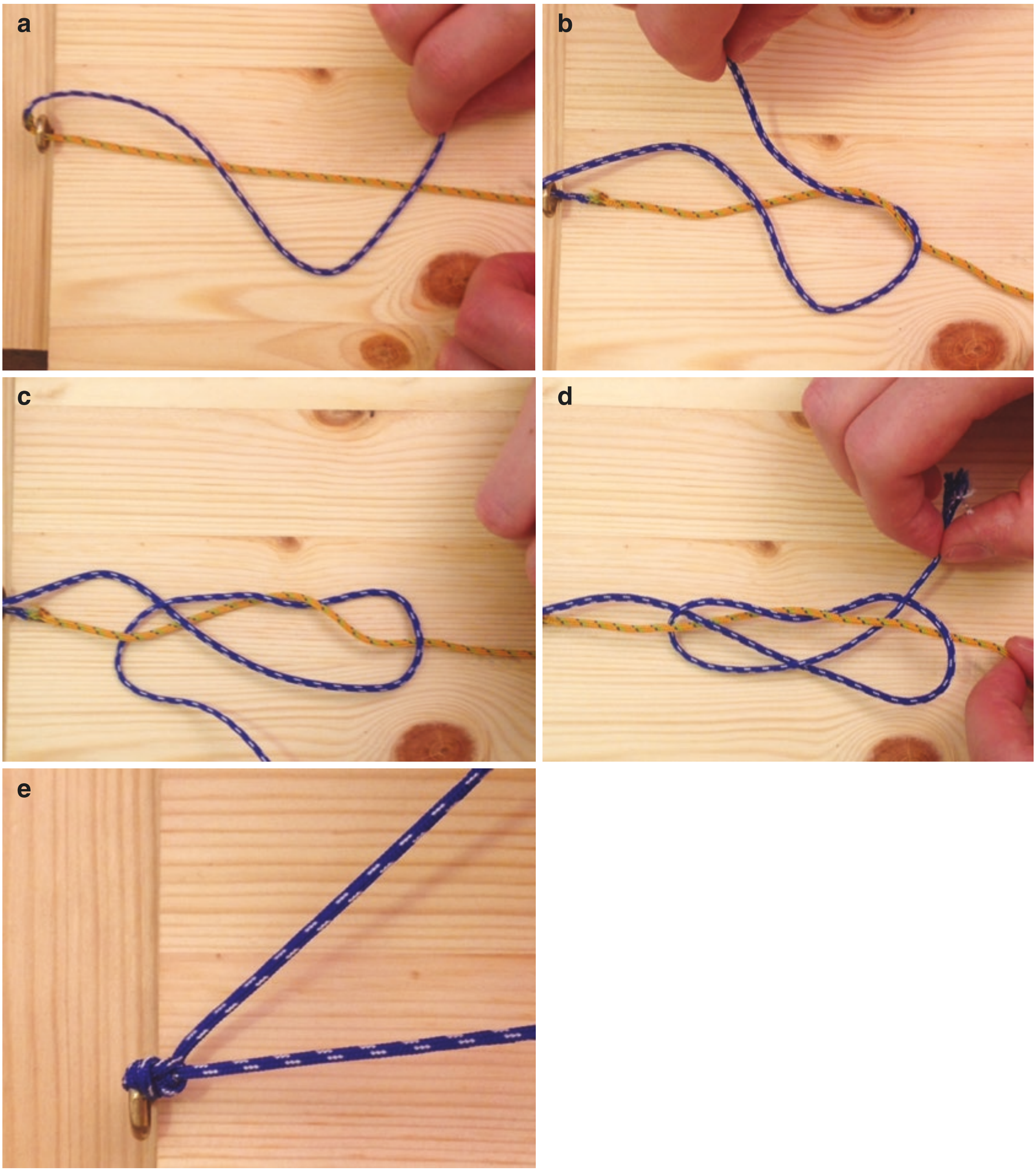

Fig. 16.8 Steps of the Dines Knot

16.3.5 The Dines Knot

It has exhibited good loop security, knot security, knot weight, and resistance to reverse slippage [10].

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post.
2. Place the non-post limb on the post limb as shown to create a loop close to the tissue (Fig. 16.8a).
3. Wrap the loop limb over the post in proximal direction (Fig. 16.8b).
4. Pass the loop limb through the space between the post and loop limb closer to the tissue as shown (Fig. 16.8c).

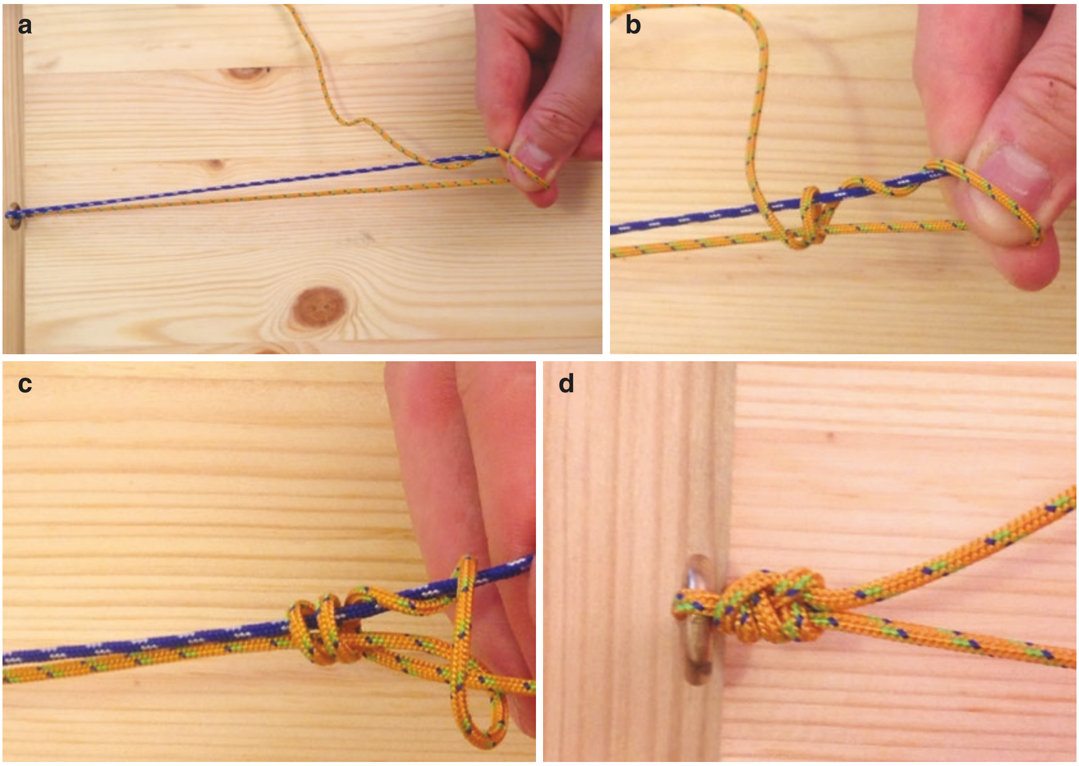

Fig. 16.9 Steps of the Tuckahoe Knot

5. Place the loop limb on itself on the distal direction and pass it between the post and the loop limb as shown in (Fig. 16.8d).
6. Advance the knot to the tissue by pulling on the post (Fig. 16.8e). Once it is properly seated on the target issue, lock the knot by pulling the loop limb.

16.3.6 The Tuckahoe Knot

This knot is an easy-to-tie knot that can slide and lock. The benefit of these characteristics is that when the knot is seated and locked, it is secure and it will not slip before the three reversed half hitches with alternating posts are added [11].

Steps to Tie

1. Adjust the suture limbs for a sliding knot, with the non-post limb length that is about the double of the post, and hold both limbs between the right thumb and the second finger.
2. Throw an overhand loop over both limbs (Fig. 16.9a).
3. Wrap the loop limb on the post in the proximal direction (Fig. 16.9a).
4. Throw two over both limbs in the proximal direction (Fig. 16.9b).
5. Pass the loop limb through the loop created in the first step as shown in (Fig. 16.9c).
6. Advance the knot to the tissue by pulling on the post (Fig. 16.9d). Once it is properly seated on the target issue, lock the knot by pulling the loop limb.

16.3.7 Pretzel Knot

Pretzel is a recently described simple locking sliding knot [12]. It can be locked and unlocked easily if further tension is needed.

Steps to Tie

1. Throw an overhand half hitch on post (Fig. 16.10a).

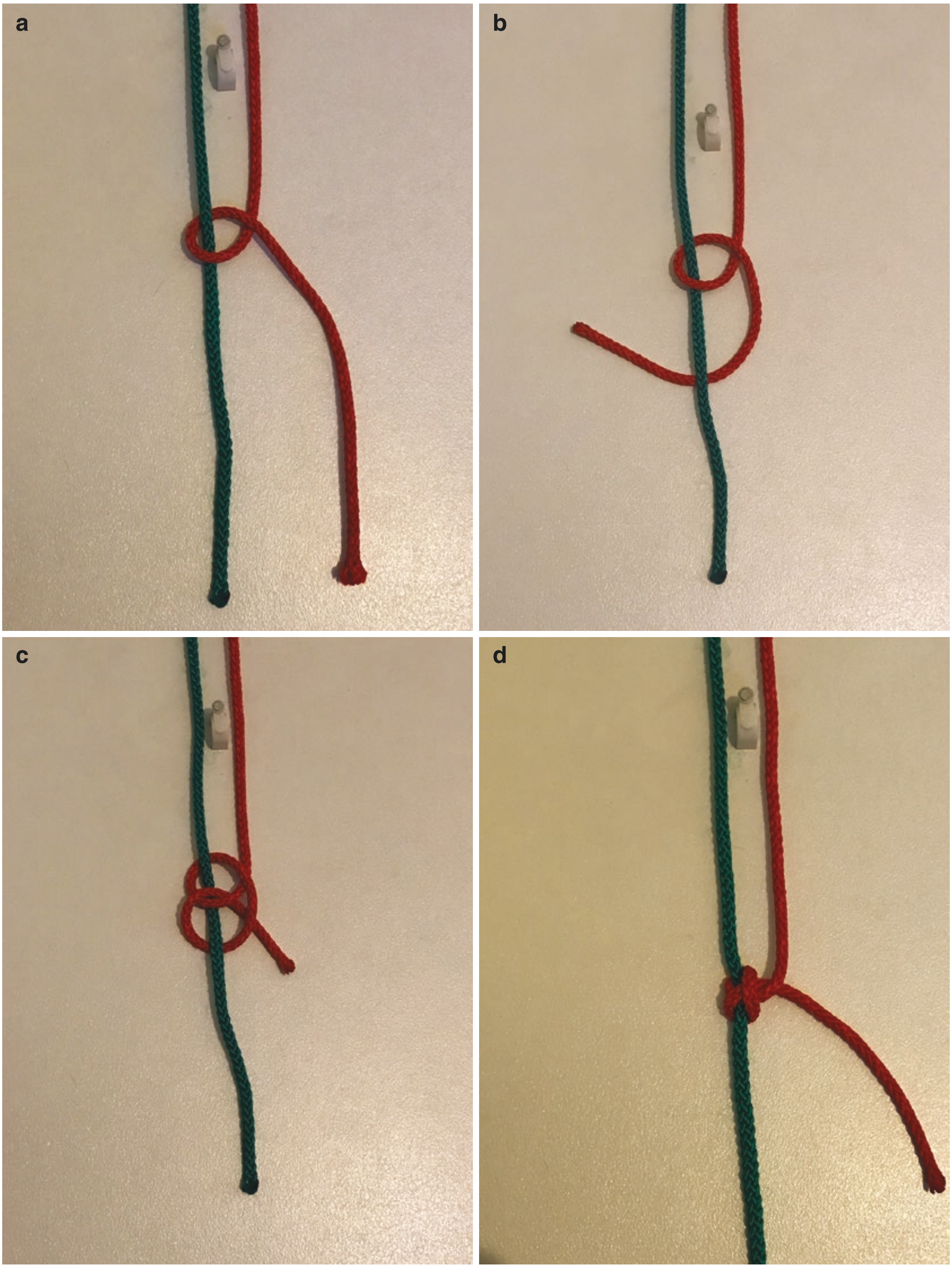

Fig. 16.10 Steps of the Pretzel Knot

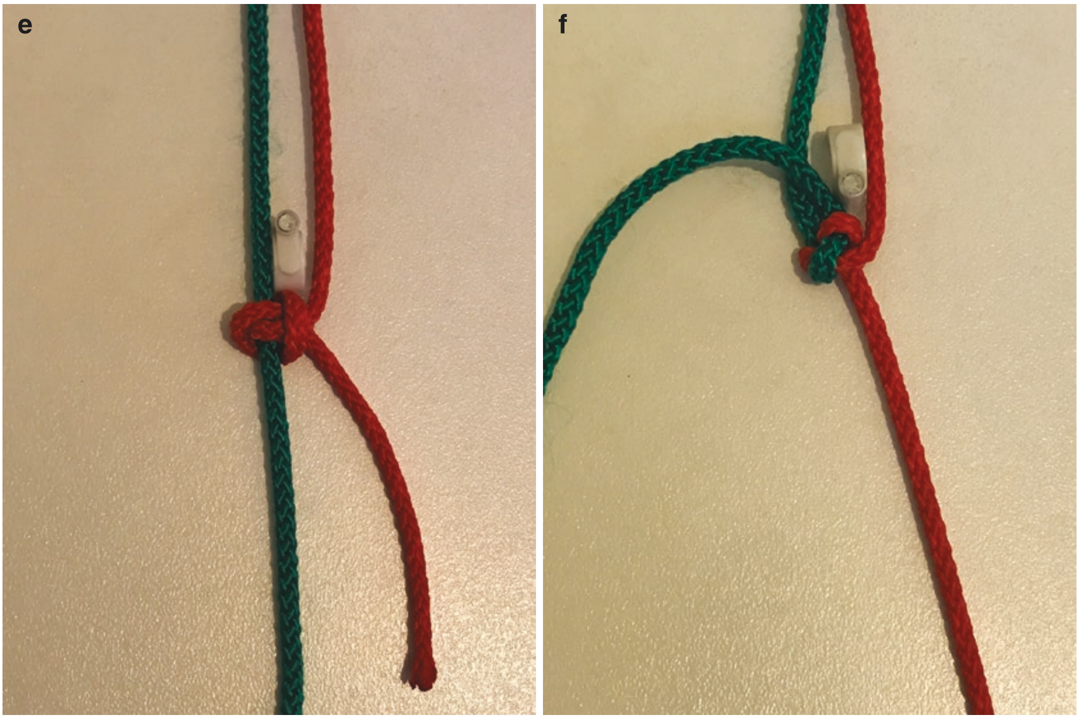

Fig. 16.10 (continued)

2. Begin to throw an underhand half hitch on the post (Fig. 16.10b).
3. Pass the non-post limb through the overhand half hitch formed on the first step (Fig. 16.10c).
4. By a gentle traction on the non-post limb, slacks are removed (Fig. 16.10d).
5. Pull the post and advance the knot on position (Fig. 16.10e).
6. When the knot is on desired position, pull the non-post limb to flip and lock the knot (Fig. 16.10f). 3 reverse half hitches on alternating posts are advised to secure the knot.

The list of the locking sliding knots can be extended, various knots are used by surgeons (Figs. 16.11 and 16.12). Although locking sliding knots prevent reverse slippage of the initial loop, some authors suggest at least two or three additional half hitches to achieve an optimal knot-holding capacity.

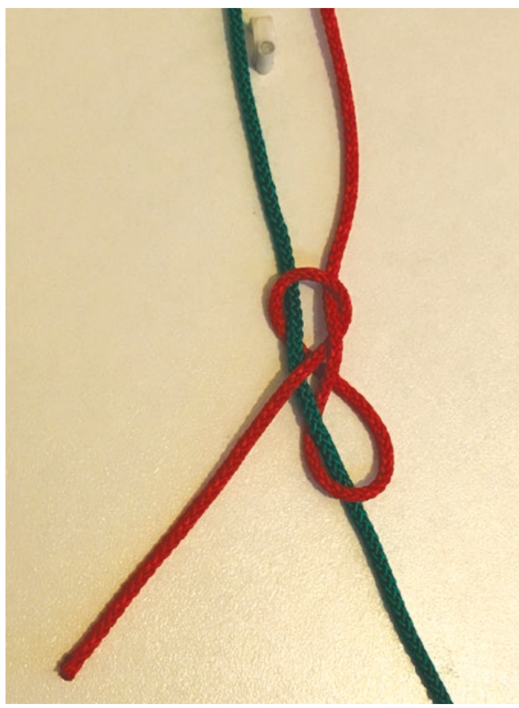

Fig. 16.11 Snyder knot

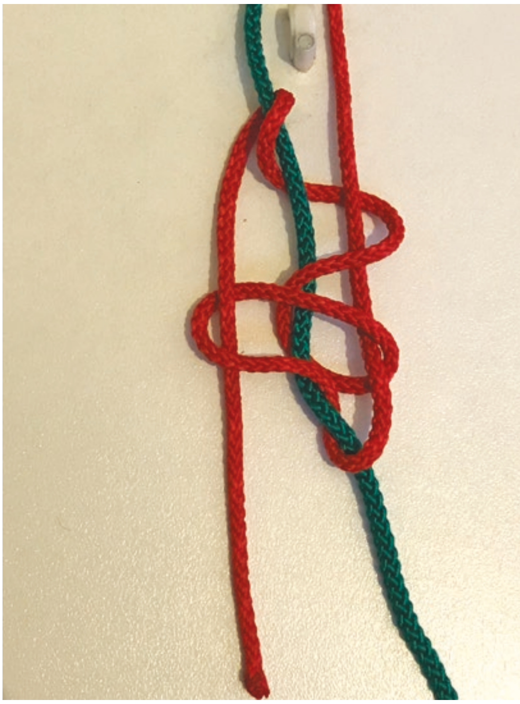

Fig. 16.12 Field knot

Conclusion

The ability to perform a sliding knot is an essential skill required in many different arthroscopic prosedures. During the years, surgeons developed different arthroscopic knots, usually they modified knots from other fields such as fishing and climbing into the operating room. The aim of this chapter was to provide a practical guide for surgeons to show a step by step demonstration of the common sliding knots. Authors believe that surgeons should train knot tying in the dry lab prior to surgeries and be able to tie at least one locking and one non-locking knot flawlessly.

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Part IV

Literature Review

17 Literature Review of Suture Materials

Ersin Erçin and Mustafa Karahan

Sutures are used on a daily basis in orthopedic surgery for a wide variety of purposes. Although mostly depended onto the surgeon preferences, the selection of suture material is based on the tissues to be repaired. As surgical procedures and the handled tissues vary, it is important to understand the basic types of the suture materials. Synthetic suture materials overcome the use of natural suture materials for years. With modern sutures, it is likely to perform many surgical procedures with more confidence. This review will cover several different features of suture materials that are commonly used.

Sterility, uniform diameter and size, amount of tissue reaction, uniform tensile strength for each size, pliability for good handling, and knot security are essential suture characteristics that all manufacturers consider before producing a new suture material to the market. Reaction to the surrounding tissue, tensile strength, and knot security are very important characteristics directly related to the suture materials. Forces with repetitive loading on the repair site can jeopardize appropriate healing [1]. Arthroscopic sutures require different characteristics such as greater strength for small sizes, easy to pass through arthroscopic suture passers, ability to be knotted in the arthroscopic environment, and ability to slide through arthroscopic equipment. Suture materials have different biomechanical properties in arthroscopic conditions (in wet) than in dry conditions [2].

17.1 Suture Materials

Suture materials can be classified as natural or synthetic, monofilament or multifilament, and absorbable and non-absorbable. Natural suture materials are made from natural materials derived from collagenous tissues of animals. These materials may cause tissue reaction, and antigenicity of the material may lead to inflammatory reactions. Synthetic suture materials are produced by an industrial process; synthetic non-absorbable materials do not elicit tissue reaction as they are not absorbed. Synthetic absorbable materials are polymers which resemble sugars in their chemical structure; therefore, they are eliminated easily. Absorption is by hydrolysis which causes very little tissue reaction in contrast to natural materials which go to enzymatic degradation and cause more tissue reaction. Therefore, most of the natural suture materials were abandoned and synthetic suture materials have been dominantly used in surgeries for years.

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Monofilament suture is made of a single strand which presents less resistance to passage through tissue layers than multifilament materials. Monofilaments are stiffer and generate difficulties during suture knotting. The surface of the monofilament sutures can be smooth as traditional or barbed. Barbed sutures are relatively new type of sutures which have little barbs projecting from a monofilament base. These knotless sutures emerged to the market with the advantage of lowering surgery time by skipping knotting tread. Although monofilament sutures are resistant to the colonization of microorganism, colonization with bacteria underneath the barbs is possible and should be judged in septic cases [3].

Multifilament sutures are composed of several filaments that are twisted or braided together. This type of sutures generally has better handling properties and enhanced knot security and is more easily bendable but has a higher coefficient of friction. Multifilament sutures are generally coated to reduce capillarity and friction through tissue. Also to reduce bacterial colonization, manufacturers have introduced antimicrobial-coated sutures. Studies show that antimicrobial agent triclosan-coated sutures decrease the surgical site infections [4].

A suture material is considered absorbable if it loses most of its tensile strength within 60 days of tissue implantation and used when their presence require temporarily in tissues. A natural absorbable suture is degraded by proteolysis, whereas a synthetic absorbable suture is degraded by hydrolysis [5]. In contrast, non-absorbable sutures go to encapsulation with an acellular response and retain most of their tensile strength after 60 days.

Absorbable synthetic suture materials are polyglycolic acid, polyglactin, and polydioxanone. Tissue reactivity with polyglactin is less than polyglycolic acid. In a biomechanical study, comparing knot security of suture materials included chromic gut, nylon, silk, and Vicryl (polyglycolic acid). Authors found Vicryl had the greatest knot security and silk had the least [6]. Polydioxanone suture knots must be properly tied because it is stiff and has a "memory" with the tendency for knots to unravel if sufficient number of reinforcing half hitches are not placed [7]. Non-absorbable synthetic suture materials are polyamide, polypropylene, polyester, and ultrahigh molecular weight polyethylene (UHMWPE)-containing sutures. Despite being made of the same material, there is variability in suture performance in between different brands of polyamide [8].

Ultrahigh molecular weight polyethylene (UHMWPE)-containing sutures are consisted of UHMWPE fibers which are characterized by high tensile strength in smaller volumes. This high-strength braided suture may be further classified according to their structural combination as solitary UHMWPE, UHMWPE and polyester combination, and UHMWPE and polidiaksonon and polyglactin combination.

1. Solitary UHMWPE: Ultrahigh molecular weight polyethylene fibers are characterized by high tensile strength even in small sizes. As suture materials composed of braided polyethylene fibers do not have a longitudinal core, the coreless design makes the profile of the suture flatter with a, respectively, better knot security.
2. UHMWPE + polyester: This material has braided polyester coat around a central core of multiple small strands of UHMWPE. Core design makes the shape of material more round and requires more knot throws. Also, type I bovine collagen-coated form is available.
3. UHMWPE + polidiaksonon + polyglactin: This material comprises a polidiaksonon (PDS) core with a UHMWPE sleeve and coated with polyglactin 910 [9]. This configuration is intended to leave a lower-profile suture after the PDS has dissolved and retain strength from the outer sleeve. Suture material becomes flatter after resorption of PDS core [10]. Different UHMWPE-containing sutures and structural properties are listed in Table 17.1.

Before the development of UHMWPE sutures, non-absorbable braided polyester sutures, such as Ethibond, were the suture of choice for soft tissue repairs and for suture anchors. Braided

Table 17.1 UHMWPE-containing sutures according to suture brand, company, material, and structure

Suture brand	Company	Material	Structure
Ultrabraid	Smith & Nephew, Memphis, TN, USA	UHMWPE	Braided polyethylene fibers without a longitudinal core
Herculine	Linvatec, Largo, FL, USA	UHMWPE	Braided polyethylene fibers without a longitudinal core
Force Fiber	Teleflex, Research Triangle Park, NC, USA	UHMWPE	Braided polyethylene fibers without a longitudinal core
MaxBraid	Biomet, Warsaw, IN, USA	UHMWPE	Braided polyethylene fibers without a longitudinal core
MagnumWire	ArthroCare, CA, USA	UHMWPE	Braided polyethylene fibers without a longitudinal core
FiberWire	Arthrex, Naples, FL, USA	UHMWPE Polyester	Braided polyester coat around a central core of multiple small strands of UHMWPE
Collagen Coated FiberWire	Arthrex, Naples, FL, USA	UHMWPE Polyester Collagen	Braided polyester coat around a central core of multiple small strands of UHMWPE Coated with type I bovine collagen
Orthocord	DePuy Mitek, Raynham, MA, USA	UHMWPE polidiaksonon (PDS) Polyglactin	Polidiaksonon (PDS) core with a UHMWPE sleeve and coated with polyglactin 910

polyester has been replaced in most arthroscopic applications and in all current suture anchors by high-strength UHMWPE-containing sutures. The ultimate strength of UHMWPE-containing suture materials was found to be 2–2.5-fold greater than that of polyester (Ethibond) or polydioxanone (PDS) sutures. Also, resistance to the fraying of UHMWPE sutures was found to be up to 500-fold greater than that of polyester or polydioxanone sutures; this superior property yields to numerous advantage to be used in suture anchors [11].

Studies comparing mechanical properties of different types of UHMWPE-containing sutures found ultrahigh molecular weight polyethylene core filaments resisted bending abrasion failure better than other core materials due to the load spreading and abrasion resistance of these filaments. Also sutures with UHMWPE cores had high resistance to tensile failure [12]. Besides the existence of a core, other important factors of UHMWPE suture structural construct are twist angle and picks per inch, which is also related with suture abrasiveness. Significant differences in suture abrasiveness were found among high-strength braided sutures, which are correlated with lower twist angle and lower picks per inch [13]. UHMWPE braided polyester suture has increased abrasive properties compared with monofilament suture on the suture tendon interface [14].

Tying load tests conducting different suture materials (No. 2 Vicryl, FiberWire, and PDS) highlighted the importance of the number of throws and proper appliance of throws rather than more intense tying. Especially, a minimum of six square knots is recommended when tying FiberWire to hold under high load [15]. This high-strength braided suture may also result in increased glove tears compared with monofilament sutures [16]. UHMWPE sutures are susceptible to slippage which is also dependent on the type of knot used [17]. The bulkiness of arthroscopic knots is especially important. Arthroscopic knots are significantly bulkier than 5-throw openly tied square knots. In comparison with different materials, square knots openly tied with FiberWire or Ultrabraid are bulkier than if tied with Ethibond or Orthocord [18]. Finally, two important factors, abrasion debris with potential inflammatory response and interactions between knot and suture materials, need to be investigated further.

Conclusion

The choice of the proper suture type is as important as the correct application. Awareness of the different types of suture materials will guide the surgeons through the procedures and may overcome the problems about tissue fixation. Through the development of regenerative medicine and tissue engineering, new-generation bioactive sutures may emerge as the next step.

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18 Literature Review of Arthroscopic Knots

Maristella F. Saccomanno and Giuseppe Milano

Knot tying is a basic surgical skill. As the indications for arthroscopy have expanded, attention has turned to how arthroscopic surgery compares with open surgery, so the ability to tie secure knots arthroscopically is essential for surgeons who wish to achieve results comparable with open repairs [1]. Successful arthroscopic repair depends on several factors, including the surgeon's technique, tissue quality, and security of the arthroscopically tied knot. Of these factors, a surgeon's technique can progressively improve, and proper selection of patients can reduce the failure rate related to tissue quality. Unfortunately, though the principles of open and arthroscopic repair are the same, arthroscopic knots are more difficult than hand-tied ones because they must be performed at a distance, in a wet field, and then tightened at the level of the target tissue by using a knot pusher, which results in asymmetric tensioning between the two limbs of the knot. Therefore, ensuring proper tension is surely challenging.

The knots used today have their roots in fishing and sailing. These basic knots have been tailored and customized into thousands of variations with both specific and general uses. Since the introduction of arthroscopic surgery, surgeons have been constantly looking for better and stronger suture materials, knot configurations, and instrumentation in order to decrease the discrepancy between the arthroscopic and open approaches [2, 3]. Recently, several arthroscopic and hand-tied knot configurations have been compared to demonstrate the equality or superiority of the arthroscopic knots [4, 5]. Despite the large number of knot options and suture types, most of the time, the choice of the knots is not based on scientific evidence but on empirical data and surgeon's preference. By the way, all effective knots must be properly performed so that the sutures do not slip or cut into itself. The ideal knot is one that ensures maximum strength with the smallest bulk and greatest ease of tying.

The aim of the following chapter is to review different arthroscopic knots and their biomechanical properties.

18.1 Biomechanical Features

Knot configurations should be always tested before the clinical application, so the findings allow the surgeons to choose arthroscopic knots on evidence-based principles. Testing should be carried out under conditions that most closely approximate the in vivo setting and take the laws of physics into account to gain significant findings [4].

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Knot failure (loss of soft tissue fixation) is defined as 3 or more mm of displacement [1, 6, 7], based on the assumption that 3 mm of displacement is the cutoff value for suture breakage, suggesting that the suture loops fail by a combination of knot slippage and suture elongation.

The ideal arthroscopic knot should have optimal loop and knot security, low knot profile, ease of tying, and low incidence of premature or unintended locking.

Loop security is the ability of the suture passed through the tissue (loop) to keep initial tension on the post strand as the knot is tied [8]. Loop security should be interpreted as the performance of the knot at time zero before any load is applied. To the surgeon, this correlates to how closely the suture loop can be made to ideal and how closely the tissue can be approximated intraoperatively. Factors that may affect loop security include the expansion of the loop and the deformation of the knot that may occur during knot locking.

Knot security is defined as the effectiveness of the knot at resisting slippage when load is applied. It depends on three factors: friction, internal interference, and slack between throws [9].

Loop and knot security are the two main biomechanical features for a knot to be effective and able to securely hold and approximate tissue. They are of course interrelated and partially dependent on each other: any tied knot can have good knot security but poor loop security (a loose suture loop) and therefore be ineffective in approximating the tissue edges to be repaired.

Many types of high-strength suture materials are nowadays available for arthroscopic surgery. The main advantages of newer suture materials are that they have superior tensile strength and are difficult to break. High-strength suture materials are constructed of braided ultrahigh molecular weight polyethylene (UHMWPE) with or without a core filament. However, literature demonstrated that particular type of high-strength suture material may have a higher chance of knot slippage because of its surface characteristic and frictional property [10–12]. Thus, it is important to take into account that besides knot configuration, suture materials also influence loop and knot security.

Finally, ease of knot placement is the ability to advance the knot along the post using minimal force [13].

Actually, no study reported direct comparison of all arthroscopic knot configurations with all the combinations of available suture materials. However, several studies examined biomechanical properties of the most commonly used knots. Interpretation of these studies is not easy because there is no uniformity in the knot configurations and suture materials used. By the end, there is no consensus on the ideal arthroscopic knot, although it has been demonstrated that most arthroscopic knots tied with three reversing half hitch knots on alternate posts resist physiologic forces [14, 15].

18.2 Knot Nomenclature

Many knot configurations have been described and applied to arthroscopic surgery. Knots can be classified into two main categories: sliding and non-sliding (Table 18.1). A good arthroscopic surgeon needs to be familiar with both knot patterns.

Sliding knots are indicated when the suture limbs slide easily through the soft tissue and the suture anchor eyelet. The key advantage of the sliding knots is the possibility of opposing tissue under tension. Main shortcoming is the risk of tissue injury by cutting through it and consequent poor fixation. Therefore, it is advisable not to use sliding knots when tissue quality is poor [16]. Another limitation of these knots is that they can slide backward after being pushed into its position and loop security can be compromised. Two methods have been developed to prevent loosening:

(a) Throwing additional loops on top of the sliding knot after it is seated (non-locking sliding knots)
(b) Changing the sliding knot into a non-sliding knot after it is seated (locking sliding knots)

Table 18.1 Knot nomenclature

	Sliding knots	
Non-sliding knots	Non-locking	Locking
Stacked half hitches [43] Surgeon's [41] Arthroscopic square [42] Revo [2, 7, 26, 27]	Duncan's loop [17] French [34] Double twist [35]	Nicky's [21] Modified taut line hitch [20] Lafosse or giant [25] Field [32] Dines [20] SMC [22] Tennessee slider [23] Weston [19] Roeder [2] Savoie-modified Roeder [7] Lieurance-modified Roeder [7] Snyder slider [20] San Diego [10] Pretzel [36] Modified slippage-proof [39] Modified racking hitch [47] Inverse [48] Hu [49] Triad [50] Chula [51]

Non-locking knots, such as the Duncan loop [17], can be easily ensured by performing three additional alternating post half hitches. Conversely, the locking effect, also known as "one-way ratchet effect" or "self-locking effect," consists of flipping the knot by pulling on the loop limb so that the loop becomes the post, preventing the knot from backing off. Theoretically, this is accomplished after the knot has been seated and good loop tension has been achieved. However, it must be noticed that the knot can be inadvertently locked at any point in the tying process. Moreover, even if these knots are "self-locking" by definition, it has been shown that additional half hitches increase loop security [18]. Locking knots have been further subdivided into three categories based on the region of flipping: proximal, middle, and distal locking. Although still debated, Weston [19], Roeder [2], and Dines [20] knots are examples of distal-locking knots, Nicky's knot [21] has a proximal-locking mechanism, and SMC [22], Tennessee [23], and San Diego [10] have middle-locking characteristics. Theoretically, distal locking can prevent knot slippage better than proximal locking, but they are difficult to lock when tension in the knot loop is high. The proximal-locking knots can easily be locked under the desired loop tension, but they can also easily loose tension during additional locking half hitches. Middle-locking knots provide the advantages of both proximal- and distal-locking knots: they prevent easy slippage of loop security like distal locking and also can easily be locked like proximal-locking knots, even with high loop tension [24]. The last category of the locking sliding knots is the ratchet knot, which allows movements in only one direction. Modified taut line hitch [20] and Giant knot [25] belong to this category.

Non-sliding knots, such as the Revo knot [2, 7, 26, 27], are indicated when suture limbs do not slide freely through either the anchor or soft tissue and in case of low tissue quality, when a vigorous pulling could weaken the soft tissue and the suture itself. The tissue has to be held approximated while the knot is being placed, as these knots by definition do not slide, to provide further compression of the repair.

18.3 Biomechanical Studies

18.3.1 Sliding Knots: Locking vs. Non-locking

Loutzenheiser et al. [1, 28] were the first to recommend that sliding knots should be locked with three reversing half hitch knots on alternate posts. Since then, numerous studies have been conducted on the mechanical characteristics of sliding knots with or without three half hitch knots on alternate posts [4, 6, 11, 14, 15, 18, 29–31]. It has been shown that when this recommendation is followed, knot security will depend mostly from the half hitch throws and will be independent of sliding-knot configuration [11, 14].

Therefore, most of the knots are not significantly different in load to failure and clinical use when tied with three additional loops [6, 30]. To compare the mechanical characteristics of sliding knots, it is more relevant to evaluate the initial loop security without additional loops on the top of the knot [8, 26].

Most sliding knots have been shown to have excellent loop security, although some differences between knots were reported [4, 6, 11, 14, 15, 18, 29–31]. Lo et al. [6] compared six commonly used knots (Duncan loop, Nicky's knot, Tennessee slider, Roeder knot, SMC knot, Weston knot) performed by using No. 2 Ethibond (Ethicon, Somerville, NJ) or No. 2 Fiberwire (Arthrex, Naples, FL) sutures, with and without a series of three reversing half hitches on alternating posts. The authors showed that the Roeder knot with the additional loops provided the best balance of loop security and knot security regardless of suture type. Conversely, the Weston knot showed the highest load to failure when compared with other sliding knots without additional loops. This result has been confirmed by a subsequent study, which also showed that the Tennessee slider knot has the lowest loop security in all suture materials [11]. Two mechanisms causing suture loop enlargement were observed by Lo et al. [6]. First, in the Duncan loop, because no mechanism for locking the knot exists, the suture loop expands until the knot tightens to a point where its knot security can resist the applied load. The second can be seen in almost every knot that required a flipping maneuver to be locked, which prevents the knot from slipping backward, but it also enlarges the suture loop. Moreover, it was noticed that distal-locking knots tended to cause less enlargement of the suture loop than proximal-locking or middle-locking knots [6]. Another study [29] which compared ten different knot configurations (Dines knot, Duncan loop, Field knot [32], Giant knot, Lieurance-Modified Roeder knot [7], Nicky's knot, SMC knot, Snyder knot [33], Tennessee slider knot, Weston knot) tied with No. 2 Ethibond (Ethicon, Somerville, NJ) actually showed that Dines knot has superior biomechanical properties, as subsequently confirmed by recent studies [4, 30]. Baumgarten et al. [31], after comparing 16 arthroscopic knots (Revo knot, Duncan loop, French knot [34], the Roeder knot, Tennessee slider, double-twist knot [35], Nicky's knot, the modified taut line hitch, the Savoie-Modified Roeder knot [7], Lieurance-Modified Roeder knot [7], Field knot, SMC knot, Giant knot, Weston knot, Snyder slider [20], and Dines knot), concluded that locking knots did not improve loop security over non-locking knots, since Nicky's knot and the French knot were most consistently ranked within the top 5 knot types for each of the biomechanical parameters. In 2010, Karahan et al. [36] introduced the Pretzel knot, a new locking knot. The authors, after comparing mechanical properties of the new knot with other five locking knots (SMC, Giant, Dines, Nicky's, and Tennessee slider), showed that the Pretzel knot has superior loop security [37]. Finally, Kim et al. [38] recently compared six different locking sliding knots (Weston, Nicky, Roeder, SMC, San Diego, and Dines) and showed that the locking mechanism is maintained only when the suture loop is tensioned at both strands; otherwise, if tension is applied only to the post strand, the knots slide and fail more easily.

Although post switching and loop reversal have been shown to be the key to arthroscopic knot security, the optimal number of additional half hitches is still a matter of debate [14, 15, 39]. After comparing four configurations of arthroscopic knots (Duncan loop, Field knot, Giant knot, and SMC), Kim et al. [14] showed that all knots have a near plateau in knot security with three or more additional half hitches. However, in case of a non-locking knot, such as the Duncan loop, more than three additional half hitches could be needed to ensure optimal security. Conversely, in case of locking knots, such as the SMC knot, a minimum of two additional half hitches could be enough. A subsequent study [15] confirmed that the optimized configuration for arthroscopic sliding knots required a locking knot, such as the SMC or Weston knots, with only two additional throws if the first half hitch was switched to the loop limb. Finally, a recent study [39] showed that the modified slippage-proof knot, a new arthroscopic locking knot, has biomechanical properties comparable to the SMC and Revo [27] knots despite only requiring one added half hitch.

18.3.2 Sliding vs. Non-sliding Knots

Although sliding and non-sliding knots are supposed to have different indications, some surgeons, in their daily practice, perform only a knot configuration, based on personal skill and experience. Several studies compared biomechanical features of sliding and non-sliding knots showing controversial results [5, 6, 34, 40]. Some studies showed that non-sliding knots, such as the surgeon's knot [41], provided the highest knot security and the tightest loop circumference [6], whereas some others showed that sliding knots, such as the French knot, had the best biomechanical performance [34, 40]. In 2006, Elkousy et al. [5], after comparing the arthroscopic square knot [42] with the open square knot, arthroscopic and open half hitches [43] with alternating posts, and the Duncan loop, showed that arthroscopic square knots have the same or greater strength when compared with other arthroscopic or open knots tied with the same suture type (No. 2 Ethibond suture or No. 2 FiberWire).

Although there is no consensus regarding the ideal knot configuration or suture material, basic knot-tying principles that improve knot and loop security have been identified. Reversing the direction of half hitches and switching the post limb between throws increase knot security by increasing friction and internal interference [6, 43]. Thus, a series of reversed half hitches on alternating posts is also the most secure configuration for non-sliding knots consisting of stacked half hitches [43]. Furthermore, the addition of three reversed half hitches on alternating posts has also been shown to maximize the knot security of most sliding knots [6, 43]. A recent study [44] investigated shortcuts for throwing three reversed half hitches on alternating posts by using three techniques: (1) rethreading (standard reference), (2) knot "flipping" (switching posts simply by alternating tension on the suture limbs) where half hitches were tensioned by past-pointing (the knot pusher is advanced beyond the knot stack, while the surgeon maintains tension on the post limb), and (3) knot "flipping" where half hitches were tensioned by alternating past-pointing and over-pointing (the knot pusher is advanced directly over the knot stack while maintaining tension on the post strand and pulling slack from the loop strand). The effect on a surgeon's knot and a Tennessee slider was evaluated. The authors showed that surgeon's knot outperforms Tennessee slider. Moreover, shortcut techniques do not alter the properties of surgeon's knots. However, when used to secure Tennessee slider knot, shortcuts lead to unacceptably high rates of knot slippage and decreased knot security.

18.3.3 Inter-Surgeon Variability and Ease of Tying

An increasing number of surgeons are performing arthroscopic surgery, sometimes without a specific training. Moreover, with the heightened popularity of arthroscopic surgery, the number of procedures requiring arthroscopic knots increased. Ease of knot placement in the surgical setting is important for efficiency and pliability of repair in general. Two important factors in arthroscopic knot tying are (1) the ability of the surgeon to learn and tie an arthroscopic knot and (2) the ability of the knot to resist displacement and failure. Thus, to the surgeon, consistent knot tying requires practice. Although several studies investigated biomechanical properties of different knots, only few studies have evaluated the ease of learning and tying knots [13, 45]. In 2007, Baumgarten et al. [13] asked 23 surgeons in training to grade ten arthroscopic knots (Duncan loop, Revo knot [27], Roeder knot, French knot, SMC knot, Tennessee slider, Nicky's knot, Field knot, Giant knot, and double-twist knot) with regard to ease of learning and tying using a 10-cm visual analog scale for No. 2 Ethibond and No. 1 polydioxanone (PDS) II suture. The study revealed that the Tennessee slider, Duncan loop, Revo knot, and Nicky's knot were the easiest for the surgeons in training to learn and use.

More recently, Hanypsiak et al. [45] asked 73 independent expert orthopedic arthroscopists with different level of experience to tie five of the same type of their preferred knots. Each knot was mechanically tested for ultimate load to failure and clinical failure. The authors reported substantial variation and inconsistencies in knot tying not only between knots tied by different surgeons but also between knots tied by the same surgeon on the same occasion, suggesting that knot security is affected not only by knot configuration but also is highly dependent on the individual surgeon. Interestingly, surgeons with less than 10 years in practice were able to tie knots more consistently than surgeons with more than 10 years of experience; and surgeons performing more than 200 arthroscopic shoulder cases annually failed to tie stronger or more consistent knots than their counterparts performing fewer cases. Finally, an Internet-based survey directed to the members of the American Orthopaedic Society for Sports Medicine (AOSSM) has been recently conducted to determine arthroscopic knot preferences [46]. Nine hundred thirty-seven members agreed to participate in the survey. The authors showed that, regardless of the results of biomechanical studies, the most common sliding knot used is the Duncan loop. Moreover, less than half of respondents used three reversed half hitches on alternating posts when using non-sliding knots, and only one third of respondents used three reversed half hitches on alternating posts to reinforce sliding knots.

Conclusions

Arthroscopic knot tying is an exciting aspect of arthroscopy that significantly expands the arthroscopist's abilities. Despite knot configuration, consistent knot tying requires practice. Several knots with different mechanical properties have been described in the literature, but the ideal knot has been not identified yet. Backing up the knots with three reversed half hitches on alternating posts ensures knot security and eliminates differences in initial loop security. Clinical experience shows that the ideal knot is probably the knot with which the surgeon feels more comfortable.

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