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Tırmanmanış Düğümü Güvenliğinin Değerlendirilmesi: Güvenliğe Öncelik Veren Üç Aşamalı Bir Protokol

Evaluating Climbing Knot Safety: A Three-Phase Testing Protocol Prioritizing Security

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Öz

Düğüm performansı, yapısal nüanslara ve bağlama malzemesinin özelliklerine bağlıdır. Kazalar tipik olarak hatalı düğümler, yanlış uygulamalar ve bağlama hatalarından kaynaklanan güvenlik sorunlarının sonucudur. Üç aşamalı bir değerlendirme protokolü önerilir. Faz I, topolojik büküm dalgalanmasını ve dolaşım enerjilerini matematiksel olarak modelleyerek bükülme ve döngü güvenliğini önceliklindedir. Çekme testleri, yapısal performansı değerlendirmek için yüzey pürüzlülüğü olmayan, düşük sürtünme katsayısı ve zayıf düğümlenebilirdik olan bağlama malzemesini kullanır. Olağandışı koşullar altında alabora olma potansiyelini belirlemek için düzensiz yükleme kullanılır. Düğüm fonksiyonuna bağlı olarak döngüsel yükleme testleri gerekebilir. Durdurucu düğümler ve aksamalar uygulamaya özel yöntemlerle değerlendirilmelidir. Çekme mukavemeti testleri asama I'i tamamlar ve düğüm verimliliği doğrudan ölçülemez olduğu için veriler bir olasılık yoğunluk fonksiyonu ile analiz edilmelidir. Faz II, işlevsellik ve kolaylık özelliklerine ayrılmıştır. Faz III, öğretme kolaylığı, öğrenme, hatırlama ve hata tespiti gibi davranışsal konuları değerlendirir.

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Abstract

Knot performance depends on structural nuances and the tying material's properties. Accidents are typically the result of security issues caused by faulty knots, improper applications and tying errors. A three-phase evaluation protocol is recommended. Phase I prioritizes bend and loop security by mathematically modelling topological twist fluctuation and circulation energies. Pull tests utilize tying material with no surface asperities, a low coefficient of friction and poor knottability to assess structural performance. Irregular loading is employed to determine capsizement potential under unusual conditions. Cyclic loading tests may be required depending on knot function. Stopper knots and hitches must be evaluated with application-specific methods. Tensile strength tests finish phase I, and data should be analysed with a probability density function because knot efficiency is directly immeasurable. Phase II is devoted to functionality and characteristics of convenience. Phase III evaluates behavioural issues such as ease of teaching, learning, recall and error detection.

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Geniş Özet

Bazen güvenlik düğümleri trajik sonuçlarla yanlış bağlanır veya kullanılır. Tüm kritik, önemli ve arzu edilen düğüm özelliklerini etkin bir şekilde değerlendiren ve geçerli ve güvenilir sonuçların çıkarılabileceği standartlaştırılmış bir test protokolüne ihtiyaç vardır. Tırmanma düğümlerinin değerlendirilmesi ve güvenli bir şekilde kullanılmasıyla ilgili çeşitli zorluklar vardır: farklı terminoloji, tutarsız test verileri, malzeme değişkenliği, kullanıcı anlaşmazlığı, devam eden düğüm değişiklikleri ve kararsız düğümler. Daha titiz bir değerlendirme prosedürü önerilmektedir. Operasyonel özellikleri ve kademe davranışının etkisini değerlendirirken güçten çok güvenliği vurgular.

Her kategori altında varyasyonları olan dört temel düğüm türü vardır: durdurucular, halkalar, kıvrımlar ve bağlantılar. Dört tip çeki demiri vardır: sabit, hareketli, yük aktarma ve halat çeki demirleri. Farklı düğüm türleri, uygulamaya özel test yöntemleri gerektirir. Bir düğümün güvenliğini ve gücünü birkaç yapısal özellik etkileyebilir: geçiş sayısı, kıvrımlı olması ve birleştirme. Düğüm atılabilir olması ve bir tekstilin sürtünme katsayısı düğüm güvenliğini etkiler. Ayrıca, bir ipin yapısı, yaşı ve durumu çalışma özelliklerini etkiler.

Düğüm Tanımlama ve Yapısal Nüans: Test düğümlerinin doğru bir şekilde tanımlanması, bağlanması ve belgelenmesi, herhangi bir araştırma için esastır. Düğüm tanımlamasını ve testini düzeltmek için gerekli olan birkaç ayrıntı vardır. Kiralite, ayna görüntüsüne sahip olma kalitesi, bir özelliktir. Çalışma uçlarının veya kancaların ve ayakta duran parçaların veya sehpaların göreceli konumları başka bir şeydir. Farklı düğümlü yapı, farklı performans özellikleri sergileyebilir.

Düğümler Nasıl Başarısız Olur: Düğüm hızlı tutar ve kaymazsa, yeterli kuvvet uygulandığında ip düğümden veya yakınında yırtılır. Düğümler, malzeme yırtılmasına neden olması beklenen herhangi bir şeyin çok altındaki yüklere maruz kaldığında gevsek çalışabilir ve çözülebilir. Düğüm güvenilirliğini değerlendirmek için en sık kullanılan yöntemler, çekme mukavemetini belirlemek için yavaş çekme testleri olmuştur. Bazı araştırma raporları kesin sayıları belgelemektedir. Bununla birlikte, düğüm verimliliği doğrudan ölçülemez. Kati bir yaklaşım olasılık yoğunluk fonksiyonu kullanılarak hesaplanmalı ve bir aralık olarak ifade edilmelidir. Modern sentetikler, çeşitli tırmanma amaçları için kesinlikle yeterince sağlamdır. Kaza raporlarına göre, düğüm arizaları, bağlama hatalarının veya çözülen kalitesiz düğümlerin yanlış uygulanmasının sonucudur. Bağlama malzemesine ve diğer faktörlere bağlı olarak, alabora, çevirme, uçma ve geri çekilme dahil olmak üzere, düğümlerin yanlışlıkla deforme olmasının ve kendiliğinden çözülmesinin birkaç yolu vardır. Bu nedenle, güvenlik daha fazla inceleme gerektiren bir önceliktir.

Operasyon ve kademe davranışı ile ilgili özellikler: Dağcılar, genellikle kritik güvenlik gerekliliklerinden daha fazla rahatlıkla ilgili olan bir dizi arzu edilen düğüm özelliğinden bahseder. Bunlar, çok yönlülük, öğretme ve öğrenme kolaylığı, etkili hatırlama ve bağlama, bağlama hatası şeffaflığı ve yüklendikten sonra çözme kolaylığını içerir ancak bunlarla sınırlı değildir. Düğüm özellikleri, güvenliğe dayalı önceliklere ve düğüm arizasının anlık sonuçlarına göre sıralanmalıdır. Güvenlik ve güç kritik öneme sahipken, operasyon ve kademe davranışıyla ilgili ikincil özellikler önemli veya arzu edilen olabilir.

Önerilen Değerlendirme Protokolü: Aşama I – Güvenlik ve Gücün Değerlendirilmesi: İlk aşama, matematiksel modelleme ve basit çekme testleri kullanarak bir düğümün göreceli güvenliğinin yaklaşık bir tahminini sağlar. Bunu, alabora ve diğer bozulma potansiyelini değerlendirmek için olağandışı yük konfigürasyon testleri takip eder. Döngüsel yükleme ve belki de atalet testi, belirli düğümlere getirilen pratik taleplere göre gerekli olabilir. Sonraki değerlendirmelere geçmeden önce birkaç güvenlik testinin sonuçları karşılaştırılmalıdır. Söz konusu düğüm temel güvenlik testinde başarısız olursa, pratik kullanım için düşünülmemelidir. Güvenlik yeterliyse, çekme kopma testleri yapılabilir ve veriler bir olasılık yoğunluk fonksiyonu kullanılarak değerlendirilebilir.

Aşama II – Operasyonel Özellikler: İkinci aşama, düğümü operasyonel özelliklerine göre değerlendirir. Hangi ikinci aşama testi yapılırsa yapılsın, düğümün güvenilir bir şekilde performans göstermesinin bekleneceği koşullara bağlı olarak kontrol edilmesi gereken tüm önemli ve arzu edilen özellikleri ele almalıdır.

Aşama III – Kademe Davranışı: Kademe davranışıyla ilişkili özellikler daha sonra üçüncü aşamada değerlendirilir. Hareket ve davranışsal ilkeller olarak adlandırılan bağlama eylemlerinin sayısı, düğüm karmaşıklığının ve hata potansiyelinin yaklaşık bir tahminini sağlayabilir. Öğretme ve öğrenme süresi, tutarlı öğretim yöntemleri ve farklı kademe deneyimleri dikkate alınarak ölçülebilir. Zaman içinde saklama ve hata sıklığı bu değerlendirmenin bir parçası olmalıdır.

Sonuç: Uygun düğüm değerlendirmeleri, bilişsel karmaşayı ortadan kaldırmalı ve doğrulama ve devam yanlılığını azaltmalıdır. Yargı araştırmaları, ilgili bilgileri değerlendirmek için iyi tasarlanmış

algoritmaların kullanılmasını önermekte ve burada açıklanan protokol bu gereksinimi karşılamaya çalışır. Belirli bir amaç için birkaç düğüm seçeneği uygun olabilir, ancak güçlü ve zayıf yönleri açıkça belirlenmeli ve sıralanmalı ve uygun uyarılar dikkate alınmalıdır. Sonuç olarak, iyi bilgilendirilmiş dağcı karar vermeli ve buna göre hareket etmelidir.

Introduction and Rationale

Knots are critical to the safety of mountaineers, rock climbers, ice climbers, canyoneers and cavers. Safety knots are utilized for anchoring, harness attachment, belaying, ascending, rescue and other fall-protection functions (ACMG & AMGA, 1999; Chisnall, 1985; Fusulo, 1996; Graydon, 1992; Luebben, 1993; Raleigh, 1998; Tyson & Loomis, 2006; Wheelock, 1967). Controversies persist and safety knots are often employed according to habit, tradition, bias and informal experimentation. Sometimes safety knots are tied or utilized incorrectly with tragic results (AAC, 1980; Child & Hill, 2002; Douglas, 2012; Jackson, 2012, 2016a, 2016b; Jackson & Whiteman, 2002; MacDonald, 2016, 2020a, 2020b, 2020c; Prohaska, 2005; Rock and Ice, 2010, 2012; Tuohy, 2005; Williamson, 2003; Yosemite Climbing Information, 2020). Therefore, there is a need for a standardized testing protocol, one that effectively evaluates all critical, important and desirable knot characteristics, and from which valid and reliable conclusions can be drawn. There are several challenges associated with effectively evaluating and safely utilizing climbing knots:

***Disparate Nomenclature* –** Mainstream knotting terminology varies, knot names are inconsistent and structural differences are subtle (Ashley, 1944; Budworth, 1983; Chisnall, 2016, 2024; Graumont & Hensel, 1952). Scholarly research literature presents disparate nomenclature as well (Johanns, et al., 2024; Sáez, et al., 2024; Sano, et al., 2022; Šimon et al., 2020; Šimon & Ftorek, 2022; Tong, et al., 2023; Tong, et al., 2024).

***Inconsistent Data* –** Research data do not agree and some test results may be unreliable and invalid (Baillie, no date; Birch, 2022; Evans, 2016; McKentley, 2014; Moyer, 1999; Pope, 1972; Powick, 2016; Prohaska; 2001; Sáez, et al., 2014; Šimon et al., 2020; Šimon & Ftorek, 2022; Warner, 1996).

***Material Variability* –** How knots behave under a variety of circumstances in different materials is not thoroughly understood (Birch, 2022; Šimon et al., 2020; Šimon & Ftorek, 2022; Warner, 1996).

***User Disagreement* –** Climbers do not agree about which knots are safe under specific circumstances and which are not (Brumbagh, 2013; Chisnall, 2006a, 2006b, 2020, 2021; Flashman, 2017; Gommers, 20132019; Jones, 2012; Kirkpatrick, 2011; Lottoman, 2018; Martin, 2009; Momsen, 2016; Prattley, 2016; Roy, 2012; Siacci, 2019).

***Knot Modifications* –** Historically, climbers have improvised, modified, enhanced and adapted knots to new applications (ACMG & AMGA, 1999; Chisnall, 1985; Forrest Mountaineering, 1974; Fusulo, 1996; Graydon, 1992, Luebben, 1993; Pegg, 2001; Prohaska, 198, 1995, 1996, 1998, 2005; Raleigh, 1998; Tyson & Loomis, 2006; Wheelock, 1967; Wright & Magowan, 1928).

***Unstable Knots* –** Certain knots in general use are inherently unstable and intolerant of some situational demands. Occasionally they fail (AAC, 1980; Douglas, 2012; Jackson, 2012, 2016a, 2016b; Jackson & Whiteman, 2002; MacDonald, 2016, 2020a, 2020b, 2020c; Prohaska, 2005; Rock and Ice, 2010, 2012; Tuohy, 2005; Williamson, 2003; Yosemite Climbing Information, 2020).

Figure 1. Examples of common climbing knots, from top to bottom: Figure Eight Stopper Knot, Figure Eight Loop, Bowline, Flemish Bend, Double Fisherman's Knot, Clove Hitch, Munter Hitch, Prusik Knot. (These commonplace knots have multiple names, variations and enhancements for added security).

These problems suggest that a carefu evaluation of mainstream and innovative knots could be beneficial to climbers. The purpose here is to propose a more rigorous and focussed testing protocol, a general procedure that emphasizes security over strength while assessing operational characteristics and the influence of tier behaviour.

Foundations

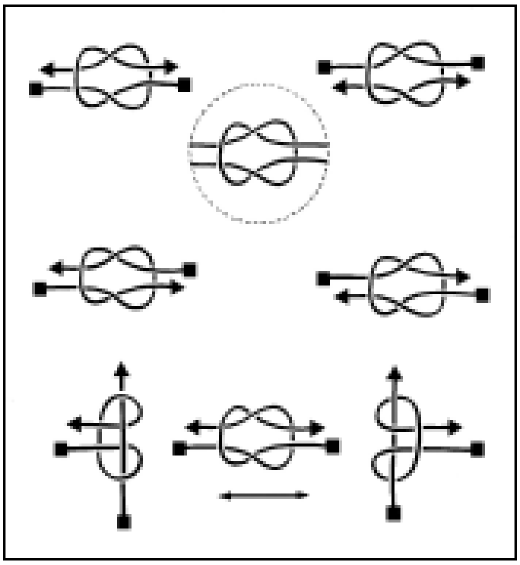
There are four basic types of knots with variations under each category: stoppers, loops, bends and hitches (ACMG & AMGA, 1999; Ashley, 1944; Chisnall, 1985; Fusulo, 1996; Graydon, 1992; Graumont & Hensel, 1952; Luebben, 1993; Raleigh, 1998; Tyson & Loomis, 2006; Wheelock, 1967). Some common climbing knots are presented as examples in Figure 1. Many other esoteric knots and alternatives have been devised and used by climbers. A stopper knot is any tangled mass in a strand of rope that will not fall apart. It has no loops and is unconnected. The Figure Eight Knot, for example, prevents the end or ends of the rope from slipping out of a belay or rappel device when there is insufficient slack. The omission of stopper knots has resulted in ground falls (MacDonald, 2018a, 2018b, 2020a, 2020b). Loop knots comprise single or multiple loops or bights. The Figure Eight Loop, Bowline and Bowline variants have served as harness and anchor connectors, and their use has been a topic of disagreement amongst climbers (Brumbagh, 2013; Chisnall, 2006, 2021, Flashman, 2017; Gomers, 3013, Kirkpatrick, 2011; Roy, 2012). A bend is a knot employed to join two ends of rope or cord, like the Double Fisherman's Knot and the Flemish or Figure Eight Bend for joining accessory cord ends to create cordelettes, and the Overhand Side Bend for joining rappel lines, another controversial knot Moyer, 1999; Powick, 2016; Chisnall, 2020; Gommers, 48; Jones, 2012; Martin, 2009; Momsen, 2016; Prattley, 2016; Siacci, 2019). A hitch is a knot employed to attach a rope to an anchor, and it will usually fall apart when removed from its attachment point. There are four types of hitches: fixed, movable, load-transfer and rope hitches. Examples include the Clove Hitch for anchoring (fixed) and the Munter Hitch for belaying (movable). Rope hitches are used to secure a bight of cord to a thicker main line and they can be intentionally moved along the main line but they grip when loaded. The Prusik Knot or Hitch is one example. Loadtransfer hitches – like the Munter Mule (Figure 2) – are used for improvised rescue purposes and typically incorporate a slip knot that facilitates the released of a loaded rope hitch. Different types of knots require applicationspecific testing methods, more than can be thoroughly outlined in a few pages. Therefore, the focus here will be bends and loops tied in rope or cord. Stopper knots, fixed hitches and rope hitches will be discussed briefly. Several structural characteristics can affect a knot's security and strength (Warner, 1996; Chisnall, 2020). The number of times a rope crosses itself in a simplified two-dimensional planar projection is an indicator of complexity (Adams, 2001). Sinuosity – known as ropelength in topology and spelled as one word (Buck & Simon, 1999) – is the length of rope contained within the knot proper. It increases with knot complexity and entanglement. Concatenation, the qualitative nature of a knot's structural nuances, also influences its behaviour and stability. For example, Bowlines are post-bight loop knots because tying takes place after the working end has been inserted through a

Figure 2. The Munter Mule, consisting of a Prusik Knot on the main line and a Munter Hitch secured with an Overhand Slip Knot and a backup knot. The slack loops are linked for additional security.

harness or passed around an anchor point. The Figure Eight Loop, in contrast, is a pre-bight loop knot because tying occurs before as well as after the working end is linked to an anchor or harness (Chisnall, 2021; Gommers, 2019).
The tying material's braided structure influences knot safety. Along with its knottability, a textile's coefficient of friction affects knot security. Further, a rope's age and condition influence its working properties (Warner, 1996). Kernmantel ropes have relatively uniform cores and sheaths, although Union Internationale des Associations d'Alpinisme (UIAA) standards allow for a 0.2 millimetre variation in new climbing rope diameters. Surface texture or asperities (a term used in the medical literature) can influence knot security (Abdessalem, 2009; Datta, et al., 2019). Considerable surgical knot testing has been performed, and the results are suggestive of climbing knot performance (Abdessalam, 2009; Avoine, et al., 2016; Hanypsiak, et al., 2014; Burkhart, et al., 2000; Lee, et. al, 2019; Livermore, et al., 2010; Lo, et al., 2010; Rana, et al., 2012; Thacker, et al., 1977; Wong & McGrouther, 2023). Tier behaviour is another critical determinant. Knot complexity, asymmetry and situational factors can impact the teaching, learning, recall and tying of particular knots and may increase the probability of tying errors (Craik, 2014; Cross, et al., 2017; Jenkins & Matariæ, 2002; Michel & Harkins, 1985). User judgment, habits and attitude are similarly affected

Knot Identification and Structural Nuance

Accurately identifying, tying and documenting test knots is fundamental to any research. This is vital because it is easy to make subtle structural errors, as made evident in some published illustrations (Bayman, 1977; Ewing, 1973). Accurate images must accompany any test reports so other investigators can precisely replicate that research. Credible mainstream references may assist in proper structural identification. Numerous sources are required for verification (ACMG & AMGA, 1999; Ashley, 1944; Chisnall, 1985; Fusulo, 1996; Graumont & Hensel, 1952; Graydon, 1992; Luebben, 1993; Raleigh, 1998; Tyson & Loomis, 2006; Wheelock, 1967).



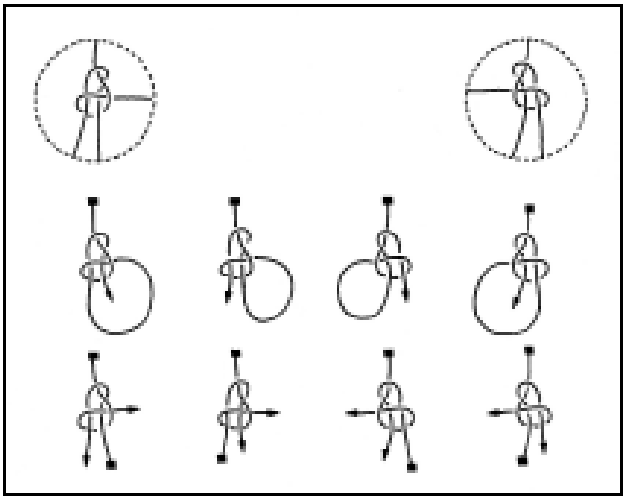


Figure 3(left). Structural variance, chirality, capsizement and flipping, from top to bottom: Z/S Reef Knot (left) and mirrorimage S/Z Reef Knot (right); isolated Conway tangle without wends and stands and six planar crossings; insecure Tumbling Thief Knots that are equivalent with a z-axis rotational transformation; Reef Knot (centre) can capsize to form Two Reversed Half Hitches (left and right) which can flip back and forth, (There are not proper climbing knots.)

Figure 4(right). Structural variance, from top to bottom: d (left) and b (right) Conway tangles, d Bowlines (Standard and Ring versions, left) and b Bowlines (Ring and Standard versions, right), analogous Sheet Bends.

There are several details essential to correct knot identification and testing. Chirality, the quality of having a mirror image, is one characteristic (Figures 3 and 4) (Chisnall, 2010, 2016). The relative positions of working ends or wends and standing parts or stands is another. This is related to what van de Griend (1992) calls algorithmical, structural and applicational proximities. Bends and loops may appear to have the same essential structure, but a knot's function and manner of loading can alter its behaviour. Many knots have identical planar Conway tangles, which are knotted structures in isolation (Adams, 2001). However, joining wends and stands converts bends to loop knots, and vice versa when loops are disconnected (Chisnall, 2020). Switching wends and stands produces direct, oblique and indirect bends, each exhibiting different performance characteristics (Figures 3-5) (Shaw, 1933).

Figure 5. Chirality, flyping and structural variants, from top to bottom: Z (left) and S (right) mirror-image Figure Eight Knot enantiomers; the Figure Eight Knot can flype back and forth to form a Pretzl Knot; how a planar projection of a Figure Eight knot appears with the minimum 16 crossing (Reidemeister simplification); a dressed Figure Eight Loop as it would appear in three dimensions with 20 crossings; two versions of a Figure Eight End Loop or Follow-Through (note wend positions); two versions of the Flemish Bend (note wend positions); Figure Eight Side Bend (note wend positions) which can flype towards the wends.

How Knots Fail

There are two ways in which knots can fail. First, if the knot holds fast and does not slip, the rope will rupture (called material fracture) at or near the knot when enough force is applied (Ashley, 1944; Bayman, 1977; Birch, 2022; Patil, et al., 2020; Richards, 2005; Maddocks & Keller, 1987; Pieranski, et al., 2001; Tong, et al., 2024; Warner, 1996). Second, and this is a key safety concern, knots can work loose and become untied while subjected to loads well below anything expected to cause material rupture. This is called topological failure by some researchers (Tong, et al., 2024). The most frequently employed methods of evaluating knot reliability have been slowpull tests to determine tensile strength (Ashley, 1944; Baillie, no date; Evans, 2016; McKentley, 2014; Moyer, 1999; Pope, 1972; Powick, 2016; Prohaska, 2001; Sáez et al., 2024; Wheelock, 1967) (Figure 6). This has been the default procedure when evaluating surgical knots, as well as fishing and climbing knots (Abdessalam, 2009; Avoine et al., 2016; Hanypsiak et al., 2014; Burkhart et al., 2000; Lee, et al., 2019; Livermore et al., 2010; Lo, et al., 2010; Rana et al., 2012; Sáez, et al., 2024; Thacker, et al., 1977; Tong, et al. 2024; Warner, 1996; Wong & McGrouther, 2023). Both formal research and grassroots testing results have been published or posted on line. Knot failure occurs at some fraction of the rope's unknotted strength. Absolute knot strength, expressed in units of force, is fundamentally a function of the tensile breaking strength of the knotted rope, cord or webbing (tape). A knot's strength also can be presented as a percentage of the unknotted material's failure load, which is called knot efficiency or residual strength.

Some research reports document exact numbers. However, knot efficiency is directly immeasurable (Šimon et al., 2020; Šimon & Ftorek, 2022). As a random variable it should be calculated using a solid approximation probability density function because multiple measurements of the tensile breaking strength of the unknotted material will vary, as will the breaking strength of any knot ruptured multiple times. Both should be expressed as ranges based on appropriate confidence intervals. Importantly, test data do not necessarily offer generalizable inferences. Many factors cause variability: the structure and chemical makeup of the knotted material, its age and condition, whether it is wet or dry, a knot's specific structure and dressing, pretest loading, and the speed of load application for example (Bigon & Regazzoni, 1981; Evans, 2016; Microys, 1977; Warner, 1996). Modern synthetics such as nylon 66, nylon 6 (perlon®), Kevlar®, High Modulus Polyethylene (HMPE)/Dyneema®, Spectra® and Vectran™ are certainly robust enough for various climbing purposes (Horrocks & Anand, 2016; ISO Standard,

Figure 6. A typical setup for testing the tensile breaking strength of a knot, in this case a Figure Eight Loop. Photo credit: M. Goulet, courtesy Petzl® America.

2019; Microys, 1977; Rana & Fangueiro, 2018; Warner, 1996). However, some materials have low glass transition temperatures and melting points. Many knot tiers assume knots, primarily bends, roughly halve the absolute breaking strength of the tying material (Warner, 1996; Bigon & Regazzoni, 1981). Of course the knotted material must meet the minimum safety factor requirement for a particular knot application, whether it is 3:1, 5:1 or 10:1. Other properties such as knot elasticity also may be important (Audoly, et al., 2007; Martin et al., 2015; Sry, et al., 2018; Warner, 1996; Weller, et al., 2015). Further, according to accident reports, knot failures are the result of tying errors or the misapplication of inferior knots that become untied (AAC, 1980; Brambagh, 2013; Child & Hill, 2002; Chisnall, 2006a, 2006b, 2020, 2021; Douglas, 2012; Jackson, 2012, 2016a, 2016b; Jackson & Whiteman, 2002; MacDonald, 2016, 2020a, 2020b, 2020c; Prohaska, 2005; Rock and Ice, 2010, 2012; Tuohy, 2005; Williamson, 2003; Yosemite Climbing Information, 2020). Hence, security is a priority requiring greater scrutiny.

There are several ways knots can accidentally distort and spontaneously untie, including capsizement, flipping, flyping and reptation (Figures 3, 7-10) (Budworth, 1983; Warner, 1996; Chisnall, 2020; Hage, 2007; Bao, et al., 2003, Moyer). A Reef Knot is not an acceptable safety knot but it affords a simple illustration of two kinds of distortion. It can capsize to form Two Reversed Half Hitches. Two Reversed Half Hitches can flip to the opposite side if the relaxed wend and stand are pulled taut while the other wend and stand are loosened (Figure 3). Flyping is an old Scottish term adapted to surgical knots that essentially turn inside out. An example of this phenomenon is the Figure Eight Knot flyping to form a Pretzel Knot (Figures 5 and 7). Reptating, a term adopted from molecular biology, is the action of a knot as it moves without changing shape or structure (Bao et al., 2003; Chisnall, 2020). The example shown in Figure 10 is the Overhand Side Bend, which has multiple names. If this bend is throughloaded as illustrated, it has a tendency to move or reptate toward the wends, depending on the tying material and other factors.

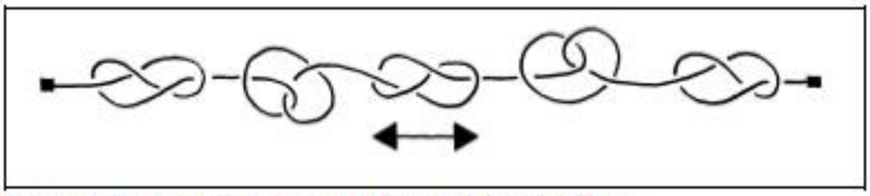


Figure 7. Flyping between a Figure Eight Knot and a Pretzel Knot.

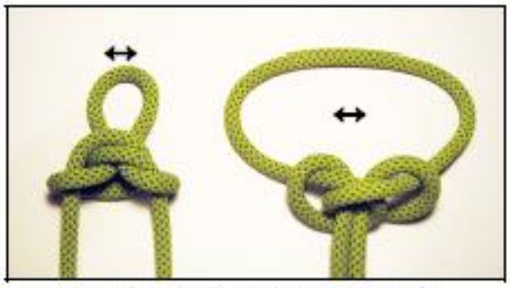


Figure 8. Left: a ring-loaded Alpine Butterfly. Right: an Inverted Alpine Butterfly after ring loading causes it to capsize and flype; it will not flype any further.

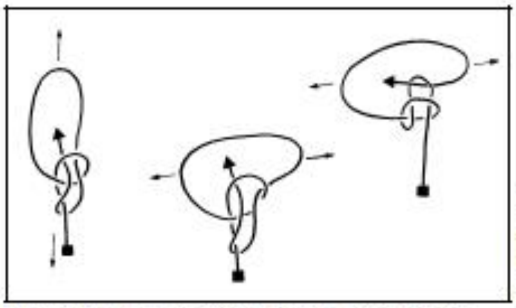


Figure 9. Left: properly loaded Bowline. Middle: ring loaded Bowline. Right: ring loading causing Bowline to capsize into a Running Slip Knot.

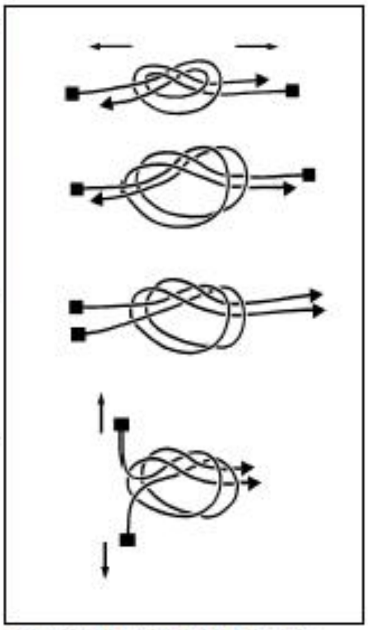


Figure 10. From top to bottom: planar projection of Water Knot with Reidemeister simplification and 12 crossing points; Water Knot dressed in with 15 crossings; Overhand Side Bend; Overhand Side Bend through-loaded, which may cause reptation toward the wends.

A knot can become insecure via one or a combination of these actions. In order to test knot security properly, the knot should be subjected to every load condition it is expected to satisfy in real-world practice as well as any extraordinary circumstances that might be revealed through accident reporting.

Characteristics Related to Operation and Tier Behaviour

Climbers cite a number of desirable knot characteristics that are often related to convenience more than critical safety requirements (ACMG & AMGA, 1999; Baillie, no date; Chisnall, 1985, 2006a, 2020a; Fusulo, 1996; Gomers, 2013, 2019; Graydon, 1992; Luebben, 1993; Momsen, 2016; Moyer, 1999; Raleigh, 1998; Siacci, 2019; Tyson & Loomis, 2006; Wheelock, 1967). These include but are not restricted to versatility, ease of teaching and learning, effective recall and tying, tying error transparency, and ease of untying after being loaded. Other characteristics of interest may include energy absorption capability under impact loads and how knot strength is reduced in dynamic situations, and the knot's contact footprint if abrasion and jamming are concerns when joining rappel lines (Gomers, 2019; Martin, et al., 2015). Further, research indicates that situational perception is inadequate when judging knot strength and security (Croom & Firestone, 2022). Knot characteristics should be ranked according to safety-based priorities and the immediate consequences of knot failure. Security and strength are critical whereas secondary characteristics related to operation and tier behaviour may be important or desirable.

Proposed Evaluation Protocol

Drawing on the work of multiple researchers, three test phases are proposed affording a more complete assessment of a knot's overall efficacy in terms of application security, strength and other features. (See Table 1.) The purpose is to acquire sufficient reliable information to facilitate unbiased knot comparisons. The main focus is phase I security testing, which will be described next. Subsequently, phase II and III procedures will be briefly outlined.

Phase I	Critical Properties: Security Strength	Model mathematically. Perform security tests. Perform tensile breaking tests
Phase II	Important & Desirable Properties: Operational Characteristics	Inventory ideal characteristics. Rank characteristics specific to tasks. Evaluate characteristics accordingly.
Phase III	Behavioural Considerations: Learning, Recall, Inspection	Analyse structural complexity. Time tying tasks and tabulate errors. Repeat tests later.

Table 1. Basic outline of a three-phase testing protocol. Phase I is critical.

Phase I – Evaluating Security and Strength

The initial phase provides an approximation of a knot's relative security using mathematical modelling and simple pull tests. This is followed by unusual load configuration tests to assess the potential for capsizement and other distortions. Cyclic loading and perhaps inertial testing might be necessary according to the practical demands placed on certain knots (Moyer, 1999; Daily-Diamond, et al., 2017). The results of several security tests should be compared before moving ahead with subsequent assessments. If the knot in question fails basic security testing, it should not be considered for practical use. If security is adequate, tensile breaking tests can be performed and the data evaluated using a probability density function, as discussed previously. A short description of three phase I procedures follows.

Stopper Knots

Stopper nots, such at the Overhand Knot, Figure Eight Knot and Double Overhand Knots, are used by climbers to prevent the ends of ropes from pulling through belay/rappel devices (Figure 11). Their main requirement is to resist untying when jammed against a rigid barrier. Higher versions of the Overhand Knot can tighten and exhibit inversion and snap bucking (Figure 12) (Tong, et al., 2023). A Figure Eight stopper knot can undergo flyping when subjected to what researchers call friction-induced twisting as it presses against a restraining plate such as a rappel or belay device (Johanns & Reis, 2024). Each stopper knot has a different crossing number and sinuosity, and each knot's resistance to becoming untied varies. This is not often examined as a safety priority. Stopper knot safety can be evaluated theoretically and practically using established research methods, as follows.

Theoretical Analysis - Discrete elastic rod models and finite element methods (FEM) are possible ways of mathematically assessing stopper knot stability (Johanns & Reis, 2024; Tong, et al., 2023; Tong, et al., 2024). The former is a geometric computational method for simulating thin, flexible entities (Kirchhoff elastic rods) using a discrete chain of nodes connected by edges to represent curvature, and which can describe bending and twisting behaviour. The latter may be utilized to demonstrate how a material or component reacts to specific external influences by dividng the whole into a finite number of connected elements.

Figure 11. Stopper knots abutting against belay devices, preventing the belay line from slipping free. Left: Double Overhand Knot. Right: Figure Eight Knot.

Practical Analysis – There are several approaches to testing stopper knot integrity. For example, mechanical tests performed by Johanns and Reis (2024) required the fabrication of composite rods by casting vinyl polsiloxane with a thin Nitinol wire embedded inside to prevent global stretching. Further, the surfaces of the knotted material were covered in talcum powder to ensure Amonton- Coulomb frictional behaviour with low static and dynamic coefficients of friction. This method is somewhat analogous to M.A.R.K. testing, which will be described shortly. A direct approach is to examine how a stopper knot tied in climbing rope behaves as it pushes against a belay device or resistance plate while force is increased (Figure 11). In tests of this kind, Figure Eight stopper knots tend to flype toward their wends, as shown previously in Figures 5 and 7 (Johanns & Reis, 2024). Inversion and snap buckling occurs when Double, Triple and higher versions of the Overhand Knot are loaded (Tong, et al., 2023). (See Figure 11.) Friction and elastic stiffness are important test material variables when testing stoppers and other knots, and the sliding, stretching and deformation of rope within a knot can be observed (Tong, et al., 2023).

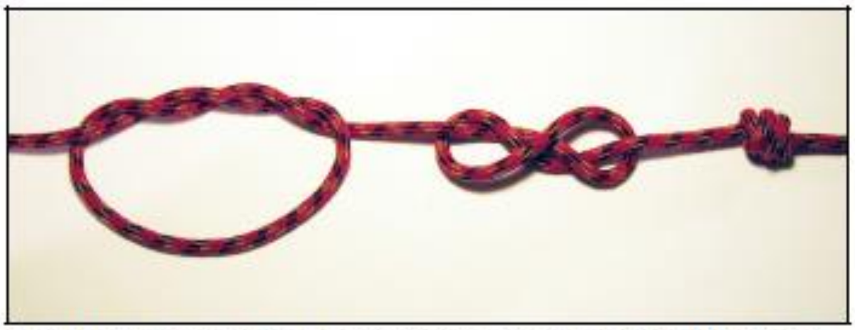


Figure 12. Left: Double Overhand Knot before being tightened. Middle: Double Overhand Knot inverting as it tightens. Right: Double Overhand Knot snap-buckled to its taut configuration.

Loops and Bends

Counting Numbers – Any attempt to mathematically model knot behaviour is, at best, an approximation. Modelling must be used in conjunction with other modes of testing and assessment. As presented by Patil et al., the counting numbers N (crossing number), ô (topological twist fluctuation energy, which is calculated using writhe) and Ã (topological circulation energy) rationalize knot stability for bends or 2-tangles utilizing oriented planar projections of knots (Patl et al., 2020). Higher values indicate greater stability and possibly strength.

There are several details to note about applying this model. First, the knot being evaluated is usually simplified as a planar projection with the minimum number of crossing points. In three dimensions, however, it may have additional crossing points, which must be factored into the calculations using an accurate planar projection Chisnall, 2020a, 2020b). (See Figures 5 and 10.) Second, this method works for bends. Mathematical modification is required to accommodate loop knots. Third, a higher sum of topological twist fluctuation and circulation energies suggests better security. However, the relationship between total energies and the crossing number is not straightforward. An informative algebraic amalgamation of the three counting numbers would be beneficial.

Minimal Allowable Resistance and Knottability (M.A.R.K.)Test – The aim of this practical procedure is to quickly evaluate a knot's underlying structural stability by minimizing the influence of rope properties that mask fundamental knot behaviour. Sheath bunching should be eliminated and cross-sectional deformation minimized. The test material must be solid and, most important, devoid of surface asperities, such as braiding texture, and it should possess a low static coefficient of friction – 0,22 or lower (the figure given for polypropylene). Further, using the European Standard EN 892 test standard (1996) for modern climbing ropes as a guide, the material should be relatively stiff, having a knottability index greater than 1,2. Test knots are then loaded manually. If a knot slips, it should be immediately rejected. Monofilament fishing line and suturing material are suitable, since no larger monofilament materials may be readily available. The main impediment with these materials is their thin diameters, making tying difficult. A dissecting microscope is required to check knot correctness and dressing before any pull test.

Load Irregularity Test – Assessing a knot's susceptibility to capsizement, flipping, flyping and reptation reveals how secure it may or may not be during unusual operating conditions. To accomplish this, a CE/UIAA-certified single climbing rope can be loaded to at least 160 kg. in various configurations. That is twice the weight of a standard UIAA drop-test mass, and doubling the mass adheres to Wexler's calculation for initial static loading (European Standard EN 892, 1997; Wexler, 1950). Test knots should be dressed beforehand and set with an initial 10 kg. load, once again following the EN 892 standard. One example of load irregularity testing is ring-loading of loop knots. Harnessing and anchoring loop knots can be ring-loaded at right angles to the usual force vector in order to evaluate their propensity for capsizement (Figures 8 and 9). Direct, oblique and indirect variants of bends can be loaded to learn if capsizement, reptation or flipping can be induced. (See Figures 3 to 5 and 10.) If the knot unties completely, it fails. If it distorts to form a less secure structure, higher force should be applied to determine if it will fail completely and the number of distinct changes should be noted.

Hitches

Theoretical Analysis – Fixed hitches can be assessed mathematically using methods devised by Bayman (1977), and Maddocks and Keller (1987). These models analyse planar tension equilibria and geodesic crossing-point friction. Bayman's model is a summation of the friction afforded at each crossing or contact point using the Euler-Eytelwein Capstan formula. Maddocks and Keller's model is more involved and requires mathematical constructions for each new knot examined. More realistic comparative calculations would require the input of rope and carabiner diameters, in addition to the static coefficients of friction for different synthetics and aluminum or steel. Rope hitches grip main lines via compression and camming action, and they can be analysed mathematically as well. Plummer (1973) examined the gripping ability of specific rope hitches employed to ascend fixed lines in caving applications. He utilized contact vectors and load angles to assesses how snugly a rope hitch is knotted around a main line, an indication of its gripping ability. The calculations are specific to hitch structure.

Practical Analysis – Another approach is to perform multiple slow-pull tests to determine a rope hitch's holding capacity before it slips, which can be surprisingly low if the hitch is tied too loosely as predicted by Plummer's analysis. To be thorough, the rope hitch should be tested first with the main line slack to permit camming and compression, and then the main line should be loaded with an 80 kg. mass in order impede the compression and camming of the main line. Some users prefer rope hitches that release easily while loaded – usually looser constructions – and, not surprisingly, those hitches typically yield at lower loads (Moyer, et al., 2000). This demonstrates the need to prioritize knot characteristics. Which is more important: holding capacity (critical security) or ease of release (an important or desirable operational characteristic)?

Phase II – Operational Characteristics

The second phase evaluates the knot according to its operational characteristics, a sample of which were mentioned previously. There are others specific to knot applications. For example, drop tests can assess energy absorption as knots tighten and the rope stretches (Auduloy, et al., 2007; Sry, et al., 2018; Weller, et al., 2015; Martin, et al., 2015; European Standard EN 892, 1996). Evaluating a knot's resistance and tendency to jam when dragged over rough surfaces is another possibility (Chisnall 2020a; Gommers, 2013). Whatever second-phase testing is undertaken, it should address all important and desirable characteristics that must be checked based on the conditions under which the knot will be expected to perform reliably. (See Table 2.)

By their qualitative nature, some characteristics require a subjective assessment and the evaluator must be aware of his or her biases and experiences during that process. Other characteristics require some sort of formal assessment that yields valid and reliable data for comparison. Relevant experimental design is essential.

General Knot Types	Common Functions
Stoppers	Belay Line Security, Rappel Line Security, Backup Knots
Bends	Cordelettes, Joining Ropes, Reepschnur Stoppers
Loops	Anchoring, Harness Attachment
Fixed Hitches	Anchoring, Personal Anchoring System
Movable Hitches	Emergency Belaying, Improvised Rappelling, Rescue Lowers
Rope Hitches	Ascending, Rappel Backup, Hauling
Release Hitches	Load Transfers, Partner Rescue

Table 2. General knot functions. Phase II testing should take into account operational demands when evaluating knot performance and safety.

List and Rank Characteristics – A complete list of operational characteristics is needed at the outset and the ranking of those characteristics requires careful thought in addition to relevant testing. Dividing functions into critical, important and desirable categories is the first step, and certainly climbers will disagree on rankings within each category. The argument herein is that the critical characteristics – security and strength – have already been dealt with in phase I. Again, the most important governing principle the immediate consequences of knot failure relative to poor functionality. A knot might be secure and strong (critical) but hard to untie after being loaded (important or desirable). In contrast, another knot utilized for the same purpose might be easy to untie after loading but less secure. If a knot joining two rappel lines unties, the consequences are instantaneous and catastrophic. If the same knot holds but tends to get jammed more often than others, the consequences are not immediate but they could lead to entrapment and a climbing party could get benighted on a long climb. This would be an important consideration. If the secure knot does not get jammed but tends to drag over rock grudgingly during rope retrieval, that is less important. Low drag might be regarded as a desirable operational characteristic. Making these distinctions in practice is not clear cut and can be a function of user bias.

Phase III – Tier Behaviour

Characteristics associated with tier behaviour are then evaluated in the third phase. The number of tying actions – called movement and behavioural primitives (Jenkins & Matariæ, 2002) – can provide an approximation of knot complexity and the potential for error. Teaching and learning time can be measured, taking into account consistent instructional methods and disparate tier experience. Retention over time and error frequency should be a part of this appraisal.

Complexity and Behavioural Primitives – A simple method of assessing knot complexity is to determine its crossing number when it is depicted as planar projection. There are several challenges with this approach. First, how are the crossings counted? As illustrated in Figure 10, the Water Knot has a minimum of 12crossing points when simplified using Reidemeister moves. Its dressed, three-dimensional counterpart has 15 crossing points when represented as a planar projection. (Of course Water Knots are usually tied in webbing (tape).) Second, the number of crossing points does not necessarily indicate the number of steps or behavioural primitives required to complete a knot. For example, a Figure Eight Loop can be tied in the bight or it can be retraced as a harness tie-in. When equally dressed in three dimensions, both knots have the same planar crossing number, namely 20. (The simplified planar projection has 16 crossings. See Figure 5.) However, their tying methods are different. The actions required determine tying complexity. Tying the Figure Eight Loop in the bight takes four steps, depending how each behavioural primitive is identified: 1. Fold the rope to make a Closed Loop or bight; 2. Cross the Loop over the standing parts to form a Crossing Loop; 3. Wrap the loop around the standing parts; 4. Tuck the bight up through the Crossing Loop. Different tiers might identify three, four or five movement primitives, so a range evaluation would be appropriate. In comparison, retracing a Figure Eight Knot when connecting the harness to the end of a rope will entail three to five movements (the initial Figure Eight Knot), and retracing the wend takes four more steps, more or less. Therefore, based on tying complexity, retracing the Figure Eight requires seven to nine movement primitives. Does a crossing count as one behavioural primitive, or does a crossing and wrap count as one? For knot comparison purposes, of course, behavioural primitives would have to be precisely defined to avoid ambiguity.

Learning, Recall and Error – Evaluating learning and recall depends on several variables, which are open to interpretation. Straightforward behavioural metrics can include tying time and number of errors. Data from multiple test subjects would be required to get a reasonable average and range. However, a tier's experience and background would affect the outcome. One approach might be to recruit 10 experienced and 10 inexperienced volunteers. (Experienced climbers would bring to this evaluation the skills and biases they've developed through practice and repetition.) An inexperienced subject should provide a behavioural tabula rasa. Ideally, an instructor using a standardized teaching method would demonstrate the tying of a knot that is unfamiliar to all test subjects. Three identical demonstrations could be the experimental standard. Then each subject would attempt to tie the newly-learned knot, the duration of the task would be timed and the number of attempts and errors would be counted. The subjects could then be tested in the same way one week later, without any review, to assess their recall. Most climbing knots are well established and known, some of which have applications in other pursuits. To evaluate the tying complexity of commonplace climbing knots, rank beginners would have to be taught and tested to determine the potential for tying error. Other evaluation strategies are feasible, but the same method would have to be applied uniformly to the set of knots being compared.

Conclusions

The main thrust of this briefly outlined test protocol is the evaluation of knot security, followed by tensile breaking strength tests. Operational characteristics and behavioural concerns should be tested as well for a complete assessment of overall knot safety and functionality. The proposed protocol requires numerous steps within three phases for a complete assessment. The time invested would provide a more reliable and informative set of conclusions for knot comparison that prioritizes critical characteristics. This protocol may be applicable to other pursuits and professions that rely on knots, including rescue operations, rope access and work at height, marine applications and surgery.
continuation bias (Kahneman, et al., 2021). Research into judgment recommends that welldesigned algorithms be employed to assess relevant information, and the protocol described herein attempts to meet that requirement. Several knot options might be suitable for a particular purpose, but their strengths and weaknesses must be clearly determined and ranked, and appropriate caveats considered. Ultimately, the well-informed climber must decide and act accordingly (Chamarro & Fernandez-Castro, 2009; Kahneman, et al., 2012; Little, 1980; Muchnik, et al., 2013; Udall, 1987; Wilde, 1988).

References

Abdessalem, S.B., Debbabi, .F, Jedda, H., Elmarzougui, S., Mokhtar, S., et al. (2009). Tensile and knot performance of polyester braided sutures. Textile Research Journal 79(3):247- 252. https://doi.org/10.1177/0040517508094090.

Adams, C.C, (2001). The knot book: An elementary introduction to the mathematical theory of knots. Providence, Rhode Island: American Mathematical Society. American Alpine Club (AAC) (1980). Fall on rock, failure of knot. In: AAC, Accidents in North American Mountaineering 4, 3(33):34.

Ashley, C.W. (1944). The Ashley book of knots. New York: Doubleday & Company Inc. Association of Canadian Mountain Guides (ACMG), & American Mountain Guides Association AMGA) (1999). Technical handbook for mountain guides: Alpine, rock, and ski guiding techniques. Golden, Colorado: AMGA; Canmore, Alberta: ACMG.

Audoly, B., Clauvelin, N., & Neukirch, S. (2007). Elastic knots. Physical Review Letters 99(16), 164301. https://doi.org/10.1103/PhysRevLett.99.164301.

Avoine, X., Lussier B., Brailovski, V., Inaekyan, K., & Beauchamp, G. (2016). Evaluation of the effect of 4 types of knots on the mechanical properties of 4 types of suture material used in animal practice. Can J Vet Res 80(2):162-170. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4836043/.

Baillie, R. (No date provided). The side figure eight knot for rappelling. Explore Magazine Technical Series No 2.

Bao, X.R., Lee, H.J., & Quake, S.R. (2003). Behavior of complex knots in single DNA molecules. Physical Review Letters 91(26 Pt 1):265506. https://doi.org/10.1103/PhysRevLett.91.265506.

Bayman, B.F. (1977). Theory of hitches. American Journal of Physics 45(2):185-90. https://doi.org/10.1119/1.10652.

Bigon, M, & Regazzoni, G. (1981). The morrow guide to knots. New York: Quill/William Morrow.

Birch, R.G. (2022). Predicting and measuring knot strength and security. Practical Knot Theory (v 1.4). https://scithings.id.au/Practical_Knot_Theory.pdf. Accessed 29 December 2024.

Brumbagh, C. (2013, edited 2018). How safe is the bowline knot in different situations? The Great Outdoors. https://outdoors.stackexchange.com/questions/3798/how-safe-is-the-bowline-knot-in-different-situations. Accessed 8 July 2020.

Buck, G. & Simon, J. (1999). Thickness and crossing number of knots. Topology and its Applications, 91(3):245-257. https://doi:10.1016/S0166-8641(97)00211-3.

Budworth, G. (1983). The knot book. Kingswood, Surrey, United Kingdom: Elliot Right Way Books.

Burkhart, S.S., Wirth, M.A., Simonich, M., Salem, D., Lancelot, D., & Athanasiou, K. (2000). Knot security in simple sliding knots and its relationship to rotator cuff repair: How secure must the knot be?

Arthroscopy: The Journal of Arthroscopic & Related Surgery 16(2):202-207. https://doi.org/10.1016/s0749-8063(00)90037-9.
Chamarro, A., & Fernández-Castro, J. (2009). The perception of causes of accidents in mountain sports: A study based on the experiences of victims. Accident Analysis & Prevention, 41(1):197-201. https://doi.org/10.1016/j.aap.2008.10.012.
Chisnall, R., Ed. (1985). The ORCA rock climbing safety manual, 2nd edition. Toronto, Ontario: Ontario Rock Climbing Association & The Ministry of Tourism and Recreation.
Chisnall, R. (2006a). The security of bowlines and figure eight loops as harness tie-ins: The principles of pre-knotting, post-knotting and concatenation, Part 1. Knotting Matters 90:14-20.
Chisnall, R. (2006b). The security of bowlines and figure eight loops as harness tie-ins: The principles of pre-knotting, post-knotting and concatenation, Part 2. Knotting Matters 91:18-21.
Chisnall, R. (2010). Knot-tying habits, tier handedness and experience. Journal of Forensic Sciences 55:1232-1244. https://doi.org/10.1111/j.1556-4029.2010.01451.x.
Chisnall, R. (2016). Structural recognition and nomenclature standardization in forensic knot analysis. Science and Justice 56:282-301. https://doi.org/10.1016/j.scijus.2016.04.002.
Chisnall, R. (2020a). A brief review of side bends: Application, rationale, accidents and testing. International Journal of Mountaineering and Climbing 3(2):38-52. https://doi: 10.36415/dagiclik.831394
Chisnall, R. (2020b). Analysing knots and ligatures: Tying principles, knot characteristics and structural changes. Forensic Science International 333 (2020) 110272. https://doi.org/10.1016/j.forsciint.2020.110272.
Chisnall, R. (2021). An analytical review of figure eight loops and bowlines as harness tie-in and anchoring knots. International Journal of Mountaineering and Climbing. 4(2):43-59. https://doi: 10.36415/dagcilik.993072.
Chisnall, R. (2024). Knotting tower of Babel. Knotting Matters 163:25-41.
Craik, F.I.M. (2014). Effects of distraction on memory and cognition: A commentary. Front Psychol 204(5):841. https://doi.org/10.3389/fpsyg.2014.00841.
Croom, S., & Firestone, C. (2022). Looking tight: Visual judgements of knot strength reveal the limits of physical scene understanding. Journal of Vision 22(14):3448. https://doi.org/10.1167/jov.22.14.3448.
Cross, E.S., Hamilton, A.F. de C., Cohen, N.R., & Grafton, S.T. (2017). Learning to tie the knot: The acquisition of functional object representations by physical and observational experience. PLOS One 12 (10), e0185044. https://doi:10.1371/journal.pone.0185044.
Daily-Diamond, C.A., Gregg, C.E., O'Reilly, O.M. (2017). The roles of impact and inertia in the failure of a shoelace knot. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 473 (2200):20160770. https://doi.org/10.1098/rspa.2016.0770.
Datta Roy, M., Ghosh, S., Yadav, A. , & Somsubhra, D.R. (2019). Effect of coefficient of friction and bending rigidity on handling behaviour of surgical suture. J. Inst. Eng. India Series E, 100, 2:131-137. https://doi.org/10.1007/s40034-019-00146-0.
Douglas, E. (2012). Climbing wall death due to knot failure. British Mountaineering Council (BMC). https://www.thebmc.co.uk/climbing-wall-death-due-to-knot-failure. Accessed 8 July 2020.
European Standard EN 892: 1996 (British Standard BS EN 892: 1997), Mountaineering equipment – Dynamic mountaineering ropes – Safety requirements and test methods.
Evans, T. (2016). A review of knot strength testing. International Technical Rescue Symposium (ITRS). http://itrsonline.org/wordpress/wp-content/uploads/2016/11/Evans_Truebe.A -Review-of-Knot-Strength-Testing_2016.pdf. Accessed 31 August 2021.
Ewing, H.A. (1973). Knots and hitches in synthetic fibre ropes. Research Division Report. The Hydro-Electric Power Commission of Ontario.
Fasulo, D.J. (1996). Self-rescue. Evergreen Colorado: Chockstone Press. Flashman, J. (2017). Tying in: The bowline vs. the figure 8 knot. https://www.climbing.com/skills/tyng-in-the-bowline-vs-the-figure-8-knot/. Accessed 8 July 2020.
Forrest Mountaineering (1974), Knots. In: Forrest mountaineering limited, catalogue and guide to natural climbing. Denver Colorado: Forrest Mountaineering Limited , pp 27-33.
Gommers M (2013). An analysis of bowlines. July 2013. Version 2.1c. http://www.paci.com.au/downloads_public/knots/Bowlines_Analysis.pdf. Accessed, 8 July 2020.
Gommers, M. (2019). Analysis of offset overhand bends. An analysis of offset abseil rope joining knots. Sep 2017. VER 1.7. http://www.paci.com.au/downloads_public/knots/Analysis_Offset-Joining-Knots. pdf. Accessed 8 July 2020.

Graumont, R., & Hensel, J. (1952). Encyclopedia of knots and fancy rope work, 4th edition. Cambridge, Maryland: Cornell Maritime Press.

Graydon, D., Ed. (1992) Mountaineering: The freedom of the hills, 5th edition. Seattle, Washington: The Mountaineers.

Hage, J.J. (2007). How capsizing, flipping and flyping of traditional knots can result in new endoscopic knots: A geometric review. J Am Coll Surg 205(5):717-723. https://doi.org/10.1016/j.jamcollsurg.2007.05.016.

Hansen, D. (2004). A look at knot strength in a dynamic situation. International Technical Rescue Symposium (ITRS) 2004. https://drive.google.com/file/d/1nJ2EIKcW2oQQT80EiXMChdjTw_9GHZBD/view. Accessed 15 February 2025.

Hanypsiak, B.T., Delong, J.M., Simmons, L., Lowe, W., & Burkhart, S. (2014). Knot strength varies widely among expert arthroscopists. The American Journal of Sports Medicine 42(8), 1978-1984. https://doi.org/10.1177/0363546514535554.

Hill, L. (2002). Climbing free: My life in the vertical world. New York: W.W. Norton & Company. Horrocks, A.R., & Anand, S.C., Eds. (2016). Handbook of Technical Textiles, 2nd edition. Technical Textile Applications. Sawston, Cambridge: Woodhead Publishing. ISO Standard 2307:2019(en) Fibre Ropes – Determination of certain physical and mechanical properties.

Jackson, J. (2012). Accident: Deadliest hitch, first-time climber dies at Raven's Roost. Rock and Ice 201:28.

Jackson, J. (2016a). Euro-death knot (flat figure-8) mysteriously fails. Rock and Ice. http://www.rockandice.com/climbing-accidents/euro-death-knot-mysteriouslyfails. Accessed 8 July 8 2020.

Jackson, J. (2016b). Rappel knot fails, climber falls to death on the Goat Wall. Rock and Ice. https://rockandice.com/climbing-accidents/rappel-knot-fails-climber-falls-to-death-on-thegoat-wall/. Accessed 8 July 2020.

Jackson, J., & Whiteman, M. (2002). Accident report: Not the knot: Bowline comes undone–again. Rock and Ice 182:30.

Jawed, M. K., Dieleman, P., Audoly, B., & Reis, P. M. (2015). Untangling the mechanics and topology in the frictional response of long overhand elastic knots. Physical Review Letters 115(11), 118302. https://doi.org/10.1103/PhysRevLett.115.118302. Accessed 17 January 2025.

Johanns, P., & Resi, P.M. (2024). Capsizing due to friction-induced twist in the failure of stopper knots. Extreme Mechanical Letters 68, 102134. https://doi.org/10.1016/j.eml.2024.102134.

Jenkins, O.C., & Matariæ, M.J. (2002). Deriving action and behavior primitives from human motion data. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2002(3):2552-2556. https://doi:10.1109/IRDS.2002.1041654.

Jones. T. (2012). How to tie two ropes together. Canyoneering USA (CUSA). https://www.canyoneeringusa.com/techtips/tying-two-ropes-together. Accessed 8 July 2020.

Kahneman, D., Sibony, & O., Sunstein, C.R. (2021). Noise. Dublin, Ireland: Harper Collins Publishers.

Kirkpatrick, A. (2011). Ban the bowline? https://www.andy-kirkpatrick.com/blog/view/ban_the_bowline/. Accessed 8 July 2020.

Lee, S.W.Y., Wong, Y.R., & Tay, S.C. (2019). Biomechanical investigation of different tying forces on knot security. Biomed J Sci & Res 17(2):2019. https://doi.org:10.26717/BJSTR.2019.17.002985.

Little, J.F. (1980). Critical thinking and decision making. Toronto, Ontario: Butterworth and Company (Canada) Limited.

Livermore, R.W., Chong, A.C.M., Prohaska, D.J., Cooke, F.W., & Jones, T.L. (2010). Knot security, loop security, and elongation of braided polyblend sutures used for arthroscopic knots. Am J Orthop 39(12):569-576.

Lo, .IK.Y., Ochoa, E. Jr., & Burkhart, S.S. (2010). A comparison of knot security and loop security in arthroscopic knots tied with newer high-strength suture materials. Arthroscopy: The Journal of Arthroscopic and Related Surgery 26(9 Suppl):S120-S126. http://doi.org/10.1016/j.arthro.2009.12.009.

Lottman, D. (2018). One of these knots can kill you. https://northeastalpinestart.com/2016/09/27/one-of-these-knots-can-kill-you/. Accessed 8 July 2020.

Luebben, C. (1993). Knots for climbers. Evergreen, Colorado: Chockstone Press.

McKentley, J. (2014). Rescue knot efficiency revisited. International Technical Rescue Symposium (ITRS). http:itrsonline/rescue-knot-efficiency-revisited. Accessed 8 July 2020.

MacDonald, D., Ed. (2016). Fall on rock, incomplete tie-in knot. Accidents in North American Climbing 11,1(69):129.

MacDonald, D., Ed. (2018a). Rappel error, uneven ropes, no stopper knots. Accidents in North American Climbing 11, 3(71):99.
MacDonald, D., Ed. (2018b). Simul-rappelling error, no backups. Accidents in North American Climbing 11, 3(71):94.
MacDonald, D., Ed. (2018c). Rappel error, no backups, no helmet. Accidents in North American Climbing 11, 3(71):38-39.
MacDonald, D., Ed. (2018d). Lowering errors, ropes too short, helmet/no helmet. Accidents in North American Climbing 11, 3(71):39-40.
MacDonald, D., Ed. (2020a). Lowering error, rope too short, no stopper knot. Accidents in North American Climbing 12, 1(73):66-67.
MacDonald, D., Ed. (2020b). Lowering error, no stopper knot. Accidents in North American Climbing 12, 1(73):103-104.
MacDonald, D., Ed. (2020c). Fatal lead, fall on rock. Accidents in North American Climbing 12, 1(73):124-125.
MacDonald, D., Ed. (2020d). Fatal lead fall, inadequate knot. Accidents in North American Climbing 12, 1(73):71.
MacDonald, D., Ed. (2020e). Fall from anchor, incorrectly tied knot. Accidents in North American Climbing 12, 1(73):92.
Maddocks, J.H., & Keller, J.B. (1987). Ropes in equilibrium. SIAM Journal of Applied Mathematics 47(6):1185-1200. https://doi.org/10.1137/0147080.
Martin, J.D. (2009). The euro death knot. American Alpine Institute. http://blog.alpineinstitute.com/2009/03/euro-death-knot.html. Accessed 8 July 2020.
Martin, D.A., Boron, K., Obstalecki., Kurath, P., & Horn, G.P. (2015). Feasibility of knots to reduce the maximum dynamic arresting load in rope systems. Journal of Dynamic
Behavior of Materials 1:214–224. https://doi.org/10.1007/s40870-015-0015-5. Michel, G.F., Harkins, D.A. (1985). Concordance of handedness between teacher and student facilitates learning manual skills. Journal of Human Evolution 14(6):597-601. https://doi.org/10.1016/S0047-2484(85)80085-3.
Microys, H.F. (1977). Climbing ropes. American Alpine Journal 21:130-147. https://publications.americanalpineclub.org/articles/12197713000/Climbing-Ropes. Accessed 15 February 2025.
Momsen, R. (2016). The euro-death knot is not. Common Climber. https://www.commonclimber.com/edk.html. Accessed 8July 2020.
Moyer, T. (1999a). Rope and gear testing, pull tests of the “Euro Death-Knot.”https://user.xmission.com/-tmoyer/tsting/EDK.html. Accessed 8 July 2020.
Moyer, T. (1999b). Water knot testing. International Technical Rescue Symposium (ITRS) 1999. http://caves.org/section/vertical/nh/46/waterknot.html.
Moyer, T., Tusting, P., & Harmstrom, C. (2000). Comparative testing of high strength cord. International Technical Rescue Symposium (ITRS) 2000. https://user.xmission.com/~tmoyer/testing/High_Strength_Cord.pdf. Accessed 15 February 2025.
Muchnik, L., Aral, S., &Taylor, S.J. (2013) Social influence bias: a randomized experiment. Science 341(6146):647-651. https://doi:10.1126/science.1240466.
Patil, V.P., Sandt, J.D., Kolle, M., & Dunkel, J. (2020). Topological mechanics of knots and tangles. Science 367(2020):71-75. https://doi.org/19.1126/science.aaz0135.
Pegg, D. (2001). Techtip sport: no more tears — a trim knot that unties easily. Climbing 208:102.
Pieranski, P., Kasas, S., Dietler, G., Dubochet, J., & Stasiak, A. (2001). Localization of breaking points in knotted strings. New Journal of Physics 3(2001)10.1-10.13. https://iopscience.iop.org/article/10.1088/1367-2630/3/1/310/meta.
Pope, J.F. (1972). Tests of knots. Summit 18, 2.
Powick, K. (2016). QC lab: What is the strongest rappel knot? Black Diamond®. https://www.blackdiamondequipment.com/en_CA/experience-story?cid=qc-labwhat-is-the-best-rappel-knot. Accessed 8 July 2020.
Prattley, G. (2016). Which bends for joining ropes? Testing and analysis of flat bends used for rope retrieval (Version 2.0). Over The Edge Rescue. https://canyonsandcrags.com/pdf/which-bend.pdf. Accessed 8 July 2020
Prohaska, H. (1988). The double bight bowline. Summit 34(3):22-23.
Prohaska, H. (1995). Le nnoeud de sangleo: problème et solution. Les Alps 71(11):492-493.
Prohaska, H. (1996). Techniques: a knotty problem. Climber Autumn 29.

Prohaska, H. (1998). Gefahren bei anseilknoten. Die Alpen 2(1998):28-30.
Prohaska, H. (2001). Knotentests -das verhalten von seilknoten. Erweitertung Zum Kongresslband Psyche und Berg 2001:1-13.
Prohaska, H. (2005). Bowline failure. Knotting Matters 88:19.
Plummer, W.T. (1973). Appendix B: Theory of the climbing knot. In: Thrun, R. (editor &author) Prusking. Austin, Texas: The Speleo Press. pp 61-74.
Raleigh, D. (1998). Knots & ropes for climbers. Mechanicsburg, Pennsylvania: Stackpole Books.
Rana, M., Savant, V., & Prydal, J.I. (2012). A study of slippage of various knot configurations. Eye 26:1491-1493. https://doi:10.1038/eye.2012.156.
Rana, S., & Fangueiro, R. (2018). Braided structures and composites: production, properties, mechanics, and technical applications, 1st edition. Boca Raton, Florida: CRC Press.
Richards, D. (2005). Knot break strength vs rope break strength. Vertical Section of the National Speleological Society. http://www.Caves.org/section/vertical/nh/knotrope=hold.html. Accessed July 8, 2020.
Rock and Ice. (2010). Bowline comes untied, climber falls to ground. Bowline comes undone— again. Rock and Ice. https://rockandice.com/climbing-accidents/bowline-comes-untied-climber-falls-toground/. Accessed 8 July 2020.
Rock and Ice. (2012). John Long seriously injured in fall. Rock and Ice. https://rockandice.com/climbing-news/john-long-seriously-injured-in-fall/. Accessed 8 July 2020.
Roy, A. (2012). Bye bye bowline: Time for a new knot. Outside. http://www.outsideonline.com/1911861/bye-bye-bowline-time-new-knot. Accessed 8 July 2020.
Sáez, P.I., Carrión, E.Á., Ferrer, B., García, E., & Monge, J. (2024). Determining the safest anchoring knot in a fall arrest system by means of static tests. Symmetry16(2)167). https://doi.org/10.3390/sym16020167.
Sano,T.G., Johanns, P., Grandgeorge, P., Baek, C. & Reis, P. (2022). Exploring the inner workings of the clove hitch knot. 55, 101788. Extreme Mechanical Letters 55(2022):101788. https:/doi.org/10.1016/j.eml.2022.101788.
Shah, M.R., Strauss, E.J., Kaplan, K., Jazrawi, L., & Rosen, J. (2007). Initial loop and knot security of arthroscopic knots using high-strength sutures. Arthroscopy: The Journal of Arthroscopic and Related Surgery 23(8):884-888. https://doi.org/10.1016/j.arthro.2007.02.007.
Shaw, G.R. (1933). Knots: Useful & ornamental. New York: Collier Books. Siacci, R. (2019). In defense of the european death knot. https://www.climbing.com/skills/in-defense-of-the-european-death-knot. Accessed July 8, 2020.
Šimon, J., Dekýš, V., & Paèek, P. (2020) Revision of commonly used loop knot efficiencies. Acta Physica Polonica Series A 138(3):404-420. https://doi:10.12693/APhysPolA.138.404.
Šimon, J., Ftorek, B. (2022). Basic statistical properties of the knot efficiency. Symmetry 14(9), 1926. https://doi.org/10.3390/sym14091926.
Smith, R.A. (2002.) The development of equipment to reduce risk in rock climbing. Sports Engineering 1(1):27-29. https://doi.org/10.1046/j.1460-2687.1998.00008.x.
Sry, V., Mizutani, Y., Endo, G., Endo, G., Suzuki, Y., & Todoroki, A. (2018). Estimation of the longitudinal elasticity modulus of braided synthetic fiber rope utilizing classical laminate theory with Unix N/tex. Appl. Sci. 8(7):1096. https://doi.org/10.3390/app8071096.
Thacker, J.G., Rodeheaver, G., Kurtz, L., Edgerton, M., & Edlich, R.F. (1977). Mechanical performance of sutures in surgery. The American Journal of Surgery 133(6):713-715. https://doi.org/10.1016/0002-9610(77)90161-1.
Tong, D., Choi, A., Joo, J., Borum, A, Jawed, M.K. (2023). Snap buckling in overhand knots. ASME J. Appl. Mech. 90(4):041008. https://doi.org/10.1115/1.4056478
Tong, D, Khalil, M.I., Silva, M.J., Wang, G., Koga, B., & Jawed, M.K. (2024). Mechanical response of fisherman's knots during tightening. Journal of Applied Mechanics 91(3):031008. https://goi.org/10.1115/1.4063895.
Tuohy, M. (2005). Accident report: Knot, don't fail me now! Rock and Ice. 144:36. Tyson, A., Loomis, M. (2006). Climbing self-rescue: Improvising solutions for serious situations. Mountaineers Outdoor Expert Series. Seattle, Washington: The Mountaineers Books.
Udall, J. R. (1987). Thinking about safety. In: Meier, J.F., Morash, T.W., & Welton, G.E., Eds. High-Adventure Outdoor Pursuits. Columbus, Ohio: Publishing Horizons, Inc. van de Griend, P. (1992). Knots and rope problems. Århus, Denmark: Privately published in limited edition (ISBN 87-983985-4-7).

Warner, C. (1996) Chapter 10 Studies on the behaviour of knots. In: Turner, J.C., & van de Griend, P., Eds. The history of science and knots, Series on Knots and Everything –Vol. 11. River Edge New Jersey: World Scientific Publishing Co., pp. 181-203.

Weller, S.D., Davies, P., Vickers. A.W., & Johanning, L. (2015). Synthetic rope responses in the context of load history: The influence of aging 96(1):192-204. https://doi.org/10.1016/j.oceaneng.2014.12.013.

Wexler, A. (1950). The theory of belaying. American Alpine Journal 7(4):379-405.

Wheelock, W. (1967). Ropes, knots & slings for climbers, revised edition. Glendale, California: La Siesta Press.

Williamson, J. (2003). Knot failure. Rock and Ice 127:106.

Wright, C.E.I., & Magowan, J,E, (1928), Knots for climbers. The Alpine Journal 40:120-141 (Part I), 340-351 (Part II).

Wilde, G.J.S. (1998). Risk homeostasis theory: An overview. Injury Prevention 4(2):89-91. https://doi.org/10.1136/ip.4.2.89.

Wong, Y.R., & McGrouther, D.A. (2023). Biomechanics of surgical knot security: a systematic review. International Journal of Surgery 109(3):481-490. https://doi:10.1097/JS9.0000000000000298.

Yosemite Climbing Information. (2020). Accident report: Incorrect leader tie-in, Five & Dime Cliff. https://www.climbingyosemite.com/portfolio/accident-report-incorrectleader-tie-in-five-dime-cliff/. Accessed 31August 2021.