International Journal of Mountaineering and Climbing, 2021, 4(2), 43-59

Derleme (RE)
Review (RE)

An Analytical Review of Figure Eight Loops and Bowlines as Harness Tie-in and Anchoring Knots

Sekizli Düğümleri, Bulin Düğümü ve Ana Emniyet Noktası Düğümleri Üzerine Analitik Bir Derleme

Robert CHISNALL
chisnall@kingston.net
0000-0002-8822-8127

Makale Geçmişi:
Başvuru tarihi: 8 Eylül 2021
Düzeltme tarihi: 29 Eylül 2021
Kabul tarihi: 24 Aralık 2021

Anahtar Kelimeler:
İp, Düğüm, Sekizli Düğüm

Öz

Emniyet kemerinde kullanılan sekizli düğümleri ve standart bulin düğümünün güçlü ve zayıf yönleri nitel detaylar ve nicel verilerle analiz edilmiştir. Emniyet noktaları uygulamaları da kısaca tartışılmıştır. Düğüm sonlarına atılan backup-ek güvenlik- düğümlerinin çeşitlerine de özellikle yer verildi. Ayrıca hata sebepleri, düğüm hataları, kazalar, gereksiz davranış ve teknikler ve uygulamaların çeşitli standartları incelendi. Bu düğümler, mukavemet, halkaların esneklik fonksiyonu ve atış yöntemi ile yapısal bütünlük açılarından karşılaştırıldı. Güvenlik konusu bükülme ve kuvvetin yön değiştirmesi durumlarına göre nitel özellikleri ve bağıl konumları, biçimlerinden ve büyüklüklerinden ayrı olarak ele alınarak analiz edilmiştir.

Article history:
Received: 8 September 2021
Adjustment: 29 September 2021
Accepted: 24 December 2021

Keywords:
Rope, Knots, Eight Loops.

Abstract

The strengths and weaknesses of Figure Eight Loops and standard Bowlines as harness tie-in knots are analysed and compared with reference to qualitative details and quantitative data. Their anchoring applications are discussed briefly as well. Attention is paid to variants and the importance of backup knots. Further, causes of error, knot failure, close calls and accidents, behavioural and technical redundancy, and variable standards of practice are examined. These knots are compared in terms of strength, elasticity as a function of sinuosity, and structural integrity by way of concatenation. Security is analysed using topological twist fluctuation and circulation energies.

Corresponding author e-mail address: chisnall@kingston.net
e-ISSN: 2667-6923.

DOI: 10.36415/dagcilik.993072

Introduction

Climbing and work-at-height activities rely on strong and secure harness tie-in knots and anchoring procedures. However, there are ways in which all knots can fail. Typically, modes of failure are linked to structural integrity and tier behaviour. Knowing the weaknesses of knots and how to mitigate those shortcomings is critical to maximizing safety. Two of the most poplar loop knots have traditionally been the Figure Eight Follow-Through Loop (Figure 1) and the standard Bowline (Figure 2). (The former is also called the Figure Eight Loop, the Double Figure

Eight Loop, the Figure Eight End Loop, the Retraced Figure Eight, and other names depending on the tying method.) How these knots can fail will be analysed in detail. In conjunction with a discussion of knot applications and tier behaviour, this analysis will review some examples of recurring accidents and close calls along with the structural and functional idiosyncrasies of these ubiquitous knots. Options for redundancy and increased security will be examined.

Figure 1. From left to right: S Figure Eight Knot, S Overhand Loop, Z Figure Eight Loop, Z Figure Eight Knot. The loop structures are analogous to the simple Figure Eight Knots by way of chirality. In topology, theoretical Figure Eight Knots have no ends and are therefore amphichiral. Real world Figure Eight Knots have chirality relative to their working ends (Chisnall, 2006a).

Literature Review and Analysis

Preliminary Terminology and Concepts

To avoid ambiguity, several preliminary concepts and terms should be clarified. A perusal of the climbing, safety and knotting literature will reveal a lack of consistency and even contradictions in how knots and knot characteristics are labelled. As those researching the evolution of language point out, word usage varies and changes according regional colloquialisms, cultural developments and new technology (Bowren, 2015; Steels, 2017). Herein, the most common knot names will be utilized, some alternatives will be mentioned in passing, and all knot names will be capitalized according to established convention (Ashley, 1944; Graumont & Hensel, 1952; Chisnall, 2016a, 2020).

Most real-world knots are chiral because they have mirror images known as enantiomers. Knot chirality is related to a tier's procedural memory, tying habits and handedness (Chisnall, 2010). Figures 1 and 2 illustrate the chiral versions of the Figure Eight Loop and the standard Bowline. Knot tiers identify three basic rope parts when tying knots. The working end or wend is employed in the actual tying. The bight forms the knot proper. The standing part, standing end, stand or stend is the unused end of the rope (Chisnall, 2020). There are four basic types of practical knots: stopper knots, loops, bends and hitches. The focus herein is loops, specifically end loops intended for harness attachment and anchoring purposes. Other terms, such as pre-bight and post-bight knots, will be explained later as they appear in this discussion.

Figure 2. Top: Overhand Knots, S (left) and Z (right). Bottom: Bowlines, b (left) and d (right). Knot chirality is indicated by S and Z, and b and d. A "d" Bowline can capsize and release into a Z Overhand Slip Loop, while a "b" Bowline can capsize and release into an S Overhand Slip Loop (Chisnall 2016a, 2016b).

Incomplete Figure Eight Follow-Through Loop Without a Backup

Incomplete Figure Eight Follow-Through Loops have often been reported and observed in accidents and close-call events (Douglas, 2012; MacDonald, 2016; Osius, 2015, 2020, 2021;

Yosemite Climbing Information, 2020). Lynn Hill's ground fall in 1989 is one notable instance (Hill, 2002). While distracted, a climber can fail to properly complete his or her Figure Eight Follow-Through Loop, as shown in Figure 3, and inadvertently produce a Figure Eight Slip Loop, as illustrated in Figure 4. This dangerous error can be overlooked if the belayer and climber fail to perform a pre-climb check. Without a backup knot, a Figure

Eight Slip Loop cannot hold weight. As illustrated in Figure 4, the wend will simply migrate and release, and the knot will fail when the climber loads the line (Chisnall, 2020).

Close calls have been witnessed at commercial climbing gyms and at local crags. In these cases, the Figure Eight Tie-In Loops were not finished correctly, usually owing to in attentiveness. As stand-alone slip knots, they were insecure. Fortunately, a Doubled Overhand Keeper Knot (sometimes called a Barrel Knot or incorrectly referred to as a Fisherman's Knot, amongst other names) was added as a backup each time. That additional knot saved the climbers when they weighted their belay lines. The backup knot slid down and jammed against the initial Figure Eight Knot, consequently preventing the end from releasing or pulling free (Figure 5).

Figure 3. Method of tying the Figure Eight Follow-Through Loop by retracing the wend, moving from left to right.

Figure 4. A Figure Eight Slip Loop, moving from left to right.

Several lessons emerge. First, climbers should complete harness tie in knots without distraction until finished (Craik, 2014; Couffe & Michael, 2017). Second, a backup or keeper knot should be added for technical and behavioural redundancy. (In this context, behavioural redundancy should not be confused with Colby's (1958) definition pertaining to the equilibrium theory of redundancy as it applies to the study of cultural and personal value systems.) From a technical standpoint, the keeper knot backs up the main harness tie-in knot. If the Figure Eight Follow Through Loop is incomplete or incorrect, the backup knot should prevent total detachment. From a behavioural perspective, the tying of that keeper knot punctuates the completion of the tying-in process, triggering the need to self check and partner check knot integrity. Nothing is finished until the keeper knot is added, the climber carefully confirms that he or she has tied in correctly, and the belayer does the same.

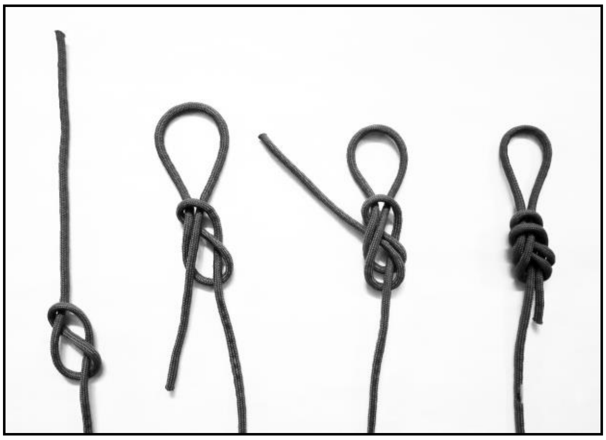

Figure 5. Left: A Figure Eight Slip Loops (an incomplete Figure Eight Follow-Through), with a Double Overhand Keeper Knot as a backup. Right: When loading occurs, the backup knot migrates until it stops at the Figure Eight Knot.

Figure 6. A completed Figure Eight Loop with a Double Overhand Keeper Knot as a backup, for harness and anchor attachment.

Several lessons emerge. First, climbers should complete harness tie in knots without distraction until finished (Craik, 2014; Couffe & Michael, 2017). Second, a backup or keeper knot should be added for technical and behavioural redundancy. (In this context, behavioural redundancy should not be confused with Colby's (1958) definition pertaining to the equilibrium theory of redundancy as it applies to the study of cultural and personal value systems.) From a technical standpoint, the keeper knot backs up the main harness tie-in knot. If the Figure Eight Follow Through Loop is incomplete or incorrect, the backup knot should prevent total detachment. From a behavioural perspective, the tying of that keeper knot punctuates the completion of the tying-in process, triggering the need to self check and partner check knot integrity. Nothing is finished until the keeper knot is added, the climber carefully confirms that he or she has tied in correctly, and the belayer does the same.

Adding a keeper knot, as shown in Figure 6, is a practice often seen in rope access, rigging work, and high-angle rescue operations (Brown, 2000; Vines & Hudson, 1989). The Figure Eight loop is commonly used in recreational contexts, such as rock and ice climbing and mountaineering, but the use of backup knots is inconsistent (Association of Canadian Mountain Guides, 1999; Chisnall, 1985; Graydon, 1992; Microys, 1977; Osius, 2015, 2020; Petzl®, 1995, 2020; Raleigh, 1998; Smith & Padgett, 1996). Some climbing gyms and instructors do not utilise backup knots. Many climbers insist that backup knots are unnecessary, if the tie-in knot is completed correctly. Nevertheless, reports about keeper knots preventing accidents indicate that backups are beneficial, especially when it comes to learning environments and commercial contexts. Should different standards be applied according to context? Professional climbers, elite competitors, rescue personnel and riggers certainly should be expected to always tie in correctly. Nevertheless, accident records indicate this is not always the case (Osius, 2021). With regard to beginners, recreational climbers, and especially minors and those whose skill level is typically lower, enhanced safeguards are essential. Outdoor guiding services, aerial parks, and commercial climbing gyms maximize their duty of care by making backup knots standard practice.

Interestingly, the types and qualities of backup knots employed by competitive climbers are not consistent. The International Federation of Sport Climbing states in its guidelines for competition officials, "Check if the competitor is ready for climbing: climbing harness correctly closed, figure of eight knot with an extra knot in the rope, climbing shoes on." (IFSC, 2020, p. 4). The type of "extra knot" is not specified or illustrated. As observed during the 2020 Tokyo Olympics held in August of 2021, the backup knots tied by the 40 climbers who participated in the sport climbing qualification events varied. Knot data are summarized in Table 1. Further, five backup knots were observed to be loose, two knots had short tails, and three Double Overhand Knots were inadequately dressed.

The proper and incorrect versions of the Overhand Keeper Knot are illustrated in Figure 7. A properly dressed keeper knot is more secure because it has more friction via its 13 planar projection crossing points. The incorrect dressing has 10 crossings.

There are a number of common backup knot options: the Double or Triple Overhand Keeper Knot, the Yosemite Tuck, and the European Tuck (Figures 6 through 10). The Double and Triple Overhand Keeper Knots are ubiquitous and effective backups, and they can be untied relatively easily after a climb. However, they can work loose in stiff lines, and the Single Overhand Keeper Knot is the least secure. It tends to fall apart more frequently. Further, the Double or Triple Overhand Keeper Knot sometimes gets in the way during lead climbs when the climber attempts to clip the belay line to lead draws. This problem is exacerbated if there is too much slack in the tail end of the rope and the backup knot is positioned too high. It should be situated so it contacts or almost touches the Figure Eight End Loop. Also, the end of the line often points straight up out of the Overhand Keeper Knot, and it has been known to poke top-roped climbers in the eye if they are not vigilant. The Yosemite Tuck uses minimal rope, it orients the end away from the climber's face, and it adds security to the knot (Figure 8). The disadvantage of this backup option is how difficult it is to untie the knot after long falls or prolonged suspension. The European Tuck or Olevsky Finish shown in Figure 9 is similar to the Yosemite Tuck, and it has the same advantages (Olevsky, 2003). However, although it is not obvious, the European Tuck partially unties the Figure Eight Follow-Through Loop, making it less secure. Nevertheless, the Yosemite and European Tucks can be combined safely (Figure 10).

Table 1. Backup knots tied at the 2020 Olympics sport climbing qualification events. These are approximate figures because observations were made from event broadcasts, and the chirality of some knots may be inaccurate.

Plurality → Chirality ↓	**Single Overhand Knot**	**Double Overhand Knot**	**Totals**
S Enantiomorph	14	8	22
Z Enantiomorph	15	3	18
Totals	29	11	40

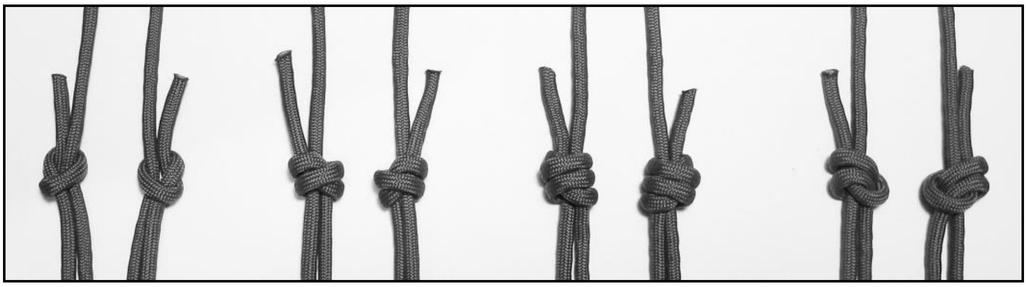

Figure 7. From left to right: S and Z Single Overhand Keeper Knots; S and Z Double Overhand Keeper Knots; S and Z Triple Overhand Keeper Knots; improperly dressed S and Z Double Overhand Keeper Knots.

orients the end away from the climber's face, and it adds security to the knot (Figure 8). The disadvantage of this backup option is how difficult it is to untie the knot after long falls or prolonged suspension. The European Tuck or Olevsky Finish shown in Figure 9 is similar to the Yosemite Tuck, and it has the same advantages (Olevsky, 2003). However, although it is not obvious, the European Tuck partially unties the Figure Eight Follow-Through Loop, making it less secure. Nevertheless, the Yosemite and European Tucks can be combined safely (Figure 10).

Alternative Harness Connections

Some climbing gyms and adventure organizations opt to tie permanent Figure Eight Loops and Double Overhand Keeper Knots in the ends of belay lines and attach ropes to climbers' harnesses with locking carabiners. Tying errors are thereby avoided, usually. Some organizations utilize single locking carabiners without captive eyes. (Dual carabiners, and single fixed or captive-eye carabiners are used on auto-belayers, such as devices available from Perfect Descent Climbing Systems and Head Rush Technologies.) Single carabiner harness attachments are not recommended by many gear manufacturers because there is a lack of attachment redundancy, and a lone carabiner could be loaded along its weaker minor axis or become detached if it is not monitored. Single carabiner detachments have resulted in unfortunate mishaps (Gripped, 2018). Two opposed or reversed locking carabiners are recommended (Petzl®, 2006, 2007).

Figure 8. A completed Figure Eight Follow-Through Loop with one version of the Yosemite Tuck or Finish.

Figure 9. A completed Figure Eight Follow-Through Loop with one version of the European Tuck or Olevsky Finish, which partially unties the Figure Eight Loop (Chisnall 2006a, 2006b).

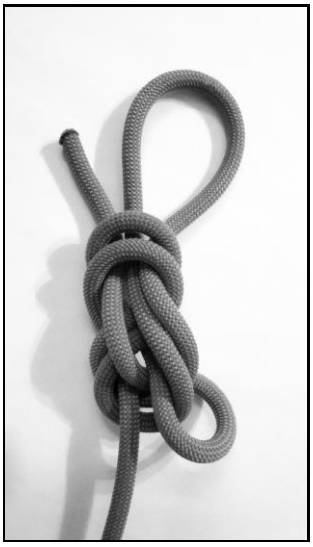

Figure 10. A completed Figure Eight-Through Loop with both a Yosemite Tuck and the European Tuck. This arrangement is secure.

For commercial operations, the adoption of specific harness attachment techniques is a matter of acceptable policies and procedures. These techniques should meet established equipment standards and manufacturers' guidelines, which stem from accident analyses and testing, but often safety decisions are based on tradition, risk perception and bias (Chamarro & Fernández-Castro, 2009; Chisnall, 2020b; Langseth & Salvesen, 2018; Llewellyn & Sanchez, 2002; Schad, 2000).

Bowline Tie-In Failures: Pre-Bight and Post-Bight Loop Knots

The use of the Bowline as a tie-in knot has long been a point of contention amongst climbers and other knot users (Figures 2 and 11) (Chisnall, 2006a, 2006b; Gommers, 2013). The king of knots, as it is sometimes called, has been used successfully and passed down through generations of climbers via instruction and tradition, often without question. Under a number of conditions, it can capsize into a Running Slip Loop which can release without a keeper knot (Figure 12) (Chisnall, 2006a, 2006b, 2020). For decades there have been reports of Bowlines accidentally untying, thereby leading to death or injury (Brumbagh, 2013; Douglas, 2012; Gommers, 2013; Jackson & Whiteman, 2002; Williamson, 2003; Kirkpatrick, 2011; Luebben, 1993; MacDonald, 2020; Michael, 2005; Nuttall, 2015; Osius, 2015, 2020; Prohaska, 1988, 2005; Raleigh, 2005, Roy, 2012; AAC, 1980; Schmidt, 2005; Schubert, 2001; Rock & Ice, 2010, 2012).

In general, the Bowline works, which provides users with an unquestioned sense of security. Unlike the Figure Eight Tie-In Loop, it can be untied relatively easily after severe or prolonged loading (deBoer, 2005; Evans, 2016; Gommers, 2013; Prohaska, 1988, 1998;

Raleigh, 1998, 2005). In the hierarchy of knot characteristics, this is not a critical advantage. However,

Figure 11. The standard Bowline with a Double Overhand Knot as a backup

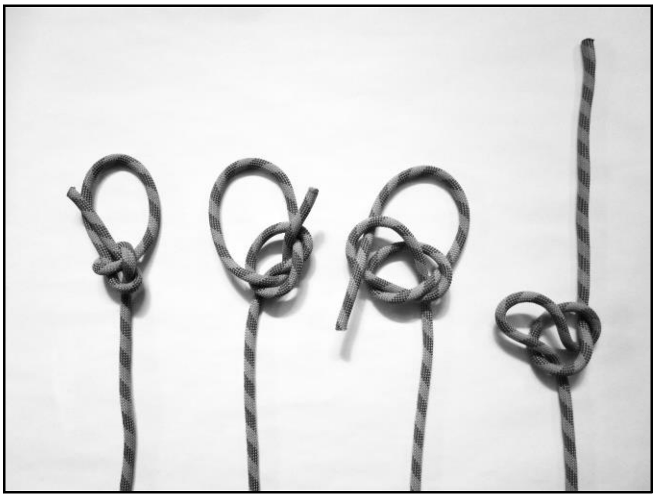

Figure 12. A Bowline without a backup knot capsizing, leaving a Running Overhand Slip Loop. The wend then Keeper migrates and releases forming an Overhand Slip Loop.

Figure 13. From left to right: Bowline, Yosemite Bowline, Yosemite Bowline with a Double Overhand Keeper Knot.

Figure 14. A sample of esoteric Bowline transformations, from left to right: Bowline with Prohaska Tuck; Bowline with Safier Tuck; Double Bowline with Lehman Tuck Double Knotted or Round Turn Bowline.

it is a qualitative telltale of the knot's relative lack of security. Climbers and knot aficionados have used a variety of transformations and backup strategies to increase security (Chisnall, 1985, 2006a, 2006b, 2020; Gommers, 2013; Pegg, 2001). Some of these strategies work well, like adding a Double Overhand Keeper Knot, using the Yosemite or Tucked Bowline, or combing both strategies for redundancy (Figures 11 and 13). Many of the improvements suggested and used over the years have indeed enhanced Bowline security, but at the expense of simplicity in some cases (Figure 14). Some variations are rather esoteric, perhaps introducing enough complexity to tax memory and invite error.

Figure 15. Bowline tying errors, which can create insecure loop knots. The working ends are wrapped and tucked incorrectly.

The Bowline is structurally asymmetrical and it has chirality (Figure 2). Hence, depending on how the knot is learned and practised relative to the tier's perspective and handedness, there is a possibility critical tying errors may be learned and become habitual (Chisnall, 2020). Two common tying mistakes are illustrated in Figure 15, but it should be immediately obvious that these knots are incorrect. Unfortunately, certain errors can be subtle and sometimes difficult to detect. For example, there are other versions of the Bowline that may be tied unintentionally using similar but slightly modified actions. The Ring, Stopper or Cowboy Bowline and the Boas Bowline are just two examples (Figure 16). (The Ring or Stopper Bowline has been called the Left-Handed Bowline, which is inaccurate from a structural and behavioural perspective (Chisnall, 2016b).) These variants have been observed in use and their security varies.

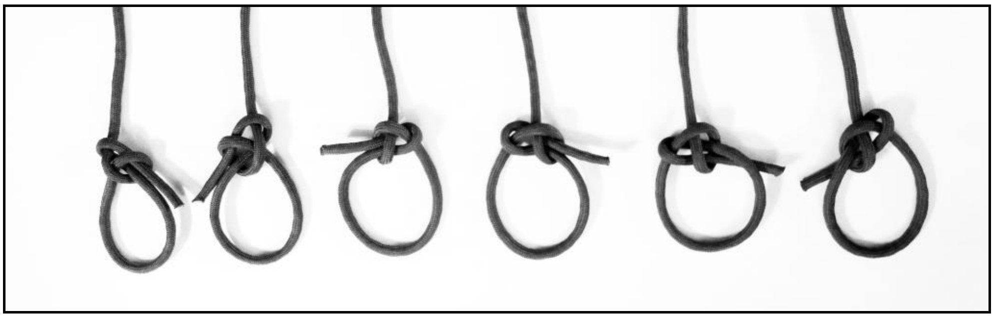

Figure 16. Bowline variations, from left to right: Ring, Stopper or Cowboy Bowlines, with the wends outside the loops (b and d); versions of the Boas Bowline, with the wends outside the loops (b and d); versions of the Boas Bowline, with wends inside loops (b and d).

Bowline applications are diverse. There are rescue groups and those working at height who employ versions of the Bowline with a backup knot only for attachment to stationary anchor points. They do not utilize the Bowline to connect the rope to harnesses or to moving loads such as stretchers. In moving applications, the knot may abrade against nearby surfaces as the line moves. The loop might become cross loaded causing the knot to capsize (Figure 12).

Discussion

Figure Eight Loop and Bowline Strength, Security and Elasticity

Any comparison of the Figure Eight Follow-Through Loop and Bowline, especially as tie-in knots, is fraught with controversy (Flashman, 2017: Gommers, 2013).

The standard Bowline is a post-bight knot (referred to by one author as "post-eye tiable" or PET for short), and this is an aspect of its concatenation, sinuosity and crossing number (Chisnall, 2006a, 2006b, 2020; Gommers, 2013). The end of the unknotted rope is passed through the harness or around an anchor point before the tying begins. Therefore, topologically, it has the capacity to capsize into a less secure formation that can slip free, especially if the loop is loaded crosswise, which is called ring loading, and lacks a backup knot (Gommers, 2013).

In contrast, the Figure Eight Follow-Through Loop or Tie-In Loop is a pre-bight knot (also referred to as "tiable in a bight"). The basic structure is tied before the wend is passed through the harness or around the anchor point, and the wend is then traced back through the initial Figure Eight Knot (Figure 3). A correctly completed Figure Eight Follow-Through Loop cannot capsize and come untied. It is tolerant of moderate sloppiness and even slight errors, provided the end has been traced through the knot adequately.

Bowline and Figure Eight Loop testing has mainly concentrated on strength rather than security (Evans, 2016; Ewing, 1973; Gommers, 2013; McKentley, 2014; Warner, 1996). Some knot failure data could be misleading if the test parameters and conditions do not satisfactorily address the specific rigours of the knot's application conditions (Chisnall, 2020). According to Evans (2017), the Bowline ranges from 41,8% to 70,7% in residual strength or knot efficiency based on 106 individual test results. There may be several reasons for this range: different experimental methods were employed, disparate ropes or cords were ruptured, different testing devices were utilised, and different Bowline variations were tested (Chisnall, 2020) (Figure 16). An example of Bowline testing can be viewed using the following link:

https://www.youtube.com/watch?v=qAOGYebFCKM, (July 8, 2020)

Although generally weaker than the Figure Eight, it is adequate for most anchoring purposes, other than rescue setups, such as high-lines and inclined lowers, which require high-strength knots. These include the Tensionless Hitch and the Wrap Four-Pull Three sling configuration (not illustrated).

There is no question the Figure Eight Loop has sufficient tensile strength. As Evans (2017) summarizes in his review of 288 individual rupture tests, the knot efficiency or residual strength of Figure Eight Loops ranges from 64,8% to 86,3%. Again, the range may be attributable to different testing protocols and variability in how the Figure Eight Loop was dressed (Chisnall, 1985, 2020). Hence, the Figure Eight Loop is adequate for harness tie-ins as well as anchoring. With or without a backup knot, it can be difficult to untie after severe or prolonged loading, a sign of its inherent security. There are a number of effective techniques for loosening the Figure Eight.

Figure 17. From left to right: S and Z Figure Eight Loops, S and Z Figure Nine Loops, S and Z Stevedore's Loops.

Similar but slightly more complex loops are much easier to untie. These include the Figure Nine or Intermediate Loop and the Stevedore's Loop (Figure 17). The former adds an extra 180-degree twist before the loop is tucked into the bight. The latter adds two twists before the tuck. Published and unpublished test results indicate the Figure Nine Loop is slightly stronger than the Figure Eight Loop, depending on how well the knot is dressed (Šimon et al., 2020). These are not suitable knots for harness tie-ins because they are bulkier and require more rope. They are better suited for anchoring tasks. The bulkier Figure Nine Loop and Stevedore's Loop reduce the untying difficulties while maintaining security, often with increased knot efficiency or residual strength. The Figure Nine Loop is based on the Intermediate Knot, and the Stevedore's Loop is based on the Stevedore's Knot (Ashley, 1944).

Two more subtle points are worth discussing briefly. The Figure Eight Loop has a higher crossing number, as well as greater sinuosity and concatenation, compared to the Bowline – hence, more friction. Topological twist fluctuation and circulation energies are theoretical measures of a bend's structural integrity, independent of rope or cord properties such as knottability and surface friction (Chisnall, 2020; Patil et al., 2020). (See Appendix.) Without going into detail beyond this paper's focus, this method of topological energies of bends can be modified to evaluate the Figure Eight Loop and the Bowline. However, rather than using a planar projection of the Figure Eight with the minimal 16 crossings, load vector orientation and writhe can be determined using a more realistic three-dimensional projection of the properly dressed knot with 20 crossings. In three dimensions the Bowline is flatter, less bulky, and its planar projection has seven crossings. Based on these structural algorithms, the Figure Eight is more secure and stable than the Bowline, as Table 2 indicates.

Table 2. Patil et al. (2020) refer to N, τ and Γ as a knot's counting numbers. The greater their magnitude, the more stable the knot is. The ô and Ã sum provides a single comparative figure independent of crossing number. Values may vary slightly according to how a planar projection is rendered and what assumptions are made regarding the load vector orientations.

Knot Properties	**Bowline**	**Figure Eight Loop**
Idealised Planar Projection Crossing Number (N)	7	16
Three-Dimensional Projection Crossing Number (N)	7	20
Topological Twist Fluctuation Energy (τ)	0,82	0,95
Topological Circulation Energy (Γ)	3,67	9,67
Combined Value = τ + Γ	4,49	10,62

Further, each knots' ability to absorb energy and reduce impact forces is linked to its sinuosity, concatenation and crossing number (Martin et al., 2015; Sry et al., 2018). Energy absorption, of course, is related to the linear modulus of elasticity for ropes, so "elastic" knots are more important in rescue and rope-access contexts where low stretch or static lines are employed (Sry et al., 2018). The Figure Eight Loop is more "elastic" than the Bowline (Audoly, 2007). The Figure Nine and Stevedore's Loops are even more resilient because they have greater sinuosity or embodied rope length (Chisnall, 2020).

Conclusions

Activities involving fall prevention and fall arrest safety systems depend on reliable knots for harness tie-in purposes in addition to anchoring. The key difference is, anchor knots are usually stationary while harness knots are mobile elements in the safety system. Securing safety harnesses to belay lines integrates a number of critical steps: selecting the proper knot, understanding its strengths and weaknesses, mitigating those weaknesses, tying the knot correctly and checking it by incorporating behavioural and structural redundancy into regular habits and procedures. No step can be ignored because there is no such thing as a perfect knot and everyone is fallible.

Appendix

Calculating Topological Twist Fluctuation and Circulation Energies

Orient load vectors in the planar projection of the knot in order to determine writhe. Calculate the topological twist fluctuation energy (τ) as follows, which is related to Ashley's (1944) principle of the knot and concatenation (Chisnall, 2020):

$$\tau = (1/N)\ \Sigma i\ (qi - q)2 \qquad (0 \geq \tau \geq 1)$$

where, qi is + 1 or -1 for each crossing or vertex twist charge and,

Wr =Σi qi (writhe)

q = (1/N)Σi qi = Wr/N (average writhe or ground-state energy density)

Calculate the total circulation energy (Γ), which assesses friction and incorporates Ashley's (1944) principle of the knot, as follows:

Γ = ΣF (|CF/eF)

where, CF is the friction contributed by each face or bounded area (F) according to the net circulation energy of the edges or spans circumnavigating a face, normalized by eF, which is the total number of edges per face (Patil et al., 2020).

References

American Alpine Club (AAC). (1980). Fall on Rock, Failure of Knot, Colorado, Lover's Leap. Accidents in North American Mountaineering, 4, 3 (33), 34.

Ashley, C. W. (1944). The Ashley book of knots. New York, NY: Doubleday & Company, Inc.

Association of Canadian Mountain Guides (ACMG) and the American Mountain Guides Association (AMGA). (1999). Technical handbook for mountain guides: Alpine, rock, and ski guiding techniques. Golden: AMGA; Canmore AB: ACMG.

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

Borwick, G. R. (1973). Mountaineering ropes. Alpine Journal, 1973, 62-70.

Bowern, C., (2015). Linguistics: evolution and linguistic change. Current Biology, 25 (1), R41-R43. https://doi.org/10.1016/j.cub.2014.11.053

Brown, M.G., (2000). Engineering practical rope rescue systems. Canada, United States: Delmar Thomas Learning.

Brumbagh, C. (May 12, 2013). How safe is the bowline knot in different situations? The Great Outdoors. Retrieved July 8, 2020 from https://outdoors.stackexchange.com/questions/3798/how-safe-is-the-bowline-kno t-in-different-situations

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

Budworth, G. (1999). The ultimate encyclopedia of knots & ropework. London, Great Britain: Prospero Books.

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. (1985). The ORCA rock climbing safety manual, (2nd ed.). Toronto, ON: Ontario Rock Climbing Association, 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. (2016a). 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. (2016b). Analysing knot evidence: associating innate habits with sophisticated tying tasks. Scandinavian Journal of Forensic Science, 22(2), 21-32. doi: 10.1515/sjfs-20160005.

Chisnall, R. (2020a). Analysing knots and ligatures: tying principles, knot characteristics and structural changes. Forensic Science International.
https://doi.org/10.1016/j.forsciint.2020.110272
Chisnall R. (2020b). A brief review of side bends: Application, rationale, accidents and testing. International Journal of Mountaineering and Climbing 3(2), 38-52.
Colby, B. N. (1958). Behavioral redundancy. Behavioral Science, 3 (1), 317-311.
https://doi.org/10.1002/bs.3830030129
Couffe, C., Michael, G. A. (2017). Failures due to interruptions or distractions: a review and new framework. American Journal of Psychology, 130 (2),163-81.
https://doi.org/10.5406/amerjpsyc.130.2.0163
Craik, F. I. M. (2014). Effects of distraction on memory and cognition: a commentary. Frontiers in Psychology, 204 (5), 841. https://doi.org/10.3389/fpsyg.2014.00841
doi: de Boer, C. (2005). Postbag: New Bowline? Knotting Matters, 88, 44.
Douglas, E. (April 5, 2012). Climbing wall death due to knot failure. British Mountaineering Council (BMC). Retrieved July 8, 2020 from https://www.thebmc.co.uk/climbing-walldeath-due-to-knot-failure
Evans, T. (2016). A review of knot strength testing. International Technical Rescue Symposium (ITRS). Retrieved July 8, 2020 from
http://itrsonline.org/wordpress/wp-content/uploads/2016/11/Evans_Truebe.A-Review-of-Knot-Strength-Testing
Ewing, H. A. (1973). Knots and hitches in synthetic fibre ropes. The Hydro-Electric Power Commission of Ontario, Research Division Report, 1973.
Flashman, J. (November 3, 2017). Tying in: The Bowline vs. The Figure 8 Knot. Retrieved July 8, 2020 from https://www.climbing.com/skills/tyng-in-the-bowline-vs-the-figure-8-knot/
Gommers, M. (July 30, 2013). An Analysis of Bowlines. July 2013. Version 2.1c. Retrieved July 8, fromhttp://www.paci.com.au/downloads_public/knots/Bowlines_Analysis.pdf
Graumont, R. M., & Hensel J. J. (1952). Encyclopedia of knots and fancy rope work, (4th ed.). Cambridge, MD: Cornell Maritime Press.
Graydon, D. (Ed.). (1992). Mountaineering: The freedom of the hills, (5th ed.). Seattle, WA: The Mountaineers.
Gripped. (2018). Boy seriously injured in auto-belay accident in Ontario. Retrieved August 3, 2020. from https://gripped.com/news/boy-seriously-injured-auto-belay-accident-Ontario/
Hill, L. (2000). Climbing free: My life in the vertical world.
International Federation of Sport Climbing (IFSC). (2020). Job description for event organization team. Retrieved September 3, 2021 from
https://cdn.ifsc-climbing.org/images/ifsc/Footer/Officials/
130117_DLD_JobDescriptionEOTEAM.pdf
Jackson, J., & Whiteman, M. (2002). Accident report: Not the knot: Bowline comes undone–again. Rock and Ice, 182, 30.
Kirkpatrick, A. (November 24, 2011). Ban the Bowline? (Posted 24 November 2011) Retrieved July 8, 2020 from
https://www.andy-kirkpatrick.com/blog/view/ban_the_bowline/
Langseth, T., Salvesen, Ø. (2018). Rock climbing, risk, and recognition. Frontiers in Psychology, 9, 1793. https://doi.org/10.3389/fpsyg.2018.01793
Lipke, R. (1997). Technical Rescue Riggers Guide (revised ed.) Bellingham, WA: Conterra Technical Systems Inc.
Llewellyn, D. J., Sanchez, X. (2002). Individual differences and risk taking in rock climbing. Psychology of Sport and Exercise, 9 (4), 413-426.
https://doi.org/10.1016/j.psychsport.2007.07.003

Luebben, C. (1993). Knots for climbers. Evergreen, CO: Chockstone Press.
MacDonald, D. (2016). Fall on rock, Incomplete tie-in knot. Accidents in North American Climbing, 11 (1) Issue 69, 129.
MacDonald, D., (2020). Fatal Lead fall on rock. Accidents in North American Climbing, 11 (4) Issue 72, 124-125.
Martin, D. A., Boron, K., Obstalecki, M., 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
McKentley, J. (2014). Rescue knot efficiency revisited. International Technical Rescue
Symposium (ITRS). Retrieved July 8, 2020 from http:itrsonline/rescue-knot-efficiency-revisited
Michael, T. (2005). Accident report: knot, don't fail me now! Rock and Ice, 144, 36.
Microys, H. F. (1977). Climbing ropes. American Alpine Journal, 21, 130-147.
Moyer, T., Tusting, P., & Harmston, C. (2000). Comparative testing of high strength cord.
International Technical Rescue Symposium (ITRS). Retrieved July 30, 2020 from https://user.xmission.com/-tmoyer/testing/High_Strength_Cord.pdf
Nuttall, O.K. (2015). The RAM-BOW-LINE. Knotting Matters, 128, 16-18.
Olevsky, R. (2003). Better beta: A better mousetrap. Rock and Ice, 129, 88.
Osius, A. (May 11, 2015). TNB: When your rope falls off–and 5 ways to prevent the nightmare. Rock and Ice. Retrieved July 8, 2020 from
https://rockandice.com/tuesday-night-bouldering/tnb-when-your-rope-falls-off-an d-5-ways-to-prevent-the-nightmare/
Osius, A. (2020). Stay safe: buddy-check your knots. Rock and Ice. Retrieved July 8, 2020 from https://rockandice.com/inside-beta/stay-safe-buddy-check-your-knots/
Osius, A. (2021). Is your knot tied? Even the best get it wrong. Don't let it happen to you. Climbing. Retrieved August 31, 2021 from
https://www.climbing.com/skillsis-knot-tied-5-tips-avoiding-common-causeaccidents/
Patil, V.P., Sandt, J. D., Kolle, M., & Dunkel, J. (2020). Topological mechanics of knots and tangles. Science, 367, 71-75. https://doi.org/10.1126/science.aaz0135
Pegg, D. (2001). Techtip sport: no more tears — a trim knot that unties easily. Climbing, 208, 102.
Petzl®. (2006). Carabiner use and misuse. Rock and Ice, 153, 102.
Petzl®. (2007). Examples of dangerous carabiner loading. Retrieved July 8, 2020 from https://www.petzl.com/I/en/Sport/Examples-of-dangerous-carabiner-loading
Petzl®. (1995-2020). Knots. Retrieved July 8, 2020 from https://www.petzl.com/INT/en/Sport/Knots
Pope, J. F. (1972). Tests of knots. Summit, April, 18 (2).
Prohaska, H. (1988). The Double Bight Bowline. Summit, 34 (3), 22-23.
Prohaska, H. (1998). Gefahren bei anseilknoten [Dangers with rope knots]. Die Alpen 2/1998, 28-30.
Prohaska, H. (2001). Knotentests -Das verhalten von seilknoten [Knot tests - The behavior of rope knots]. Erweitertung zum Kongressl-band Psyche und Berg, 2001, 1-13.
Prohaska, H. (2005). Bowline failure. Knotting Matters, 88, 19.
Raleigh, D. (1998). Knots & ropes for climbers. Mechanicsburg, PA: Stackpole Books.
Raleigh, D. (2005). Double trouble? Rethinking the Double-Loop Bowline. Rock and Ice, 144, 106107.
Rock and Ice. (2010). Bowline comes untied, climber falls to ground. Bowline comes undone — again. Retrieved July 8, 2020 from
https://rockandice.com/climbing-accidents/bowline-comes-untied-climber-falls-toground/

Rock and Ice. (December 6, 2012). John Long seriously injured in fall. Retrieved July 8, 2020 fromhttps://rockandice.com/climbing-news/ john-long-seriously-injured-in-fall/

Roy, A. (2012). Bye Bye Bowline: Time for a new knot. Outside. Retrieved July 8, 2020 from http://www.outsideonline.com/1911861/bye-bye-bowline-time-new-knot

Schad, R. (2000). Analysis of climbing accidents. Accident Analysis & Prevention, 32 (2), 391-

396. https://doi.org/10.1016/S0001-4575(99)00026-3

Schmidt, D. (2005). Tech tip trad: Twisting time. Climbing 242, 98.

Schubert, P. (2001). Sicherheit und risiko in fels und eis 01 [Safety and risk in rock and ice 01]. Germany: Bergverlag Rother.

Šimon, J., Dekýš, V., & Palèek, P. (2020). Revision of commonly used loop knots efficiencies. Acta Physica Polonica A 138 (3).

Smith, B., Padgett, A. (1996). On rope: North American vertical rope techniques (new revised ed.). Huntsville, AL: Vertical Section, National Speleological Society.

Sry, V., Mizutani, Y., 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. Applied Sciences, 8 (7), 1096.

doi:10.3390/app8071096.

Steels, L. (2017). Do languages evolve or merely change? Journal of Neurolinguistics, 43 (Part B), 199-203. https://doi.org/10.1016/j.jneuroling.2016.10.001

Vines, T. & Hudson, S., (1989). High angle rescue techniques. Dubuque, IA: National Association for Search and Rescue.

Warner, C. (1996). Studies on the behaviour of knots. In J. C. Turner & P. van de Griend (Eds.).

The history of science and knots, Series on Knots and Everything – Vol. 11. (pp. 181203). River Edge, NJ: World Scientific Publishing Co.

Wheelock, W. (1967). Ropes, knots & slings for climbers, (revised ed.). Glendale, CA: 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).

Yosemite Climbing Information. (2020). Accident report: Incorrect leader tie-in, Five & Dime Cliff. Retrieved August 31, 2021 from

https://www.climbingyosemite.com/portfolio/accident-report-incorrect-leader-tie-infive-dime-cliff/