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Top-Rope Tırmanışda Emniyet Noktalarının Teorik Analizi; Yedeklilik ve Göreceli Başarısızlık Potansiyeline Odaklanma

A Theoretical Analysis Of Top-Rope Climbing Anchors Focussing On Redundancy And Relative Failure Potential

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Öz

Civata kullanan üst halat kurulumları ile ilgili olarak, kordeletin iki versiyonu, dörtlünün üç versiyonu ve temel iki askılı ankraj kurulumu, bileşen fazlalığı ve arıza potansiyelinin birleştirici bir analizi kullanılarak değerlendirilir. İki askılı kurulum, her bileşen kopyalandığı için tam aktif yedeklilik sunar. Dörtlüyü kurmak için iki ilmek düğümü gereklidir ve bu düğümlerin yedeği yoktur. Benzer şekilde, kordeletin ana bağlantı noktasını oluşturmak için kullanılan ilmek düğümü gereksiz değildir. Üst halat ankrajlarında kullanılan sapanlar ve kordonlar, düşme ve alçalma sırasında yükün yanal olarak kayması durumunda aşınma hasarına karşı savunmasız olabilir. Düğümler aşınmaya özellikle duyarlı olabilir. Ankraj düğümlerinin kütlesi ve yapısı, muhtemelen kaya sürtünmesinin ve potansiyel sistem arızasının ortak belirleyicileridir. Dört ilmek düğümlerinin tek ve çift versiyonlarının özellikleri gözden geçirilmiştir. Bu karşılaştırmada diğer kurulum özellikleri ve bağlamsal faktörler dikkate alınır.

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Abstract

With regard to top-rope setups using bolts, two versions of the cordelette, three versions of the quad, and a basic two-sling anchor setup are evaluated using a combinatoric analysis of component redundancy and failure potential. The two-sling setup offers complete active redundancy because each component is duplicated. Two loop knots are required to set up the quad and those knots have no backup. Similarly, the loop knot employed to create the cordelette's master point of attachment is not redundant. Slings and cords utilized in top-rope anchors can be vulnerable to abrasion damage if the load shifts laterally during falls and lowers. Knots may be particularly susceptible to wear. The bulk and structure of anchoring knots are likely co-determinants of rock chafing and potential system failure. The characteristics of single and double versions of four loop knots are reviewed. Other setup characteristics and contextual factors are considered in this comparison.

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Geniş Özet

Kordelette ve dörtlü, spor tırmanışlarında standart demirleme stratejileri haline gelmiştir (Beverly ve digerleri, 2005; Uzun, 1993; Long ve Gaines, 1996; Smith ve Padgett, 1996; Stewart-Patterson, 2018; UIAA-Petzl Vakfi, 2013). Bu kurulumların genel yedekliliği, analiz edilen ana özellik olacaktır. Ancak, ilgili yerlerde diğer özelliklerden kısaca bahsedilecektir. Bağımsız halkalar oluşturmak ve bir bağlantı noktasının arızalanması durumunda gevsekliği azaltmak için aksesuar kablosuna stratejik olarak ek düğümler bağlanır. Kordelette (perlon) ile bir ana bağlantı noktası oluşturmak için bir düğüm bağlanır. Kendi kendini ayarlamayı ve yük dağılımını kolaylaştırmak için dörtlüye iki düğüm bağlanır. Güvenlik sistemi bileşenleri, bir zincirdeki bağlantılar gibi seri olarak bağlanabilir, bu da birbirlerine bağli oldukları anlamına gelir. Herhangi bir bileşen arızalanırsa, sistem başarısız olur. Kurulum, yalnızca en zayıf veya en güvensiz bileşen kadar güvenilirdir. Yedeklilik, paralel sistem bileşenleri kullanarak oluşturulur. Bir bileşen başarısız olursa, en az bir yedekleme vardir. Aktif yedekli ankraj sistemlerinde, iki ankraj noktası tarafindan tutarlı bir şekilde paylaşılmadığı takdirde, yükü desteklerken her iki paralel bileşen de değişebilir. Kordelet kurulumu, kordelet kollarına yük eşit olarak uygulanmadığında bu şekilde çalışır. Örneğin, tırmanıcı iniş sırasında yanal olarak sallanırsa, kuvvet iki kol arasında değişir. Paylaşılan yük sistemi kendi kendini ayarlar ve yükün her zaman paylaşılması beklenir. Kordelette yükü dağıtabilse de, dörtlünün paylaşılan yük veya yük dağıtım sistemi olarak daha tutarlı olduğu kabul edilir. Genel olarak, bireysel ankraj arızası olasılığı daha yüksek olabilir, ancak potansiyel şok yüklemesi genellikle eşitlenmemiş sistemlerde daha düşüktür (Chisnall, 1985). Tersine, kendi kendini eşitleyen kurulumlar kullanılırken, tek tek ankrajlarin başarısız olma olasılığı daha düşük olabilir, ancak bir tarafın bağlantısı kesilirse, şok yüklemesi için daha büyük bir potansiyel olabilir ve belki de bir zincirleme reaksiyon ankraj arızası meydana gelebilir. Bunlar öncelikle, sabit civataların olmadığı durumlarda ankraj istasyonlarının doğaçlama yapıldığı ve erişilebilir kaya özellikleri ve mevcut ekipman kullanılarak inşa edildiği birçok geleneksel tırmanma ve dağcılık durumuyla ilgilidir (Long ve Gaines, 1996; Vogwell ve Minguez, 2007). Bazı çapalar idealden daha az olabilir (Law & Hawkshaw, 2012). Teorik sistem arızası olasılığı; paralel elemanların kombinasyonları ve permütasyonları göz önünde bulundurularak, bu analizde olasılığın toplama ve çarpma kuralları uygulanacaktır (Freund, 1971). Her sistem bileşenine teorik bir arıza olasılığı atanacaktır (mühendislik literatüründe güvenilirlik olarak bilinir). Her hata olayı ikili olarak kabul edilir: bileşen ya başarısız olur ya da tutar. Basitlik adına, analiz edilen sistemlerdeki her düğümün, düğüm verimliliği ve aşınma nedeniyle tam olarak düğümde bağımsız bir arıza olasılığına sahip ayrı bir bileşen olduğu varsayılacaktır. Benzer şekilde, kablo kurulumlarının halkaları ve kolları ayrı sistem bileşenleri olarak ele alınacaktır. İki ayrı sapan ve dört kilitli karabina kullanan bir sistem, civatalardan emniyet hattına kadar gerçekten gereksizdir. Her şey paralel ve yedeklidir. İlgili tüm faktörler eşit olduğunda, başarısız olma olasılığı en düşük olanıdır. Yükü her zaman eşit olarak dağıtmaz, ancak kurulumda ekstra gevşeklik olmadığı için olası şok yükleri minimum olmalıdır. Buna karşılık, dörtlü ve kordelette tamamen gereksiz değildir. Dağcılar, ankrajları birbirine bağlamak için kordelette ve dörtlüyü kullanır ve teknik bir kısayol olarak ilmek dügümleri ekleyerek tek parça aksesuar kablosuyla yedeklilik oluşturur. Aksesuar kabloları bu düğümlerde gereksiz değildir. Kordelette bir düğüm içerir ve dörtlü iki düğüm içerir. Yedeklilik açısından, ayrılmış karabinalara sahip geleneksel dörtlü kurulum, üst halat uygulamaları için en az uygun olanıdır. Koşum takımlarının ve bel cihazlarının bir araya toplanmak yerine düzenli ve ayrı tutulmasının önemli olduğu ve potansiyel düğüm sürtünmesini yakından izleyebildiği çok adımlı tırmanışlar için daha uygundur. Çok adımlı tırmanışlar için dörtlüyü kurmanın başka yöntemleri de vardır. Kayar veya sihirli X konfigürasyonuna benzeyen eşleştirilmiş karabinalara sahip dörtlü, üst halat amaçları için geleneksel dörtlüden daha yedeklidir.

Diğer faktörler; dörtlüyü eşleştirilmiş karabina modunda kullanmak, kablonun iki alt halkası birbirini geçerken ve bazen sıkışırken potansiyel naylon üzerinde naylon sürtünmesine ve aşınmaya neden olur. Bu, özellikle küçük çaplı Dyneema® veya Spectra® sapanları ile ilgilidir. Naylon ve Kevlar'dan® çok daha düşük bir erime noktasına sahiptirler ve sürtünme hasara neden olabilir. Yüklü bir kordon veya askı, tırmanıcı yanal olarak hareket ederse veya sallanırsa, yana doğru hareket edebilir, böylece düğümü veya düğümleri kayaya karsi aşındırabılır. Kordon kollarının uçları da civata karabinalari döndükçe aşınabılır. Bu, yükün yönüne göre ayarlandığı için dörtlü için özel bir endişe kaynağı olsa da, kordelette yanal hareketle de aşınabilir. Daha önce de belirtildiği gibi, bazı hacimli düğümler daha güçlü ve çözülmesi daha kolay olsa da, önemli ölçüde daha fazla kordon gerektirirler ve bağlı sistemin kollarını oluşturmak için mevcut miktari azaltırlar. Genel olarak, düğüm ne kadar hacimli ve ne kadar çok kesişme noktasına sahipse, o kadar güçlüdür ve çoğu durumda yapısal nüanslara bağlı olarak çözülmesi daha kolay olacaktır (Peranski ve digerleri, 2010). Döngü düğümü özellikleri; dağcılar, dörtlüyü kurarken tipik olarak iki basit Overhand Loop'u ve cordelette'i kullanırken sekizli düğümü bağlarlar. Yeterli kordon varsa, bazı dağcılar dörtlüye iki sekizli düğümü bağlamayı seçerler. Dokuzlu ve Stevedore Döngüleri de seçeneklerdir. Kaya aşınması ve kesilmesi yoluyla bir düğümde kordon kopması olasılığının belirlenmesine gelince, hangi düğümlerin daha yüksek potansiyel başarısızlık olasılığına sahip olduğunu gösteren ampirik bir kanıt yoktur. Bununla birlikte, en az iki temel düğüm özelliği, temas yüzey alanını ve aşınma potansiyelini nasıl etkiledikleri konusunda ortak belirleyici olabilir. Sonuç; kordelette ve dörtlüyü kurmak için kullanılan düğümler gereksiz değildir. Düğümlerin yapısına ve diğer bağlamsal faktörlere bağlı olarak aşınma hasarına ve ardından arızaya eğilimli olabilirler. Genel olarak, kordelette dörtlüden daha gereksizdir, ancak tamamen gereksiz değildir. Buna karşılık, dörtlü, kuvveti kordeletten daha iyi ayarlamalı ve dağıtmalıdır, ancak bu garanti edilmez. Deneyim ve detaylara gösterilen özen, uygun tekniklerin kullanılmasıyla ankraj güvenilirliğini en üst düzeye çikarabilir. Aşındırıldığında hangi düğümlerin başarısız olma olasılığının daha yüksek olduğu daha fazla araştırma konusudur.

Introduction

General categories of anchor and belay setups include fixed-point or direct belays, resilient or harness belays, and load-distribution or self-equalizing anchors. There are numerous methods of setting up an anchoring system using two bolts, whether for top-roping purposes, single-pitch leads or multi-pitch climbing. These include the cordelette, the equalette, the sliding or magic X, the quad, the ponytail, the banshee belay, Chamonix anchoring, and so forth – terms that are sometimes applied changeably or ambiguously (Debruin, 2019; Gibbs, 2012, Long, 1993; Long & Gaines, 1996).1 The principal context herein will be top-rope anchoring in a one-pitch environment, and three basic anchoring techniques will be compared.

The cordelette and the quad have evolved to be standard anchoring strategies on sport climbs (Beverly et al., 2005; Long, 1993; Long & Gaines, 1996; Smith & Padgett, 1996; Stewart-Patterson, 2018; UIAA-Petzl Foundation, 2013). The general redundancy of these setups will be the main characteristic analysed. However, other features will be briefly mentioned where relevant. For the purposes of comparison, a third technique will be included in the discussion, a basic top-rope setup employing two independent sewn slings with locking carabiners. As will be discussed, there is no such thing as a perfect safety technique nor one that is suitable for all occasions (Chisnall, 1985, 2023). Every method has benefits and drawbacks, and one or more potential modes of failure.

Overview

When setting up top-rope anchors, modern sport climbers typically utilize a loop of accessory cord or a sewn sling and four locking carabiners for maximum security. To reduce gear weight and setup time, some climbers opt to use two non-locking carabiners at the bolts, which are not as secure as locking carabiners. Two locking carabiners are paired to connect the rope to the anchor setup. Paired carabiners are typically reversed or opposed to minimize the chances of accidental detachment (Figure 1). Parallel carabiners should be avoided. Security can be further enhanced by using auto-locking carabiners, or manually-locking carabiners oriented so that vibration and gravity tighten rather than loosen their screw sleeves.

Figure 1. Carabiner orientations, from left to right: unsafe parallel D carabiners because they open on the same side in the same direction; reversed D carabiners, which open in opposite directions; opposed HMS carabiners, which open on opposite sides.

Anchoring cords can be fashioned from six to seven metres of a 7-millimetre polyamide synthetic, usually DuPont™ nylon 66 or IG Farben Perlon™ (nylon 6). Thinner, lighter and stronger products include 5.5-millimetre or 6-millimetre accessory cords comprising ultrahigh molecular weight polyethelene (UHMWPE), such as Honeywell™ Spectra® and DSM Dyneema®, or the DuPont™ aramid Kevlar®. Accessory cords containing the Teijin Aramid copolyamide called Technora® or the Kuraray America Incorporated liquid-crystal polymer Vectran® are available as well (Flory, et al., 2015; McKenna, et al., 2004). These synthetic fibres have different characteristics and advantages.

Figure 2. Fisherman's Knots, from left to right: Single, Double and Triple Fisherman's Knots.

To create a closed loop, the ends of thinner accessory cords are secured with a Triple Fisherman's Knot to maximize security (Smith & Padgett, 1996). Larger diameters of nylon accessory cord are often tied with Double Fisherman's Knots. (See Figure 2.) The Single Fisherman's Knot is an inadequate bend because it has insufficient topological circulation energy and twist fluctuation energy (Chisnall, 2020, Patil, et al., 2020) and is therefore less secure. Depending on the diameter of the accessory cord, the length of the tails, the bend selected, and how that knot is dressed and tensioned, the knot and the working ends will occupy 50 to 80 centimetres of cord. That leaves an effective cord circumference of between 5,0 and 6,5 metres, roughly, depending on the initial cord length. Long sewn slings can be used in place of accessory cord on sport climbs as well as for mountaineering and ice climbing (Stewart-Patterson, 2018; UIAA-Petzl Foundation, 2013). The longest slings available measure 120 and 150 centimetres in length, or 2,4 and 3,0 metres in circumference. Hence, sling length can be a limiting factor. Two slings can be used in parallel to improve redundancy.

Additional knots are strategically tied in the accessory cord to create independent loops and to reduce slack in case one attachment point fails. With the cordelette, one knot is tied to establish a master point of attachment. Two knots are tied in the quad to facilitate self adjustment and load distribution. Some climbers elect to leave the knots pre-tied in their quad and even their cordelette. Pre-tied knots save time, but they are prone to gradual tightening and localized wear. Removing and retying those knots promotes differential wear. Additionally, if system knots have not been fully tightened by way of repeated loading, they can serve as minor shock absorbers (Beverly & Attaway, no date cited). The knots dissipate some of the kinetic energy as they tighten when force is applied.

Redundancy

Safety system components can be connected in series, like links in a chain, which means they depend on each other. If any component fails, the system fails. The setup is only as reliable as the weakest or most insecure component. Redundancy is created by employing parallel system components. If one component fails, there is at least one backup. Several types of redundancy are distinguished in the scientific literature focussing on Markov-based reliability engineering, electrical power delivery, management and information hierarchies, structural safety, computer infrastructures, and various other connected systems (Fang & Fan, 2011; Kim, 2023; Peiravi, et al., 202; Nesgaard & Andersen, 2004; Pierre, 2021). The terminology employed in these fields can be descriptive of climbing anchor setups as well, and a two-bolt top-rope anchoring system may be regarded as having double modular redundancy. Herein, the terms passive or standby, shared-load, and active redundancy will describe the anchoring systems analysed:

Passive (Standby) – One component takes the load while a parallel component remains relaxed, ready to be tensioned if the former component fails. Most modern anchor setups do not fit this model. However, some antiquated setups utilized passive redundancy.

Active – With active-redundancy anchoring systems, both parallel components can alternate when supporting the load if it is not consistently shared by the two anchor points. The cordelette setup performs in this manner when the load is not applied equally to the cordelette arms. The force switches between the two arms if the climber swings laterally during lowers, for example.

Shared-Load – The system self adjusts and the load is expected to be shared at all times. Although the cordelette can distribute the load, the quad is deemed to be more consistent as a shared-load or load-distribution system.

Load Distribution

It is beneficial to compare the strengths and weaknesses of self-equalizing (shared-load) and non- equalizing (active) systems in terms of fundamental anchor strength and system failure potential. If the integrity of the rock anchors themselves is in question – whether they are bolts, pitons, chocks or cams – load distribution and potential shock loading can become critical issues. In general, the likelihood of individual anchor failure may be higher but potential shock loading is usually lower with non-equalized systems (Chisnall, 1985). Conversely, when using self- equalizing setups, individual anchors may be less likely to fail but if one side disconnects, there could be a greater potential for shock loading, and perhaps a chain-reaction anchor failure will occur. That likelihood might have been overestimated in the past (Debruin, 2021; Jenks, 20202). Although it seems counterintuitive, there is some evidence to suggest that an equalizing or load- distribution system may not be as effective as an active or non-equalizing system in some situations (Owen & Naguran, 2004).

With regard to the cordelette, especially if it has three arms as in trad situations, some research suggests that the shortest or shorter arm sustains higher loads, even when the arms appear to distribute the load evenly (Beverly, et al., 2005). The theory is that the central knot tightens and the longer arms stretch more thereby reducing their share of the overall load. Of course this may depend on how the central knot is dressed. The bights of each arm can reside within the knot proper in different configurations – whether they are located on the outside or inside. Another factor is whether or not low-stretch or dynamic accessory cord is employed. Slings tend to have low stretch.

These are primarily concerns in many traditional climbing and mountaineering situations where anchor stations are improvised and constructed using accessible rock features and available equipment when there are no fixed bolts (Long & Gaines, 1996; Vogwell & Minguez, 2007). Some anchors can be less than ideal (Law & Hawkshaw, 2012). Modern sport climbs are usually equipped with at least two modern and reliable bolts with appropriate hangers or anchoring hardware that accommodates belays, lowers and rappels (Chisnall, 2023).

Theoretical Probability of System Failure

By considering combinations and permutations of parallel elements, the addition and multiplication rules of probability will be applied in this analysis (Freund, 1971). Each system component will be assigned a theoretical probability of failure (known as reliability in the engineering literature). Each failure event will be considered binary: the component either fails or it holds. Partial damage and gradual degradation will not be considered. The total theoretical probability of complete system failure will be determined by considering all possible methods of detachment via combinatorics (Wilson, 2016). Rope and belay failure will not be included in the analysis as they are assumed to be equal probabilities in all four setup analyses.

For the sake of simplicity, it will be assumed that each knot in the analysed systems is a separate component with an independent likelihood of failure exactly at the knot due to knot efficiency and abrasion. Similarly, the loops and arms of the cord setups will be treated as separate system components, with failure likely at the carabiner attachments or as a result of abrasion damage. Knot testing has shown that cord failure often occurs slightly outside the knot (Pieranski, 2010). Failure can also occur inside the knot at a critical point where force is concentrated at a sharp bend in the cord.

The main questions of interest in this discussion are as follows. How redundant are popular top- rope anchor systems? What is the comparative theoretical probability of failure for each setup, no matter how low? How can the probability of failure be minimized through redundancy? The analysis herein will examine two versions of the cordelette, three versions of the quad, and a setup utilizing two independent sewn slings.

The simplified theoretical probabilities of overall system failure for two-bolt top-rope anchor setups are determined below, where:

B = Bolt
C = Carabiner
A = Cord or sling arm (single or double) connecting the bolt to the centralized anchor point
K = Knot
L = Centralized loop (single or double) connecting the anchor system to the belay line P(x)
= Hypothetical probability of component x failing
p = Total probability of system failure

Figure 3. Two slings and four locking carabiners employed to set up a truly redundant but non-adjusting anchor system. Rope attached to reversed D carabiners.

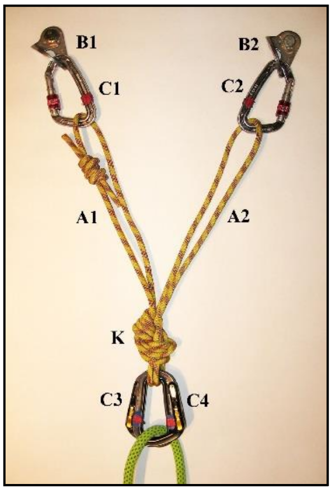

Figure 4. A cordelette tied with a single cord. Rope attached to opposed HMS carabiners and multi-strand Figure Eight Loop.

Figure 5. A cordelette tied with a double cord. Rope attached to opposed HMS carabiners and multi-strand Figure Eight Loop. (Figure 4 labels apply to this image.)

Two Slings and Four Carabiners (Figure 3)

$$p = P(B1)P(B2) + P(B1)P(C2) + P(B1)P(A2) + P(C1)P(B2) + P(C1)P(C2) + P(C1)P(A2) + P(A1)P(B2) + P(A1)P(C2) + P(A1)P(A2) + P(C3)P(C4)$$

Cordelette (Figures 4 and 5)

$$p = P(B1)P(B2) + P(B1)P(C2) + P(B1)P(A2) + P(C1)P(B2) + P(C1)P(C2) + P(C1)P(A2) + P(A1)P(A2) + P(K) + P(L1)P(L2) + P(C3)P(C4)$$

Quad With Paired Carabiners (Figures 6 and 7)

$$p = P(B1)P(B2) + P(B1)P(C2) + P(B1)P(A2) + P(C1)P(B2) + P(C1)P(C2) + P(C1)P(A2) + P(A1)P(A2) + P(K1) + P(K2) + P(L1)P(L2) + P(C3)P(C4)$$

Quad With Separated Carabiners (Figures 8 and 9)

$$p = P(B1)P(B2) + P(B1)P(C2) + P(B1)P(A2) + P(C1)P(B2) + P(C1)P(C2) + P(C1)P(A2) + P(A1)P(A2) + P(K1) + P(K2) + P(L1)P(L2) + P(L1)P(C4) + P(C3)P(L2) + P(C3)P(C4)$$

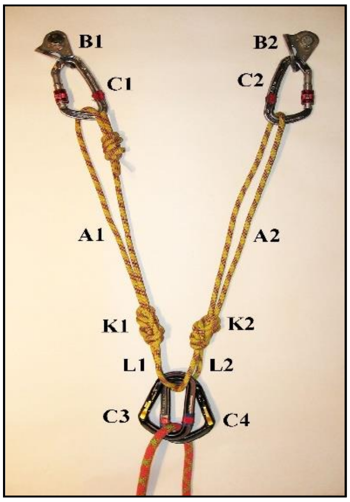

Figure 6. Quad with paired carabiners using a single cord. Rope attached to opposed HMS carabiners and cord segments isolated with two Overhand Loops.

Figure 7. Quad with paired carabiners using a double cord. Rope attached to opposed HMS carabiners and cord segments isolated with two multi-strand Overhand Loops. (Figure 6 labels apply to this image as well.)

Figure 8. Quad with separated carabiners using a single cord. Rope attached to separated HMS carabiners and cord segments isolated with two Overhand Loops.

Figure 9. Quad with separated carabiners using a double cord. Rope attached to separated HMS carabiners and cord segments isolated with two multi-strand Overhand Loops. (Figure 8 labels apply to this image as well.)

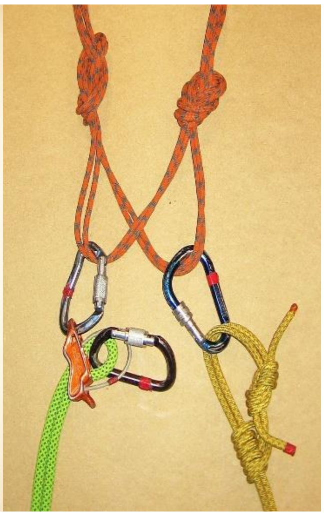

Figure 10. Quad multi-pitch setup, with system elements conveniently spaced apart. The belay is on the left and the belayer’s Purcell Prusik leash (PAS) is on the right.

Table 1. Anchor setups compared.

System (In Order of Decreasing Redundancy)	**Modes of Failure (Pairs of Components)**	**Single Components (Non-Redundant)**
Two Slings and Four Carabiners	10	0
Cordelette	10	1
Quad With Parallel Carabiners	11	2
Quad With Separated Carabiners	13	2

For the cordelette and quad, note that P(A1), P(A2), P(L1) and P(L2) are very small when the cord arms and loops are doubled. In general, cordelettes and quads are stronger and more redundant when the accessory cord is doubled. Doubling the accessory cord doubles the anchoring system arms and loops. However, P(K1) and P(K2) are presumed to be higher when the cords are doubled and the knots are bulkier. Although bulkier knots may be stronger, they can be larger abrasion targets. This concern will be discussed later. The systems analysed above are presented according to increasing theoretical failure probabilities. Provided the equipment is sound and protected from damage, the odds of catastrophic failure for all systems is low.

The system that utilizes two separate slings and four locking carabiners is truly redundant, from the bolts to the belay line. Everything is parallel and backed up. All relevant factors being equal, it is the least likely to fail. It does not distribute the load equally all of the time but potential shock loads should be minimal because there is not extra slack in the setup. In contrast, the quad and cordelette are not entirely redundant. Climbers utilize the cordelette and the quad to link anchors and create redundancy with one piece of accessory cord by adding loop knots as a technical shortcut. Accessory cords are not redundant at those knots. The cordelette contains one knot and the quad has two knots.

In terms of redundancy, the conventional quad setup with separated carabiners is the least suitable for top-rope applications. It is better suited for multi-pitch climbs where keeping harness attachments and belay devices organized and separated rather than bunched together is important, and where the belayer can closely monitor potential knot chafing (Figure 10). There are several other methods of setting up the quad for multi-pitch climbs. The quad with paired carabiners, which is akin to the sliding or magic X configuration, is more redundant than the conventional quad for top-roping purposes.

Other Factors

There are several details other than redundancy worth noting. The shorter the cord arms or slings, and the greater the distance between the bolts, the larger the subtending angle between the arms and the higher the potential forces on the bolts. This can be determined by Fa = F/2cos(è/2), where Fa is the force on each bolt, F is the total system load, and è equals the subtending angle between cord arms or slings. If the subtending angle between the cord arms is zero, the load each arm shares is approximately half the applied force. If the angle measures 120 degrees, the force doubles, subjecting each arm to the full load owing to vector multiplication. At around 170 degrees, the force on each bolt can be about 5,7 times that of the applied load (Brown, 2000; Smith & Padgett, 1996). Some research indicates that this is of little concern so along as the subtending angle does not exceed 120 degrees, and the accessory cord arms are not short and stiff (Beverly, et al., 2005).

Nevertheless, in certain types of setups a large subtending angle may cause carabiner three-way loading or side loading.

The benefits of the quad over the cordelette appear to be twofold. First, in theory, the quad has the ability to adjust if there is lateral movement during the climb, but research has shown that the load is not necessarily distributed equally (Debruin, D, 2019, 2021; Owen & Naguran, 2004). Second, using separated loops and carabiners at the lower centralized attachment points helps to keep personal anchoring systems (PAS or leashes) and belays organized and separated on multi-pitch climbs, as mentioned previously (Figure 10). Nevertheless, it is possible to keep system elements somewhat separate with the cordellete by using both the lower master point of attachment, or power point, and the shelf just above the centralized knot. There are two flaws in this arrangement, however. The cordelette shelf may be awkward to clip and unclip when the arms are tight, and the two attachment points are vertically rather than laterally aligned so there may be some overlap and interference between system elements.

Another detail has emerged from practical testing. In theory, self-equalizing systems tend to have a higher likelihood of shock-loading the anchors if one anchor point fails, compared to fixed-arm anchor systems. However, the shock loads one might expect could be lower than anticipated depending on how much rope is in the system (Jenks, 2020). In top-roping situations, shock loads may be mitigated by the dynamic nature of the belay line and the fact that knots reduce impact forces as they tighten. Test data has revealed that perfect load distribution does not occur, regardless of the system (Bedogni, et al., 2015; Beverly, et al., 2005; Debruin, 2019, 2021; Gibbs, 2012). With the cordelette, two fixed arm lengths can spread the load disproportionally by as much as an 80/20 division, depending on the initial tension in each arm and central knot tightening. Even a load-distribution or self-equalizing system such as the quad can exhibit a load division of as much as 60/40. Perhaps an even greater difference can be experienced under adverse conditions. This may be caused by fiction between the rock, the lower carabiners and the cord or slings. Carabiner orientation and whether the carabiners are separated or paired are potential contributing factors as well.

Using the quad in the paired-carabiner mode introduces potential nylon-on-nylon friction and wear as the two lower loops of cord slide past one another and sometimes pinch. This is of particular concern with small-diameter Dyneema® or Spectra® slings. They have a much lower melting point than nylon and Kevlar®, and friction could cause damage.

A loaded cord or sling may move sideways if the climber moves or swings laterally, thereby abrading the knot or knots against the rock. The tips of the cord arms also can abrade as the bolt carabiners pivot. Even though this is a particular concern with the quad as it adjusts according the direction of the load, the cordelette can abrade as well with lateral movement. Again, this is why the cordelette is not redundant at its centralized knot; nor is the quad redundant at its two arm-limiting knots. Even the Double or Triple Fisherman in one of the cord arms can be abraded. The arms themselves are redundant in both the cordelette and the quad, provided the knots are not simultaneously compromised, and doubling the accessory cord increases redundancy. Still, cord and sewn sling arms can also abrade against sharp rock when loaded and moved laterally.

Some preliminary abrasion tests using 2-millimetre nylon cord and a uniform abrasive surface indicate that both the cordelette and the quad can fail completely if all arms or two loops disconnect at the knot or knots simultaneously, as one might expect. It is unclear from this very limited investigation whether or not there is any difference between the quad and cordelette when it comes to abrasion failure vulnerability, other than the number of knots involved. Disregarding other combinatoric modes of failure, the cordelette will be compromised if the single central knot ruptures; one or both quad knots must be damaged to cause system failure. Standardised destructive testing using conventional accessory cord at an actual climbing site might reveal specific setup weaknesses according to rock type and geometry. However, this kind of testing likely cannot capture the myriad of anchoring situations encountered in the wild. Climber experience and judgment must come into play when choosing the appropriate technique. Care must be taken to ensure that all knots are free of obstacles to minimize abrasion potential.

Loop Knot Characteristics

Climbers typically tie two simple Overhand Loops when setting up the quad, and the Figure Eight Loop when using the cordelette. If there is sufficient cord, some climbers elect to tie two Figure Eight Loops in the quad. The Figure Nine and Stevedore (sometimes called Stevedore's) Loops are also options (Figure 11). Even though certain bulkier knots can be stronger and easier to untie, as mentioned previously, they require substantially more cord and decrease the amount available to form the arms of the connected system.

Figure 11. Loop knots, with equivalent stopper knots. Left column, from top to bottom: Overhand Knot, Figure Eight Knot, Figure Nine or Intermediate knot, Stevedore Knot. Right column, from top to bottom: Overhand Loop, Figure Eight Loop, Figure Nine or Intermediate Loop, Stevedore Loop.

Figure 12. Frost Knot, which is a hybrid of the Water Knot and an Overhand Loop. Left: traditional Frost Knot. Right: Frost Knot tied in doubled cord to create a master point of attachment for the cordelette.

Aside from the four loop knots mentioned, some climbers use the Frost Knot (Figure 12) to secure the cordelette. The Frost Knot combines the Water Knot (a bend) and the Overhand Loop (a loop knot) into one knot, thereby dispensing with the need for a Double or Triple Fisherman's Knot, which can sometimes interfere with setup adjustments and equalization actions. This also frees up some cord length, but the Frost Knot may have to be tied and untied each time the cord is used. This can be time consuming. As when tying any knot, dressing, tension and end lengths have to be checked to ensure optimal security and strength. There are Frost Knot versions of the other loop knots mentioned, and the quad can be set up as well using a Frost Knot and an Overhand Loop, or equivalent knots.

The amount of rope or cord contained within a knot is referred to as the knot's sinuosity (Chisnall, 2020). Using six-millimetre Kevlar® accessory cord, the sinuosity of each of four loop knots was measured after a preliminary loading of 10 kg., adhering to the EN standardized method for accessing rope knotability (European Standard EN 826, 1996). The Frost Knot was not included in this assessment. Approximate sinuosity measurements are summarized in Table 2, along with crossing numbers and approximate knot sizes.

Table 2. A comparison of loop knot characteristics.

Loop Knot	**Planar Projection Crossing Number with Reidemeister[3] Simplification**	**Approximate Cord Sinuosity (Centimetres)**	**Approximate Load-Axis Length (Millimetres)**
Overhand Loop in Single Cord	12	26	35
Overhand Loop in Doubled Cord	48	69	45
Figure Eight Loop in Single Cord	16	36	50
Figure Eight Loop in Doubled Cord	64	104	73
Figure Nine Loop in Single Cord	20	42	50
Figure Nine in Doubled Cord	80	123	74
Stevedore Loop in Single Cord	24	49	56
Stevedore Loop in Doubled Cord	96	149	78

In general, the bulkier the knot and the more crossing points it has, the stronger it is and, in many cases depending on structural nuances, it will be easier to untie (Peranski, et al., 2010). (There are exceptions.) This is usually the case with the knots listed in Table 2. However, measuring knot tensile breaking strength or efficiency and expressing it accurately is challenging because the relationship between the absolute breaking strength of the test material and the breaking strength of the knot is best determined by a probability density function and presented as a range (Šimon et al., 2022). Much published research on knot strength has not met this standard.

As for determining the likelihood of cord rupture at a knot through rock abrasion and cutting, there is no empirical evidence to indicate which knots have higher potential probabilities of failure. However, at least two key knot characteristics may be co-determinants in how they affect contact surface area and abrasion potential: size and structural heterogeneity. First, if the knot is bulkier, it presents a larger abrasion target, although the abrading force presumably is reduced by being spread over a greater surface area. In contrast, a small knot may concentrate the abrading force onto a smaller surface area and therefore encourage damage to accumulate more rapidly. Nevertheless, knots are not smooth structures. They have irregular three-dimensional features, and some areas of their surface may come into contact with abrading or cutting obstacles while other areas may be tucked away within concavities and are thereby protected. Additionally, the characteristics of the accessory cord itself may increase friction as knots come into contact with rock, thus hastening cord damage. In conjunction with knot concavities and convexities, the surface texture and bending rigidity of the accessory cord can come into play, along with the cord material and diameter. Researchers examine those characteristics when testing surgical knots tied in suture materials, referring to surface irregularities as asperities (Ben Adbessalem, et al., 2009; Datta Roy, et al., 2019). Braid angles and fibre coatings are taken into account as well. The phenomenon of knot deformation is another variable. Knots can capsize, flip, flype, reptate and otherwise change shape or position in a number of ways (Chisnall, 2020). Of course other variables such as site-specific rock texture and geometry are important too.

Conclusions

The knots used to set up the cordelette and quad are not redundant. They may be prone to abrasion damage and subsequent failure, depending on the structure of the knots themselves and other contextual factors. In general, the cordelette is more redundant than the quad, but it is not perfectly redundant. In contrast, the quad should self adjust and distribute the force better than the cordelette, but this is not guaranteed.

Therefore, top-rope climbers need to master a number of anchoring techniques to accommodate different setup requirements, which can be evaluated using several key questions. Which is the best setup for the situation presented? Does the load need to be distributed between the anchors with an adjustable system? Will the climb involve a lot of lateral movement? If so, will the anchor cord and knots abrade against the rock? Experience and attention to detail can maximize anchor reliability through the use of appropriate techniques. Which knots are more likely to fail when abraded is a matter of further research.

Endnotes

1. Academics studying language evolution note that terminology varies and changes according to regional and colloquial idiosyncrasies, the adoption of foreign-language terms, forgotten nomenclature and new technology (Bowren, 2015; Chisnall, 2016; Steels, 2017). The generic naming of climbing equipment, safety techniques, knots and free-climbing movements is no exception. Imprecision as well as multiple and shared terms can cause confusion.

2. The results from in situ tests demonstrate that an ample length of rope can act as a shock- absorber and thereby lower impact forces. Presumably the force should be higher if the load falls directly onto the anchor sling or cord without an intermediate dynamic belay line in the system.

3. Reidemeister moves eliminate extraneous crossing points in a planar projection, thus reducing a knot to its structural essence. Topologists have shown that three types of Reidemeister moves are all that are required to simplify any knot (Adams, 2001).

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