Protecting An Abseil: A Study Of Friction Knots

The article below was prompted by local Queensland bushwalking clubs having gained liability insurance for abseiling after many years of not having access to that skill. Many members needed upskilling and thus Federation Mountain Rescue took the opportunity to look at all aspects of training and methods etc. Dr. Ron Farmer is a climber of many years standing, he was present for many of the first ascents at Frog Buttress and other notable mountains and cliffs around south east Queensland and wider a field. He is a founding member and president of Federation Mountain Rescue which was formed 40 or so years ago and that organisation was responsible for vertical rescue and lost persons in remote areas rescue well before the state emergency service came into being. FMR has had a significant role in developing training methods to prevent the need for rescues both in the bush and the vertical world. FMR is now mostly a bushwalking training and occasional search and rescue organisation. This document is a continuation of that effort. - Phil Box.

Any feedback on this study is welcome.
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The original authorship rests with Dr. Ron Farmer, I have been asked to submit the study on rockclimbing.com and also on chockstone so that it`s findings are as widely available as possible to the climbing community.

EXECUTIVE SUMMARY OF AN EXPERIMENTAL STUDY OF SOME FRICTION KNOTS COMMONLY RECOMMENDED FOR PROTECTING AN ABSEIL

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AIM

The aim of this study was to examine the suitability of various knots for protecting an abseil with a self-belay. The knots and the optimal thickness of accessory cord and the most suitable number of turns within each knot were investigated. Their use was examined on climbing ropes of various sizes, typically used in the past and presently.

Webbing used for this purpose was not investigated.

These experiments were performed as part of an internal Federation Mountain Rescue analysis, but some of the findings were so disturbing, it was thought that their wider distribution would be beneficial.

This is an abbreviated version of the original report and focuses on the main conclusions.

APPARATUS

The principle test equipment was a steel 50mm*50mm box section gantry 2.05 m high and 1.8m wide. A standard climbing pulley system was used to lift the weights which simulated a suspended light-weight human body. A weight-assisted hauling system enabled repeated raising of these test weights. A Gibbs ascender locked off the hauling system and another Gibbs ascender provided the attachment for the counter-weights and foot stirrup to assist with hauling. All ropes were attached to the horizontal beam with a clove hitch and tightened to prevent slippage during testing.

An electrical insulator was placed on the rope above each knot and the downward force, measured as a weight, was determined using a set of fishing scales. The insulator was used to give, as far as possible, an even downward pressure over the whole of the upper part of the knot area. Two 'simulated human' weights were used. They weighed approximately 70kg and 100kg as determined by common bathroom scales. They consisted of bushwalking packs filled with containers of water and attached by a Big D carabiner to the hauling system used to raise them for each test.

The carabiner used in all the tests for the Bachmann knot was an aluminum alloy Bonaiti screw gate UIAA rated at 3000kg along the spine and 800kg across the locked carabiner.

Rope and accessory cord diameters were measured with a vernier. A steel tape measure was used for determining other lengths.

ROPES AND CORD

Six ropes were used in this testing. They were an 8.9mm Mammut dynamic rope of kernmantle construction, an 11mm dynamic Edelrid kernmantle rope, a 15mm Edelrid kernmantle rope, a static 12mm Bluewater II nylon rope with a kernmantle construction, an 11mm No 4 nylon laid rope and a 9mm static kernmantle rope. The last two enabled comparison with earlier studies on ropes used therein.

The accessory cords were 6mm and 7mm Edelrid with maximum rated breaking strengths of 9.8kN and 13.4kN respectively. 4mm cord was not tested despite being suggested by some sources. Other reputable sources do not recommend it. The cord manufacturer Millet is one example.

METHOD OF INVESTIGATION

Four knots, the Autoblock, the Bachmann, the Prusik and the Klemheist were tested using both 6mm and 7mm cord.

For each cord a different numbers of turns in each knot was tested. Advice from the literature, plus testing, provided the range of number of turns suitable for exploration in this work. The six different climbing ropes described above were chosen to be representative of either those likely to be used by present day abseilers or which enjoyed major use historically.

252 individual experiments were performed. For each, the rope used, the knot type, the number of turns in the knot, the cord thickness, and the weight used were all recorded. The force, measured as a weight, up to 22kg, needed to just release the knot under the load from the weight, simulating a suspended person, was noted. If the knot re-gripped the rope after downward force was removed this was recorded positively as was the downward force again needed to re-release the knot. A failure to re-grip was recorded as unsafe. Typically, after re-gripping the rope, a greater subsequent force was needed to re-release the knot, at least on the second occasion. Subsequent occasions often required the same force as after the first re-grip.

The knots were allowed to come under load gradually. So the test was very generous in this regard, as in practice a failing abseil may result in a shock load. Such would be the case for an abseiler inverting, a pendulum, a partial anchor failure, dislodgment by rock-fall or a slip by the abseiler, for example.

It is important to note that a self-belay, once activated, needs to be releasable under the full load of the abseiler, in the worst case.

This is an important and often overlooked point.

This is generally not the situation when prusiking, as weight is shifted first onto one then the other of each friction knot. In prusiking the friction knot may then be released, often with some effort, as in the case of the Prusik knot. In an abseil failure, full body weight may be applied to the friction knot. The knots reliability and releasability in these circumstances may be crucial.

A standard comment is that the abseiler add another Prusik from their gear and release the pressure on the knot which protected them. While it might be reasonable to assume climbers, cavers and mountain rescuers might readily be able to do this, bushwalkers and mountaineers, particularly those working at high altitude, would be more likely to place a premium on having a minimum of gear.

A safer general approach is that once rigged, a self-belay protected abseil should already have all the necessary equipment installed and operational in preparation for complete and speedy recovery. This further reduces subsequent complications which may arise from injury, weakness, fatigue or lack of skill in attaching gear in a compromised set of demanding or unexpected circumstances.

It is observed that the simple procedure, often recommended, of using a “simple loop from a section of the trailing rope around a foot to enable the abseiler to stand up and un-weight the knot so as to unlock it.” sometimes becomes difficult in practice, especially for a novice.

So these tests have been graded rather harshly; if the knot can not be released with a downward force less than or equal to about 20kg weight, if the knot does not re-grip firmly once the knot is released and allowed to re-engage, or if after re-gripping it becomes un-releasable under a 20kg additional weight applied by the abseiler, it is rated as unsafe or quite unsatisfactory.

Perhaps surprisingly, a fit climber may be able to apply a pressure with their hands roughly equal to their weight. A safety factor of 4 to 8, commonly applied to engineered systems indicates that 20kg weight is a reasonable and indicative figure to use as a cut-off for applied force. A fit and trim climber could be expected to apply a pressure between 80 to 160 kg on this basis. Heavier individuals may view this cut-off as conservative. This figure does however, allow for safe performance even in adverse circumstances and does not rely on the abseiler having to use excessive strength to recover from an endangered abseil. These adverse circumstances may arise from environmental or other conditions such as icy or muddy rope, poor tying of a knot, an unexpected overhang, injury, fatigue or failure of strength perhaps under fear-inducing conditions.

The standard advice that a knot should be tested for suitability prior to use is probably reasonably sound for climbers, cavers, mountaineers and vertical rescuers, who are accustomed to exercising careful judgment based on extensive development of skills and acquisition of sound knowledge. Among other groups this may be an unsafe assumption.

The development of competency-based training has led to widespread copying of the form rather then necessarily the substance of such an approach. This may lead to a person being deemed qualified because they can successfully tie a particular knot ably and they have seen it work in a particular circumstance, repeatedly, and so have developed a possibly misplaced confidence in it, in their own competence and the suitability of the knot to perform in similar but slightly different situations. As we shall see this may be very dangerous. A beginner observing training and seeking guidance from recognized references, might reasonably extrapolate to apparently similar circumstances, with unexpected and unfavourable results.

It is probably the case that most climbers value self-reliance and take responsibility for their own actions so they would probably regard an uncritical approach with a healthy caution.

Those favouring holding to the ‘tried and true’ often also view as insignificant, and of little real importance, factors such as the following;

1. The ropes for which the knots were originally designed, a Tarbuck on hemp or laid rope for example, does not necessarily give support for its same use on different and more recently designed ropes. This should be subject to testing prior to use.
2. They overlook or downplay newer knots, despite adequate demonstration of superiority, because they believe the older knot is assumed to be ‘better tested’.
3. They tend to ignore changes in the type of climbing cord, and its breaking strength for a given

diameter, over time.
4. They apply a knot useful for ascending under shifting weight conditions to descending under loaded conditions with barely a moments reflection on the importance of this change, and
5. make no allowance for any differences in past knowledge, skills acquisition and in competence of execution by their predecessors.

This study tries to examine the objects of study carefully and systematically, under controlled conditions, based on application of the underlying physics and experimental testing, followed by systematic investigation of the resulting data. No preference is given for a particular outcome other than that thrown up by the results of the tests.

RESULTS

These tests apply to clean ropes in tropical and temperate conditions. The results should be used with great care and caution under different environmental circumstances. Icy or muddy ropes and wet conditions were not tested. So no conclusions have been drawn for these predicaments.

Perhaps the most startling conclusion is the high number of apparently reasonable configurations in which each of the tested knots is either not now recommended for a variety of reasons, or is clearly unsafe or quite unsatisfactory.

No conclusions are made with respect to mechanical ascenders, used to protect an abseil with a self-belay. This needs further examination. A strong influence in this study was to achieve safety with light-weight equipment for the benefit of bushwalkers.

The relative performance of the four tested knots, over all the tests, in decreasing order, was Autoblock clearly preferable, followed by the Bachmann, Prusik and a distant last the Klemheist, for this self-belay, rappel protecting application.

From the wide variety of arguably possible cases which were tested the Autoblock, which overall performed satisfactorily in the widest variety of cases, only 47%, (34 out of the 72 tests) of cases were capable of being recommended without strong reservations. 42% of configurations were unsafe and about 11% were not recommended but might be adequate in an emergency.

Generally, the next best performing knot for protecting an abseil was the Bachmann knot which performed satisfactorily in about 32% of cases, (19 out of 60 tests), was not recommended in 20% of circumstances and was definitely unsatisfactory or unsafe in 48% of tests.

The Prusik knot performed satisfactorily in this particular application in 27% (13 out of 48 tests), was not recommended in 23% of cases and was unsatisfactory or unsafe in 50% of cases.

The Klemheist knot, properly tied, was safely useable in the smallest percentage of tests, 7% (5 out of 72 tests), was not recommended in 12.5 % and was unsatisfactory or unsafe in 80.5% of tests.

Had less defensible possible cases such as 2 turns of 2mm cord on 11mm rope also been tested, and resulted in failure, and included along with all of the actual tests, the absolute percentages would have been different and even more dismal. The absolute percentages are not in themselves of direct fundamental importance, but the relative order is certainly indicative. This is important. However, since the configurations tested all represented possibilities within the ranges recommended by at least some reputable sources, the absolute percentages do indicate the strong need for testing a possible reasonable configuration before one relies upon it.

A clear example of how the absolute figures might change by altering the cases tested is provided by the Bachmann knot. A suspected reasonably workable arrangement might be 5 turns of 6mm cord. This was not tested on the grounds that it lay outside the range of circumstances commonly recommended. Such tests might work well even so, or they may fail. Either way, or for intervening possibilities, this would have altered the overall final percentages, but would probably have had little significant effect on the final order. On methodological grounds there is no basis to include this, or any other which lies outside the scope of testing configurations, namely those which have at least some support in the relevant literature.

Another way of looking at the figures is to consider only 6 or 7 mm cords and only 9 to 11 mm ropes, which bushwalkers, as opposed to rescuers, might use. The Autoblock knot now scores 43.75% (21 out of 48 relevant tests), the Bachmann knot 18.75% (9 out of 48 relevant tests), the Prusik knot 21.875% (7 out of 32 relevant tests) and the Klemheist knot 10.5% approximately (5 out of 48 relevant tests). The slight change in order arises from rejecting ropes that might still be reasonable such as 12mm and 14mm ropes. But the general superiority of the Autoblock remains and the small improved performance of the Klemheist is still not encouraging. Looking at this another way, rejection of the heavier ropes leads to a slight drop in the re-weighted percentages for the Autoblock; a significant drop in the case of the Bachmann knot, down from 32% to 18.75%; a small drop for the Prusik knot and a small improvement of the Klemheist knot.

Even a cursory glance at the following data organised by rope type, reveals the cause of this shift. The Bachmann knot performs better on thicker ropes and excluding these ropes reduces its performance within the chosen sub-set.

Obviously, this suggests some further tests, which may demonstrate the Bachmann's usability even for thinner ropes.

Clearly, more attention and care needs to be paid to the context in which a knot fails to perform its task adequately and in the particular configuration to which it is applied.

Note that these figures do not extrapolate to the use of these knots in prusiking. The conclusions only apply in protecting an abseil. Further, they are probably more representative of consequences arising from protecting an abseil with a friction knot above the abseil device than below it. (For a friction knot below the abseil device, all knots are expected to enjoy a higher reliability in terms of being readily released.) In this later configuration these knots might not be assessed so severely. Since it is part of the purpose of this investigation to delineate a safe working range this approach may be viewed as conservative.

Counter intuitively, but in accordance with conclusions drawn from studying the underlying forces applicable under tension, an improperly tied Klemheist knot would be expected to perform similarly to an Autoblock. For this study an improperly tied Klemheist is one in which the upper loop, under load, extends beyond the bottom of the turns around the rope. In the case of 3 turns it is difficult to tie the knot so that it does not become 'improperly tied' under load. In a range of additional tests this proved to be the case experimentally, with some variability in performance. This broadly supports the theoretical conclusions. Again this variability is to be expected because of the unevenness of tension on the upper and bottom loops depending on how the knot was tied and how it transformed under load.

Note that different knot books recommend tying this particular knot in slightly different ways, which turns out to be significant in practice. Attention is not drawn to this fact in the literature known to the author

Paradoxically, one concludes that these tests indicate that a person who might fail a competency-based test because they had not tied the Klemheist knot properly might in fact have tied a knot that performs satisfactorily in a far wider range of circumstances in practice, provided the intended use was for self-belay backup for an abseil.

DISCUSSION

We assess now, a brief summary of relevant information for each knot in turn, and will then focus on a more detailed analysis of the results of this work. A representative sample of the many sources available was used to garner as wide a range of useful suggestions as possible. These are spread over several decades reflecting different usage and equipment.

THE KNOTS AND THEIR HISTORICAL USAGE

About 15 different published sources from the 1960's to the present were reviewed for this work. The list is given in the fuller report and quoted material is there referenced explicitly. Here, for brevity, only the main results are quoted without reference back to the original material.

A. **PRUSIK KNOT**

In summary, 4mm cord is recommended in two sources with 2 turns.

Five mm cord with 2 turns is recommended five times and also for using 3 turns. Two published sources recommend 5mm cord with 3 or 4 turns.

Six mm cord is recommended with 2 turns by four books. They also advocate 3 turns as does another two sources. Two published works further advise on 4 turns.

Seven mm cord is recommended with 2 and 3 turns by three authors. Another source suggests 6mm and 7mm cord and yet another suggests 6mm cord.

Of historical interest two articles show 11mm laid rope with 2 wraps.

Thus the bulk of recommendations for the Prusik fall within the range of 5mm to 7mm and 2 to 4 turns

B. **BACHMANN KNOT**

Two references show 11mm laid rope with 5 and 2 wraps respectively.

In summary, no clear advice is given on cord diameter, although it is implied that it should be within the range of 5 to 7mm. One source shows 2 turns, another 3 turns and three others suggest 4 turns.

C. **KLEMHEIST KNOT**

In summary, there is little useful specific advice other than in two places which indicate that 4 or 5 turns could be used.

D. **AUTOBLOCK**

In summary, again little specific advice other than 3 turns in one book, 4 turns in two others and 5 turns in another.

Some motivational comments are worth quoting for completeness. "Belay methods and backup knots at the end of the rappel ropes can enhance the safety of a rappel. In addition, they add security to particular risky or unnerving rappels and may save the life of a rappeller hit by rock-fall. They also help beginners gain confidence in rappelling."

Finally, the following cautionary advice is worthy of repetition. "These knots require some testing and adjustment before each rappel in order to establish the proper length (so it does not hang up in the rappel device) and the proper amount of friction (adjusted by the number of wraps) to accommodate your weight, rappel device, comfort, and any other individual considerations. Some rappellers concerned about the effects of friction, chose the more heat-resistant varieties of cord or webbing for self-belay knots."

MORE DETAILED ANALYSIS OF THE EXPERIMENTAL RESULTS

These apparently depressing results need to be viewed in context. They are definitely NOT a measure of the relative safety of the knots. These figures include configurations an experienced climber would quickly reject after testing and reflect the range of use by a novice trying to apply these knots ‘by rote’, because they read or saw that, in a similar circumstance, a certain thickness of cord or that a certain number of turns was suitable and have uncritically applied that limited knowledge unwisely.

But before looking in closer detail at the data it is worth asking if there is a clear preference for 6mm over 7mm AS A GENERAL GUIDE ONLY. The answer is a clearly in the affirmative for 6mm cord and for all knots tested.

The Autoblock is useable in 2/3 of cases for 6mm and only 28% for 7mm. For the Bachmann it is 58% as opposed to 14%. For the Klemheist 6mm it was useable in 13% of cases for 6mm and in no case for 7mm. For the Prusik 37.5% of cases were useable for 6mm and only 16.5% for 7mm. Also of the ‘not recommended’ cases 7mm was three times more likely than the 6mm experiments to be so classified.

The ‘not recommended’ category has also been judged harshly. If a knot failed for any weight it was deemed to be unsuitable for all weights even though in many cases a particular experiment revealed that it was sound for that particular weight. But clearly a light person able to use such a configuration would endanger a heavy person if they advised copying or even if they were to abseil themselves with that set-up but now wearing a full pack!

The order of definitely unsafe or quite unsatisfactory was lowest for the Autoblock (28%), then Bachmann (33%), then Prusik (62%) and last the Klemheist (83%) for 6mm cord and Prusik (37.5%), Autoblock (55.5%), Bachmann (58%) and Klemheist (78%) for 7mm suggesting a further very rough guide of 6mm being preferred for the Autoblock and Bachmann and 7mm for possible use with the Prusik knot for self-belaying. 7mm cord was marginal, that is not recommended, in 46% of Prusik knot cases, so this possibility needs to be used with great care. Here it must be stressed that the Prusik has been rated poorly because of its failure to easily release after load, but its ability to grip in an adverse event is not in doubt.

Again it needs to be emphasized these conclusions should not be taken as valid for use of these knots in their usual ascending applications where different forces apply.

All these numbers are possibly artificially conservative because configurations that an experienced person might reject are included thus biasing the figures in a precautionary direction. But this bias is in the direction of following published advice or making reasonable extrapolations. If nothing else, it stresses the clear need for detailed examination and checking of one’s personal choice in any given set-up.

This study demonstrates that a ‘risk averse’ assessment may unconsciously grade knots on their ability to hold a slip and place less concern on its subsequent release. Both factors are important for successful recovery from an abseiling incident.

Perhaps a better way of looking at the data is to turn now to each rope type and reject those cord sizes and number of turns which failed always and consider the remaining cases which worked always for further elucidation.

NOTE: THESE RESULTS SHOULD NOT BE TRANSFERRED BEYOND THE PRECISE CONDITIONS GIVEN. IT IS THEIR VARIABILITY, NOT AN OPPORTUNITY FOR ROTE MEMORIZATION FOLLOWED BY POSSIBLE SUBSEQUENT MISUSE, THAT IS THE KEY POINT. THESE NUMBERS MAY HOWEVER PROVIDE SOME GUIDANCE FOR TESTING IN DIFFERENT SET_UPS, PROVIDED THEY ARE THOROUGHLY TESTED BEFORE USE.

A further note to reiterate that all tests were performed on single strands of rope. These results should not be transferred to double strands of ropes. Further tests of knots suitable for double strands of rope are necessary.

For the Dynamic 11mm rope the following was discovered:

Autoblock always worked for
6mm, 5 and 6 turns
Bachmann always worked for
6mm, 3 and 4 turns
Klemheist never worked
Prusik never worked (in all conditions but did in 1 case)

For the Dynamic 14mm rope the following was discovered:

Autoblock always worked for
6mm, 5 and 6 turns
7mm, 5 turns
Bachmann always worked for
6mm, 4 turns
7mm, 4 and 5 turns
Klemheist never worked (in all conditions but did in 2 cases)
Prusik always worked for
6mm, 3 turns

For the Dynamic 8.9mm Mammut rope the following was discovered:

Autoblock always worked for
6mm, 4 and 5 and 6 turns
7mm, 5 turns
Bachmann never worked
Klemheist always worked for
6mm, 3 and 4 turns!
Prusik always worked for
6mm, 3 or 2 turns

Please note the remarkable difference here and the un-transferability of experience from this rope to others or conversely.

For the Static 12mm rope the following was discovered:

Autoblock always worked for
6mm, 5 and 6 turns
7mm, 5 turns
Bachmann always worked for
6mm, 3 and 4 turns
Klemheist never worked
Prusik never worked (in all conditions but did in some)

For the Static 9mm rope the following was discovered:

Autoblock always worked for
6mm,6 turns
7mm, 5 turns
Bachmann never worked
Klemheist never worked
Prusik never worked (in all conditions but did in 2 cases)

Note the total failure of the Bachmann on this rope yet its general applicability on other larger diameter ropes.

For the Static laid 11mm rope the following was discovered:

Autoblock always worked for
6mm, 4 and 5 turns
Bachmann always worked for
6mm, 3 and 4 turns
7mm, 4 turns (marginal)
Klemheist never worked
Prusik never worked

Note that from this analysis we see that for the tested configurations there was always a configuration that performed safely with the Autoblock. For the larger diameter rope the Bachmann knot always had a safe performing configuration available. But for the smaller diameter ropes this changed dramatically. It raises the possibility that 4mm cord may be suitable on these ropes using a Bachmann knot but this was not tested.

Interestingly, the light-weight 8.9mm Mammut enabled the Klemheist to work for 6mm cord using either 3, 4 or 5 turns. The robustness of this knot for this rope does not, however, extend to other ropes, even those of small diameter. The failure of the Bachmann in this case, and for the 9mm static, (two small diameter climbing ropes) further emphasizes the care needed in transferring experience from one set of conditions to another without thorough checking.

Surprisingly, in these tests, the Prusik did not work on static ropes but always worked for 6mm cord on 8.9mm and 14mm dynamic rope, but never for the 11mm rope used! The newness of the sheath and the possible retention of the talc within the rope may have contributed to this. Again the unpredictability in going from one rope to the next needs to be carefully understood.

Let us now reverse the process and take the experimental data and see how the published advice meshes, or does not, with it. This might give some confidence or otherwise on the original sources or point up areas for further consideration.

This is not a circular argument since the references provided an indication only of the ranges, which might be usefully explored. Various conditions were then examined. The low percentage of successful results is partly because cases slightly outside the normal range of applicability have been tested.

For the Prusik knot, for those arrangements which worked, they all fell within the recommended ranges for both cord diameter and number of turns. But using the knot within these ranges did not always guarantee satisfactory results. Of some surprise, was the number of times 2 turns, which is widely drawn and described, failed to work properly, either because of slipping or because of excess gripping! Possibly this is attributable to the stringency of the present acceptance criteria.

For the Bachmann knot, for those arrangements which worked, they all fell within the recommended ranges for both cord diameter and number of turns. However, the advice in one reference that 2 turns is adequate remains untested in this study.

For the Klemheist knot, for those few arrangements which worked, they all fell within the recommended ranges for both cord diameter and number of turns. In fact, the knot was found to work, in some cases, outside the recommended range.

For the Autoblock knot, for those arrangements which worked, they all fell within the recommended ranges for both cord diameter and number of turns. However, many successful applications of the knot were consistently found by increasing the number of turns to 6. Only in the case of 6 turns in 6mm and 5 turns of 7mm cord did the knot then become unreleasable under the experimental conditions of the testing. So published advice on the range of usefulness of the Autoblock may be more conservative than for the other knots tested.

Finally, given these results, some indication may be given regarding the minimum loop size necessary to cover the full range of workable possibilities under the conditions of these tests.

For 7mm cord a minimum circumference of about 900mm suffices. This implies a cut cord length of about 1.5m allowing for the Double Fisherman's knot to be tied with adequate tails.

For 6mm cord a minimum circumference of about 900mm again suffices. This implies a cut cord length of about 1.35m allowing for the Double Fisherman's knots to be tied with adequate tails.

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