Some considerations for safer belay set-ups

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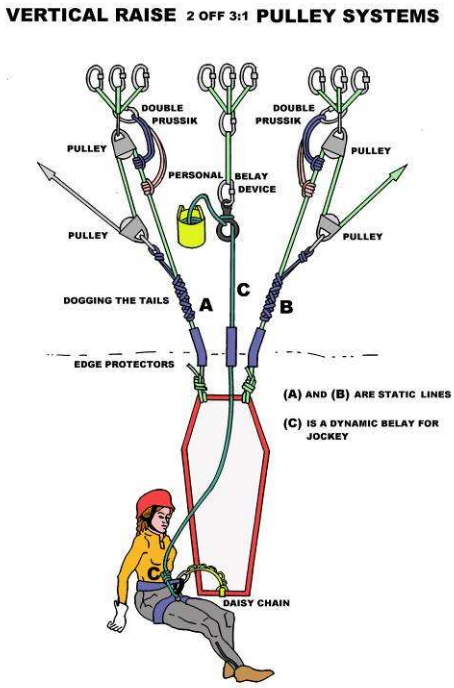
The KZN rescue team operates chiefly in the Drakensberg, where gear is sparse and the rock not known for its quality. The concepts described here arose from considering how to improve the safety of gear placements in these circumstances.

For those not familiar with rescue, general climbing belay set-ups and mountain rescue belay set-ups are similar. But rescue loads are higher because there is usually a patient and one rescuer on a stretcher, and we use low-stretch ropes. Low-stretch ropes typically stretch around 4% at full load and (obviously) do not have the stretch of dynamic climbing ropes which stretch over 30% at full load.

A typical rescue setup is shown in Figure 1. This shows that more attachment points are required than for a climbing belay.

Figure 1 Typical rescue set-up



Climbing books all emphasise the importance of equalising the load. Similarly, the mountain rescue team are taught to equalise the load, but thinking about our placement configurations, I realised we could improve the load-carrying capacity of the set-ups we were using. I did not find anything on the web about this, and the calculations need to be done iteratively, so I developed an Excel spreadsheet. This article arose from discussions after a presentation with the local rescue team.

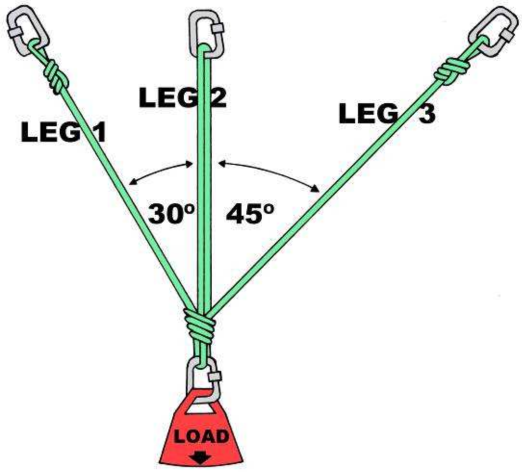
Although this is more important for rescue, where the loads are larger, the concepts are general, and a good understanding of them will help any climber to set up safer belays.

To start with it is necessary to emphasise an important concept: **the strongest setup is the one where ALL points will fail at the SAME time,** or alternatively phrased **each anchor point carries the same load up to the point of failure.**

This is not intuitive. One automatically thinks if all take equal load to start with, that is enough. But what matters is that they ALL carry equal load to the very end. If one point fails early, the other points have to carry everything and they will fail earlier. This means the TOTAL load that the system holds is reduced if one point fails before the others!

In addition, a significant shock load is caused by the first point to fail. The additional load and the sudden shock from the first piece to fail will cause the rest to break, one after the other; like a zipper.

Figure 2 Usual Belay Three Point Threading



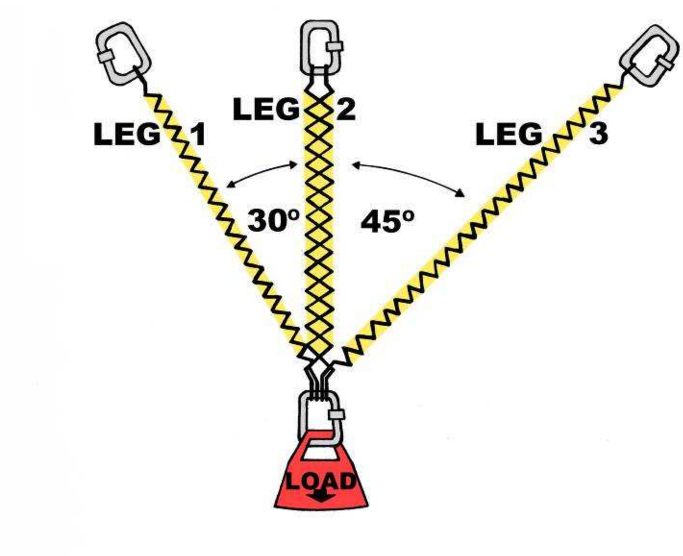
So the strongest system is where ALL points carry equal load to the point of failure. This will have the highest possible factor of safety.

The factor of safety is the failure load divided by the load we expect. Industrial lifting gear, where we know the strengths and loads, has a factor of safety of 6 to 10, Rescue loads are much more uncertain, and the strength of a few aluminium chocks jammed in a crack in the rock, even more uncertain! This makes it very important to build as much safety as we can into the system. We do not want a zipper; we want them all to fail together like a balloon.

Let us look at where this comes in to play. In rescue and in general climbing we often use three placement points. Figure 1 shows three clusters of three placement points. The easiest way to equalise the load on each of the clusters is to tie off on each end and double at the centre as shown in Figure 2. One then simply makes an overhand knot at the collection point to leave a loop to clip in to, and all is equalised. But is it?

A rope is like a spring, force is proportional to percentage stretch (or stretch divided by length). Even tape is just a stiff spring. Figure 3 shows what is happening in terms of springs. When pulled (loaded) the long springs at the angles give less force, because they are longer, and they stretch less because of the angle. The short springs in the centre stretch more and give more force – and there are two of them.

Figure 3 Usual Belay Illustrated as Springs



This means that for a typical setup as shown in Figure 2 one gets over three times as much force on the leg 2 placement as for leg 3.

For instance 20 kilo Newton (kN) is the force when things could be expected to start failing. At 20 kN load the forces on the gear are as follows:

- leg 1 - 5 kN;
- leg 2 - 13.3 kN;
- leg 3 - 3.3 kN.

(This adds up to more than 20 kN because of the effect of the angle).

Note the centre point (leg 2) carries more than three times the load of leg 3. If this fails at maximum load, leg 1 goes to 15 kN and leg 3 goes to 10 kN under STATIC conditions, so under dynamic conditions when leg 2 fails, so will the others – like a zipper.

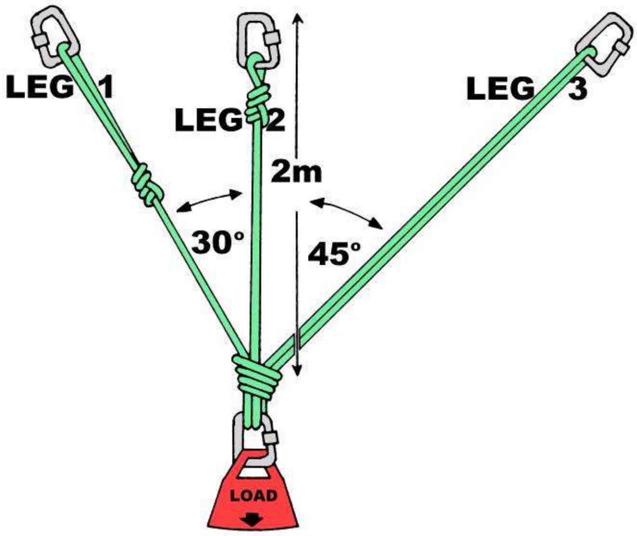
Actual loads gear can carry depends on the rock, etc., but large Friends and Camelots are rated around 14 kN, so these placements are marginal at full load. All stoppers, which are rated between 2 kN and 10 kN, could fail. Even hexes are only rated between 10 kN and 14 kN! The rule of thumb for allowable load our rescue team uses is 5 kN per anchor.

The interesting thing is that it does not matter if a dynamic rope, a low-stretch rope, or tape, is used; the relative forces keep virtually the same ratios. But at 20 kN load, the stretch of the centre changes from 27 mm to 199 mm if one changes from a low-stretch to dynamic rope.

When we view the setup as springs we see we can offset this unbalance of forces by moving the doubled rope to the longest leg and putting the single rope on the shortest leg.

It turns out that we can **roughly** balance the loads on the placements if we start threading at the shortest leg (leg 2) and then to the longest leg (leg 3) then end up on leg 1. Tie in to leg 1with a figure 8 with a long loop about a third of the leg length. This is shown in figure 4.

Figure 4 Three Point Arrangement to Maximise Load Carrying Capacity



Each placement in the optimised situation carries about 7.8 kN. **This means the system can carry a total load of 70% more** before the force on the centre leg is the same as it was with our original threading sequence! Very little effort gives us all this extra load capacity. A 70% increase in the factor of safety is not to be sniffed at – especially if you happen to be the dope on the end of the rope.

The important thing to realise is that we design the strongest setup when we **look at what is happening when the attachment points are close to failure**. Once we do that, we can use the different rope stretch of double ropes to our benefit.

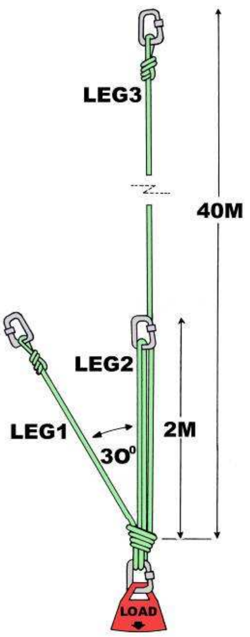
So the Rules for **points in a row** are:

1. Start on the **shortest leg** so it will be a **Single rope**.
2. Thread to the **longest run** so it will be a **Double rope**.
3. Finish on the intermediate length run with a loop of about 30% to 40 % of leg length.

These rules hold good for general climbing and rescue belays.

But what happens when the points are not in a row? In rescue we often use one good point far back. As an extreme case say we use almost a whole 50m rope for a setup. The closest point about 2 m away on leg 2 and leg 3 in line with leg 2 about 40 m away. See figure 5.

Figure 5 Extended Leg Belay Set Up



If we let Excel do the calculations again we find the following loads: 5.6 kN, 14.8 kN and 0.4 kN for legs 1, 2 and 3 respectively. In other words leg 3 carries virtually nothing until leg 2 and then leg 1 fails. To carry any load it needs to stretch. Low-stretch rope would need to stretch about 0.7 m to carry its share of the load. Dynamic rope would have to stretch over 4 m. Now it is easy to see why we use low-stretch ropes for rescue!

The one way we can get the back point to carry load is to use dynamic rope for the connection to legs 1 and 2. This allows them to stretch so the leg 3 gets to carry some load. Alternatively we would have to put slack in these legs, and with low stretch rope it turns out we need about 0.7 m of slack. With a dynamic rope we need more than 4 m slack – which is simply not practical. Although in rescue there is an initial load that would take out slack, there is still a chance of shock loading so introducing slack would be a last resort.

The permutations now get quite complex, but I think the point is made. The problem is what does one do in practice?

After investigation it turns out that there are some simple rules of thumb we can use (rescue set ups only in this case).

If the long leg is greater than 10 times the short leg length, do the following:

1. Mix rope types (preferred option)
    a. Use low-stretch rope for the long leg and double it, and dynamic rope for the other legs.
    b. Use the same basic improved configuration as before: The dynamic rope shortest leg is single, the intermediate length run with a loop of about 30% to 40% of leg length.
2. Put slack in the system (fall back option with low-stretch ropes only)
    a. If a single long rope is used; slack on the short rope is 1.5% (up to 2 %) of the length of the long rope.
    b. If you can double the long rope as in our improved standard setup, set the slack on the short rope to 0.5% of the length of the long rope.
3. In either case, where feasible, pre-tension the ropes as tight as possible in the direction of load. It makes a safer system and prevents shock loading. As the load comes on and the ropes stretch, the pre-tension is released so it does not add to the final load on the system.

Another important aspect to look at is the effect of mixing different stretch materials. Beware that mixing slings and ropes dramatically changes the forces one would expect. Even low-stretch ropes stretch a lot more than slings. So if one mixes a sling in a setup, as shown in photo 1, the sling will end up carrying virtually all the load unless considerable slack is introduced – and how much is enough? Slack also introduces the chance of shock loading so should be avoided. Once again rather try to set up using similar rope, and stiffen long lengths by doubling up.

Photo 1 A Busy Redirect

To conclude let us look at another practical example. Photo 2 is from a website on the internet showing how to equalise the load on 2 points.

A maximum fall load is usually considered to be about 12 kN. For a 12 kN fall load in the configuration shown, the short leg anchor point will reach a total force of 9.4 kN. So the long leg carries very little (only 3.1 kN) – not very well equalised.

Photo 2 Web Photo to show Equalising Two Anchors

But, as before, if we make the long leg the doubled one, the load is better equalised between the points. In this case, at a 12 kN fall load, the short leg reaches 6.4 kN and the long leg 6.1 kN. This is a 32% decrease maximum force! And this is achieved by simply using the same basic rules, to double the longer leg and a single rope on the shorter leg.

I will make the spreadsheet and more technical article available to interested people and can be contacted via the MCSA or on bsobey@gmail.com.

Note the usual disclaimers apply. It is difficult to calculate exactly what one gets in a setup and the calculations all assume the load does not move sideways to try to balance the forces. This does have some effect on the forces on the belay, but in reality the figures shown are fairly indicative of what would happen in practice. There is no doubt that using these simple rules improves the load distribution among the attachment points. Friction has also been ignored, and in practice that this can make a difference either positively or negatively if the legs of the belays are long and run over rock or soil. The settling of knots can also have some beneficial effect on load equalisation, which has been ignored. Some people may have read about self-equalizing anchors, but tests have proven that these are ineffective and they are a potential cause of shock loading. They are not recommended and not used by our rescue team.