# Friction Testing and Pulley Systems in Vertical Rescue

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## Executive Summary

- The most important factor affecting pulley friction is sheave diameter. Bigger diameter pulleys generally produce less friction.
- Reducing friction on the load line reduces the maximum load developed in the system, and so makes the system safer, as well as reducing the work required by the haul team.
- Significant benefits can be gained by using Multiplying Mechanical Advantages (XMAs) instead of traditional block and tackle rigs. XMAs use less pulleys, therefore the cumulative friction effects are less. The benefits of using XMA systems are: less work for the haul team, and the haul team has better feel for changing loads in the system. As a result, the VR operation is safer.
- Lifting Block and Tackle Haul systems should be avoided as these are the least efficient in terms of friction.
- Changing haul system pulleys from bushed pulleys to equivalent ball bearing pulleys reduces haul team effort by about 7%.
- Changing pulleys on the Larkin Rescue Frame from bushed to equivalent ball bearing type can reduce load line tensions by approximately 15%.
- If low friction ball bearing pulleys are to be used to best effect, all pulleys in the system should be of ball bearing type preferably.
- Avoid improvising redirections on moving ropes with karabiners. Even on small redirection angles (deviations) significant friction loads are added into the system.
- A single high redirection will introduce less friction, and therefore less tension increase, in the load line than the two redirections present in a Larkin Rescue Frame (LRF). For this reason, unless the LRF provides other advantages, such as isolation of the load line from abrasion points on the face of the pitch, a single high redirection should be considered as a default edge management machine wherever possible.

## Acknowledgments

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### Disclaimer

The information provided in this paper is presented in good faith. While every effort has been made to eliminate mistakes and false information from the information included in this paper, errors may occur. The authors, and The New South Wales State Emergency Service, its employees, volunteers and Units do not accept responsibility for any errors contained in this paper or for the results of the application of this information correct or otherwise. Vertical Rescue is a hazardous activity and requires appropriate quality equipment, and sound initial and ongoing training, teamwork, discipline, protocols and procedures to be executed safely. Check your vertical rescue protocols before applying the information provided in this paper.

# Introduction

During July and August 2004 Oberon State Emergency Service (SES) had possession of the load cell owned by State Headquarters of New South Wales State Emergency Service. The load cell is a Straightpoint NIP/5T 5 tonne load cell with remote digital display. Calibration data for the load cell shows it is accurate to +/- 2kgs over the full scale 0 to 5000kgs.

The author devised a method to measure the amount of friction developed in a vertical rescue (VR) pulley (and also some other devices and VR methods). The aim was to investigate friction in common rescue pulleys and devices and then draw conclusions that can be of benefit to vertical rescuers when selecting new equipment and when rigging systems.

The intention is not to complicate Vertical Rescue, and suggest that VR operators should work with actual Mechanical Advantages (MAs). For VR purposes, theoretical MAs have sufficed for many years and will continue to do so. However, there may be occasion on some technical rescues, or investigations, where actual MAs need to be estimated, and these results may be of some benefit.

# Discussion

## *Friction Test Method*

The friction testing method chosen was to anchor the load cell to the roof adjacent the mezzanine floor. A static life rescue line was attached to the load cell, looped down through a pulley (being tested) and back up to a rescue descender anchored in the roof adjacent the load cell.

A rescuer was used as the test load in order to facilitate resetting of the load for each test by simply walking up the stairs rather than carrying or hauling up a dead weight. We chose a burly rescuer in order to minimise the percentage measurement error.

Measurements were taken while lowering the test load to the ground – a distance of approximately 3 metres. Care is required to avoid dynamic load influences caused by acceleration and deceleration, so smooth lowering technique is important to good repeatable results.

Each pulley was tested twice. In some cases, the measured load would increase (by 1 kg) during the one descent. This was interpreted as being due to the load being near the change point from one reading to the next, and some minor effects due to heating or other action during the lower. For this reason, some results may have up to 4 measurements from just two test runs, but this was felt to be the best way to handle these observations.

We found it was important to achieve a free hanging pitch as just pushing off the mezzanine floor to gain clearance affected the measurements.

In most cases only one pulley of a particular make and model was tested. On a few tests, a second pulley of the same type was tested where the age or condition of the pulley was known to be significantly different to assess the importance of this difference.

A few tests were done with freshly lubricated pulleys. In each instance the same pulley as previously tested unlubricated was tested again after lubrication. The pulley was lubricated with WD-40 and then excess lubricant wiped away to avoid contamination of the rope.

Time and availability of pulleys prevented large sample sizes for each pulley, so these results cannot be definitively argued to be representative of all pulleys of the type, but most tests have produced a reasonable indication of performance for lay purposes.

## *Friction Test Measurements and Calculations*

Appendix I shows the Friction Test Results and basic calculation results. The first two columns show the test number and a description of the pulley or other device that was tested.

The pulley sheave diameter as measured with vernier callipers is recorded in column 3. This is the minimum diameter of the sheave groove, not the centre line diameter of the rope.

The “Tight Side Load, kg” is the measured load on the tight side of the pulley as the load is lowered. The deviation of the tight side tension from half the test load is a measure of half the friction of the pulley.

The 2 to 4 measurements taken for each test are averaged and this is displayed in the column marked “Average Measured Tight Side Load, kg”.

The “Tight Side Load Error, kg +/-“ is the measurement error inherent in the load cell, and so gives an indication of the accuracy and repeatability of the measurements.

The “% Load Tight Side” is calculated by dividing the Average Measured Tight Side Load for the test by that for the Test Load (recorded under “Load Calibration Tests”).

The “% Load Slack Side” is the complement of the “%Load Tight Side” so together they add up to 100% of the test load.

“Slack Side / Tight Side” is the ratio of the slack side rope tension to the tight side rope tension. This is assumed to be a constant for each pulley, as the amount of friction for each pulley is also assumed to be a constant proportion of the applied load on the pulley.

“Friction / Effort (Tight Side Tension)” is the percentage of effort applied to a pulley in a haul system that is lost as friction.

“Friction / Redirection Load” is the percentage of the load on the pulley that is lost as friction or added to rope tension as a result of friction during hauling operations. This figure is independent of the angle of wrap of the pulley.

“Friction / Load (Slack Side Tension)” is the percentage of the slack side tension that is lost as friction. In a real vertical rescue system, this represents how much the tension in the load line increases as the load line passes a 180 degree redirection pulley (such as at the top of a Larkin Rescue Frame when luffed in). This measure is affected by the angle of wrap of the redirection pulley. For a 90 degree angle of wrap, the Friction / Load ratio is multiplied by a factor or 70.71% to estimate a real tension, while for a 60 degree angle of wrap redirection, the value is halved.

The final calculated column contains the calculated error in all the calculated friction / load ratios.

## *Friction Test Findings*

Firstly when it comes to friction in pulleys, sheave size matters. Generally the larger the pulley sheave, the lower the friction. It is really the ratio of the sheave diameter to the axle diameter in bushed pulleys that matters. This ratio acts as a lever on the friction force that really acts between the axle and the bore of the pulley wheel hub.

There is a significant difference between bushed bearings and those fitted with ball bearings, provided the ball bearings are in good condition. In particular, compared the various results for an SRT P3a Pulley:

- Test 5: unlubricated - 16.4%
- Test 14: lubricated - 14.9%
- Test 19: Ball Bearing - 6.6%

The same pulley fitted with a ball bearing instead of a bush has considerably less than half the friction!

Another interesting result with ball bearing pulleys is that of the two Petzl P50’s that were tested (tests 21 and 22). The new Petzl P50 exhibited 9.7% friction / effort while the older P50 produced an equivalent 6.6% which is in the same ball park as the SRT P3a fitted with a ball bearing. At first glance this might suggest that ball bearing pulleys need to be “run in” to produce minimum friction, but the error on these calculated results is +/- 3.2% so this variation could also simply be measurement error in this experiment. Hence there is insufficient data to draw a conclusion either way and further statistical experimentation is necessary to resolve this point.

The author has limited experience with ball bearing pulleys in the VR environment, so reserves judgement about the durability of these pulleys with time. Likely threats to the performance of ball bearing pulleys are brinelling due to loading with very little movement (or an applied vibration), and contamination and possible corrosion in extreme environments such as if a pulley were allowed to heat up in the sun, before being immersed in salt water on a sea wall rescue for example. Such an example is extreme and rare, but is about the only way the author would expect a ball bearing pulley to draw sufficient contaminants into the bearing (fitted with seals) to cause deterioration in performance. The author therefore sees no reason to distinguish a bushed bearing pulley from a ball bearing pulley other than price and friction.

Lubrication of pulleys was not found to be a significant advantage from these tests. This may have been a result of the pulleys already being adequately lubricated prior to the “unlubricated” tests, or it may also be the result of the chosen lubricant, WD-40, not being the most appropriate for the conditions. Indeed in test 13, the lubricated SRT P1a Pulley, initial lubrication made a minor difference of just 2kg on the initial run, however, the friction increased by 1 kg in just the first 3m lower, and on the subsequent run the friction was the same as the unlubricated P1a (test 1). This may suggest that WD-40 is not an appropriate lubricant for VR pulleys as it is too easily squeezed out of the bearings under load, however, we must keep in mind that the variation detected in these tests is still less than the error range so this is not a definitive conclusion.

It is worthy of note, while discussing lubrication, that the Anchor 150mm Snatch Block (test 20) was dismantled to examine the bearing to see what type it had. It was found to be a cast iron wheel running on a steel shaft with no lubrication whatever, yet it demonstrated the least friction of any of the pulleys tested. This can only be attributed to the ratio of diameters of the sheave to the axle, once again reinforcing that pulley size matters.

Test 1 on the SRT P1a pulley contained only one good data point. This was because, being the initial test run, we discovered that the mere act of pushing off the mezzanine floor in order to clear it during the lower affected the results, so the initial corrupted run was discarded, and subsequently the test rig was adjusted to allow a clear pitch for the following tests.

In theory the results for the SRT P2a (test 2) and the P2Pa Prusik Minding pulley (test 8) should be the same. At first glance they differ but the degree of variation is within the error of the experiment, and may simply reflect normal pulley-to-pulley variation. It is not expected that this difference is in anyway due to the difference in cheek shape (the only design difference between the two pulleys).

Both CMI Rescue pulleys that were tested, the plastic sheaved (test 7) one and the stainless steel sheaved pulley (test 9) showed exactly the same characteristics. From this it is reasonable to draw the conclusion that the shaft and bush combination is the same regardless of the sheave material, as all other geometrical factors are the same.

A number of devices tested showed characteristics that are worthy of note. There was some difficulty in achieving friction tests on the edge rollers without additional friction of the rope rubbing on the side plates. Results both with and without side plate friction were included as it is not uncommon for this situation to arise in a real rescue or exercise.

The SRT P4Ka Knot Passing Pulley (test 18) demonstrated a tendency for the rope to run to one side and rub on the side cheek. This tendency is due to the radius of the groove in the sheave being greater than the distance from the karabiner attachment point to the face of the sheave. The author would recommend a deeper groove in the sheave of these pulleys to centre the rope and reduce friction.

Other devices apart from pulleys were also tested. Generally these are friction devices.

The simplest, of course, was simply a bight of rope around a karabiner. This would not normally be used in such as way as a friction device, but is sometimes used to build a mechanical advantage when pulleys are not available. Tests 10 and 11 were on an alloy and a steel karabiner respectively. Both produced about 50% friction / effort, with the alloy producing slightly more friction than steel.

A Kong Choy belay plate (test 29) was also tested, but as was expected, it was not a valid test of the performance of the device as the test did not allow the required bight back onto the plate for friction, so the results correspond with a rope running over a karabiner only.

Other friction devices tested included a figure eight descender (test 15), an Italian or Munter Hitch (test 16) and a round turn (test 28). The round turn on an alloy karabiner produced about 80% of the tight side tension as friction. The figure eight descender turned nearly 84% of the tight side tension into friction, but it must be kept in mind that the rope tail was parallel to the standing part (tight side) and so the figure eight would not be producing all the friction it would in normal operation. The Italian or Munter Hitch converted nearly 93% of the tight side tension to friction on an alloy karabiner.

Unfortunately many other friction devices used in vertical rescue did not readily lend themselves to this testing method, and so were not able to be tested.

## *Actual Mechanical Advantages of Common Haul Systems*

As a follow on to the friction testing of pulleys, it was decided to apply the data from the friction testing to common VR haul systems to calculate the Actual MA's that can be expected from these rigs.

Appendix II shows the calculated actual mechanical advantages of the most common VR haul systems with pulley friction ranging from 0 to 50% (friction/effort).

The "Slack Side / Tight Side" ratio is calculated from the "Friction / Effort". It is the slack / tight ratio that the actual MAs are calculated from. The "Slack Side / Tight Side" ratio also represents the actual MA of a 180 degree redirection pulley (theoretically 1:1).

2:1 MA is the simplest MA system. An example is shown in Figure 1.

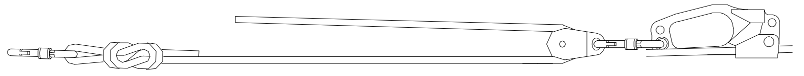

Figure 1: 2:1 Bolt-On MA

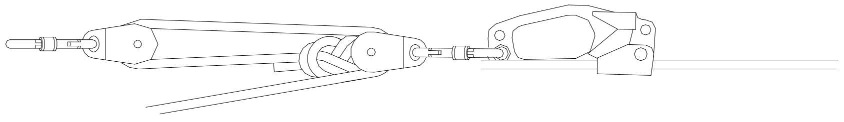

Figure 2: 3:1 Bolt-On MA

The 3:1 MA typically has two forms: either as a bolt on system (which is the same as a 3:1 block and tackle – see Figure 2) or a 3:1 Inline Z-Rig (Figure 3). From a friction point of view, both systems are exactly the same.

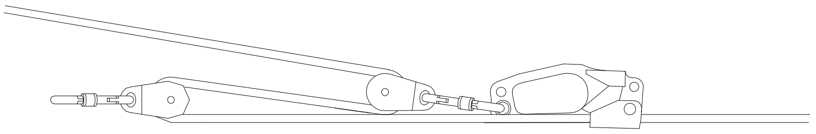

Figure 3: 3:1 In-Line Z-Rig MA

There are essentially three 4:1 haul systems: two are based around traditional block and tackle technology, and the third is a compound, or multiplying, mechanical advantage system.

The two block and tackle 4:1 systems are the 4:1 Hauling Block and Tackle (HBT) Mechanical Advantage (HBTMA), and the 4:1 Lifting Block and Tackle (LBT) Mechanical Advantage (LBTMA). In a HBT, the running end (or the rope the team hauls on) comes from the moving block. In an LBT, the running end comes from the fixed block.

The 4:1 HBTMA has a double sheave moving block, and a single sheave fixed block, while the 4:1 LBTMA has a double sheave block at both ends.

SRT Rescue-Mates, and personal MAs such as Haul-Traks, Trak-Haulers and All-Traks are all examples of LBTMAs in their normal operation mode.

LBTs are always less efficient than HBTs as the final redirection pulley adds friction without adding mechanical advantage.

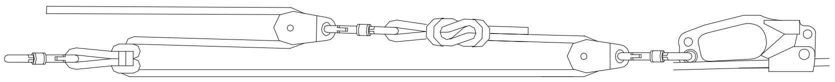

Figure 4: 4:1 Multiplying Mechanical Advantage (XMA)

The 4:1 Multiplying MA (XMA) takes this concept a step further, by eliminating all fixed block pulleys. By using a 2:1 MA to pull another 2:1 MA, the MAs are multiplied together, not just added like in a block and tackle. With no fixed end pulleys, the friction in the system is minimised, making this system more efficient than either of the block and tackle systems.

The 5:1 MAs are again based on block and tackle technology. The 5:1 HBTMA has a double sheave pulley at both ends, while the corresponding LBT has a triple sheave block at the fixed end and a double at the movable end. The 5:1 HBTMA can be produced by turning a 4:1 LBTMA around (i.e. swapping load and anchor ends).

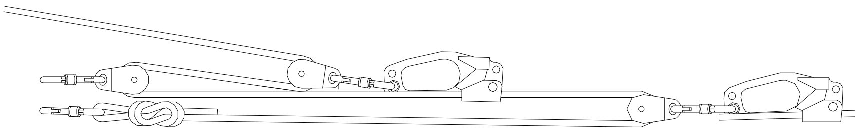

Figure 5: 6:1 Multiplying Mechanical Advantage (XMA)

The 6:1 MAs again consist of two block and tackle systems and a multiplying MA. The 6:1 HBTMA has a triple sheave block on the movable end, and a double sheave on the fixed end, while the LBTMA has triple sheave pulleys both ends.

The 6:1 XMA is produced but using either a 2:1 to pull a 3:1 or a 3:1 to pull a 2:1 MA. Figure 5 shows the simplest arrangement, with a 3:1 In-Line Z-Rig pulling the 2:1 – this arrangement can be efficiently built from the one rope. The second ascender (the one forming the Z-rig) can be replaced with a prusik loop or an alpine butterfly knot as appropriate.

The 8:1 XMA system is made by multiplying three 2:1 systems together – i.e. using a 2:1 MA to pull on a 4:1 XMA.

The final column of the table in Appendix II places the pulleys tested in the friction tests in their relative positions by friction. So based on the pulleys being used, it is possible to estimate the true or actual MA produced by the rigged haul system. Note that the author does not suggest this be done routinely at rescues. Such information is of most benefit to rescuers when deciding what system to rig, or what pulleys to buy. The theoretical MA that we have always used for rescues will still work fine!

The numerical results of Appendix II are presented graphically in Appendix III. So from either the table, or the graph, it is possible to see how much more efficient (I.e. how much less friction, and more actual MA) multiplying MAs are than their block and tackle cousins.

But why is haul system efficiency, and the elimination of friction important?

Well firstly, friction is work the haul team does for no benefit – it is wasted as heat, fatigues the haul team, and may even require more haulers.

Secondly, friction increases the loads in the ropes of the rescue system. Minimising friction – everywhere in the system – reduces loads, which in turn reduces the risk of failure.

Thirdly, reducing friction increases “feel”. That is, the haul team can feel what the load is doing rather than what the friction is doing. With good “feel” a haul team can tell when something happens on rope – like a stretcher getting snagged. With high friction and low “feel”, that is not so apparent, and the haul team may continue to load the system before realising there is a problem. The author has witnessed a rock becoming jammed in a haul system pulley. Had the team not had good “feel” and been putting a huge effort into overcoming the friction anyway, they could have pulled the rock into the pulley with the rope and cut the rope. So good “feel” also helps a VR team to remain safe, by being able to detect changes in the system when they happen, before it’s too late.

## *Case Study 1*

### Given:

A 200 kg rescue load is to be lifted 20 metres using a 4:1 Bolt-On MA. The load line runs though a Larkin Rescue Frame (LRF) fitted with SRT P4Ka Knot Passing Pulleys. The angle of wrap on the top pulley of the LRF is 120 degrees, while that on the bottom pulley is 60 degrees. The Haul System is a 4:1 LBTMA made from SRT P3a pulleys.

### Solution:

For a 1:1 haul, the number of haulers required is:

N = ((load in kgs) + (height in m)) / 20

(N.B. this formula allows for fatigue of the haulers, but also prevents overloading of the system by uncontrolled addition of haulers to the haul team)

Therefore, N = (200+20) / 20 = 11

But the MA of the haul system is 4:1, so we need 11/4 = 2.75 say 3 haulers.

The tension in the load line below the LRF is 200 kgs.

For SRT P4Ka Knot Passing Pulleys, friction / load = 19.9% (for a 180 degree angle of wrap).

For 120-degree angle of wrap, this friction is multiplied by a factor of about 85%, while for a 60-degree angle of wrap it is halved.

So the friction in the top pulley of the LRF is:

200 kgs x .199 x .85 = 33.83 kgs

So the tension between the pulleys in the LRF is **233.83 kgs**.

The friction in the bottom pulley of the LRF is:

233.83 x .199 x 0.5 = 23.27 kgs.

So the tension in the load line after the LRF is 233.83 + 23.27 = **257.1 kgs**

Now from Appendix II, a 4:1 LBTMA with SRT P3a Pulleys has an actual MA of:

MA = 264% or 2.64:1

So the haul team has to haul 257.1 kgs / 2.64 = **97.4 kgs**.

So each hauler has to haul 97.4 / 3 = **32.46 kgs**!

## *Case Study 2*

### Given:

Same scenario as Case Study 1, but we now have a 4:1 XMA Haul System made with the same pulleys.

### Solution:

The load after the LRF is still the same at **257.1 kgs**.

From Appendix II, a 4:1 XMA with SRT P3a Pulleys has an actual MA of:

MA = 339% or 3.39:1

So the haul team has to haul 257.1 kgs / 3.39 = **75.8 kgs** (compare this to 97.4 kgs!)

So each hauler has to haul 65.9 kgs / 3 = **25.2 kgs**! (Compare this with 32.46 kgs!)

So changing to a 4:1 XMA haul system makes the haul team's job 23% easier and uses less gear!

## *Case Study 3*

### Given:

Same scenario as Case Study 2, but now we substitute SRT P3a Ball Bearing Pulleys or Petzl P50 Pulleys for the SRT P3a pulleys with bushes.

### Solution:

The load after the LRF is still the same at **257.1 kgs**.

From Appendix II, a 4:1 XMA with SRT P3a Ball Bearing Pulleys has an actual MA of:

MA = 376% or 3.76:1

So the haul team only has to haul 257.1 kgs / 3.76 = **68.4 kgs**.

So each hauler has to haul: 70.4 kgs / 3 = **22.8 kgs**. (Compare this with 25.2 and 32.5 kgs!)

So changing from bushed to ball bearing pulleys in the haul system makes about 7% difference to the haul team’s effort required.

## *Case Study 4*

### Given:

The same situation as Case Study 1, except it is decided to swap the 4:1 LBTMA end for end to make it into a 5:1 HBTMA.

### Solution:

The number of haulers required is now: 11 / 5 = 2.2 so say **3 haulers** (still).

The tension in the load line at the haul system is still **257.1 kgs**.

From Appendix II, a 5:1 HBTMA with SRT P3a Pulleys has an actual MA of:

MA = 364% or 3.64:1

So the haul team has to haul 257.1 kgs / 3.64 = **70.6 kgs**.

So each hauler has to haul: 70.6 kgs / 3 = **23.5 kgs**. (Compare this with 32.46 kgs for Case Study 1, and also the 22.8 kgs of Case Study 3!)

So just by turning an LBTMA system around to make it into a HBTMA, we can use the additional MA to overcome the friction losses significantly (17% in this case).

## *Case Study 5*

### Given:

A 200 kg rescue load is to be raised 20m using a 4:1 XMA with the load line running through a Larkin Rescue Frame (LRF). All pulleys will be Petzl P50s or SRT P3a Ball Bearing types. The angle of wrap on the top pulley of the LRF is 120 degrees, while that on the bottom pulley is 60 degrees.

### Solution:

From previous case studies, the number of haulers will be 3.

The friction in the top pulley of the LRF = 200 x 0.07 x.85 = 11.9 kgs.

So the tension in the load line after the top pulley is 200 kgs + 11.9 kgs = 211.9 kgs.

The friction in the bottom pulley of the LRF is 211.9 kgs x 0.07 x 0.5 = 7.4 kgs.

So the tension in the load line after the LRF is 211.9 kgs + 7.4 kgs = **219.3 kgs**.

From Appendix II the actual MA of a 4:1 XMA with Petzl P50 pulleys is:
MA = 376% or 3.76:1

So the haul team has to haul 219.3 kgs / 3.76 = **58.3 kgs**.

So each hauler has to haul 58.3 kgs / 3 = **19.4 kgs**. Compare this with the results of Case Study 3 (22.8 kgs) to see the effect of ball bearing pulleys on the LRF – nearly 15% less load!

## *The Friction Effects of Redirections*

Redirections often get added into VR systems for a variety of reasons. It may be to correct the operational line to make better use of available anchors or to protect the load line from abrasion and friction. Redirections are always added with good reason, but they come at a cost: they add friction to the system. OK it might be less friction than not having the redirection, but eliminating the redirection by careful rigging in the first place can significantly reduce the loads in the system.

Table 1 details the amount that load line or haul line tension will increase when negotiating a redirection for particular pulleys. It doesn't take much to see that careful rigging in order to minimise the number of redirections can pay dividends both in hauler effort, and reducing load line tension.

### Table 1: Percentage Load (Tension) Increase due to Redirection

| **Pulley** | **Friction / Load 180 degree wrap** | **Friction / Load 120 degree wrap** | **Friction / Load 90 degree wrap** | **Friction / Load 60 degree wrap** | **Friction / Load 30 degree wrap** |
|---|---|---|---|---|---|
| SRT P3a | 19.6% | 16.7% | 13.9% | 9.8% | 5% |
| CMI Rescue | 14.2% | 12% | 10% | 7.1% | 4% |
| Petzl P50 | 7% | 6% | 5% | 3.5% | 2% |
| Karabiner | 100% | 85% | 71% | 50% | 27% |

A redirection with 180 degree wrap is often found at the top of a counterweight haul system, at the top of the Larkin Rescue Frame when it is luffed in, or at the back of the haul system when the haul team prefers to haul downhill towards the edge rather than uphill away from it. In this last case, the redirection is essentially doing the same thing as the redirection that turns a 4:1 HBTMA into a 4:1 LBTMA.

120-degree redirections are often found in Larkin Rescue Frames.

From Table 1 it is easy to see the value of low friction pulleys for redirections, and particularly why using a karabiner for a redirection on a moving rope, regardless of how small the angle of wrap is, is not a good thing.

While the Larkin Rescue Frame may often be considered the default weapon of choice for edge management, remember that it contains 2 redirections if used as designed. Depending on the friction the available pulleys have, a simple fixed high redirection may be a better choice in some situations.

## Conclusion

A wide range of pulleys and associated equipment has been tested for friction developed in VR systems.

The most important factors when choosing VR pulleys are sheave diameter and whether or not to choose a ball bearing pulley. Larger sheave diameters generally result in pulleys that produce less friction. Ball bearing pulleys have significantly better friction characteristics, but these must be weighed against the additional cost for these pulleys.

Lifting Block and Tackle Haul Systems should be avoided as the least efficient option. Both lifting and hauling block and tackle systems fall subject to additional friction caused by twisting of the haul system – an effect not assessed in this report. All haul systems can fall prone to twisting and the friction that it produces, but it is the author’s opinion based on experience that block and tackle systems suffer more from this than compound or multiplying mechanical advantages.

Compound or Multiplying Mechanical Advantages (XMAs) are the most efficient option for haul systems. The main disadvantage of XMAs is the distance hauled between resets is usually about half that of a block and tackle system. Never the less, if space permits, an XMA is the way to go. In very confined areas, a block and tackle system may be more practical.

Using karabiners to build mechanical advantages or even for redirections on moving ropes is really a last resort. They simply introduce too much friction into the system, which can quickly compound into difficulties operating the system or overloading.

# Appendix I: Friction Test Results and Calculations

| | | Sheave Diameter, mm | Measured Tight Side Load, kg | | | | Average Measured Tight side load, kg | Tight Side Load Error, kg +/- | % Load Tight Side | % Load Slack Side | Slack Side / Tight Side | Friction / Effort (Tight side tension) | Friction / Redirection Load | Friction / Load (Slack side tension) | % Load Error, +/- | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load Calibration Tests | | | 118 | 114 | 115 | | 115.66667 | 2 | **100.0%** | | | | | | | All tests on 11mm kernmantel rope. |
| Test 1 | SRT P1a Pulley | 28.5 | 65 | | | | 65 | 2 | **56.2%** | 43.8% | 77.9% | **22.1%** | **12.4%** | **28.3%** | 4.8% | |
| Test 2 | SRT P2a Pulley | 38 | 64 | 65 | | | 64.5 | 2 | **55.8%** | 44.2% | 79.3% | **20.7%** | **11.5%** | **26.1%** | 4.8% | |
| Test 3 | RSI Rescue Pulley | 31 | 65 | 66 | 66 | | 65.666667 | 2 | **56.8%** | 43.2% | 76.1% | **23.9%** | **13.5%** | **31.3%** | 4.8% | |
| Test 4 | SRT P3Ta Pulley (red 16mm) | 46 | 64 | 64 | | | 64 | 2 | **55.3%** | 44.7% | 80.7% | **19.3%** | **10.7%** | **23.9%** | 4.9% | |
| Test 5 | SRT P3a Pulley | 49 | 63 | 63 | | | 63 | 2 | **54.5%** | 45.5% | 83.6% | **16.4%** | **8.9%** | **19.6%** | 4.9% | |
| Test 6 | Petzl P00 Pulley wheel | 25.5 | 70 | 71 | 70 | 71 | 70.5 | 2 | **61.0%** | 39.0% | 64.1% | **35.9%** | **21.9%** | **56.1%** | 4.6% | |
| Test 7 | CMI Plastic Sheave Rescue Pulley | 53 | 62 | 61 | 62 | | 61.666667 | 2 | **53.3%** | 46.7% | 87.6% | **12.4%** | **6.6%** | **14.2%** | 5.0% | |
| Test 8 | SRT P2Pa Prusik Minding Pulley | 38 | 63 | 64 | 64 | | 63.666667 | 2 | **55.0%** | 45.0% | 81.7% | **18.3%** | **10.1%** | **22.4%** | 4.9% | |
| Test 9 | CMI Stainless Steel Sheave Rescue Pulley | 53 | 61 | 62 | 62 | | 61.666667 | 2 | **53.3%** | 46.7% | 87.6% | **12.4%** | **6.6%** | **14.2%** | 5.0% | |
| Test 10 | Alloy Karabiner | | 78 | 79 | 79 | 80 | 79 | 2 | **68.3%** | 31.7% | 46.4% | **53.6%** | **36.6%** | **115.5%** | 4.3% | |
| Test 11 | Steel Karabiner | | 76 | 77 | 76 | 77 | 76.5 | 2 | **66.1%** | 33.9% | 51.2% | **48.8%** | **32.3%** | **95.3%** | 4.3% | |
| Test 12 | CMI Plastic Sheave Rescue Pulley - lubricated | 53 | 60 | 61 | 59 | 60 | 60 | 2 | **51.9%** | 48.1% | 92.8% | **7.2%** | **3.7%** | **7.8%** | 5.1% | |
| Test 13 | SRT P1a Pulley - lubricated | 28.5 | 63 | 64 | 65 | 65 | 64.25 | 2 | **55.5%** | 44.5% | 80.0% | **20.0%** | **11.1%** | **25.0%** | 4.8% | |
| Test 14 | SRT P3a Pulley - lubricated | 49 | 62 | 63 | 62 | 63 | 62.5 | 2 | **54.0%** | 46.0% | 85.1% | **14.9%** | **8.1%** | **17.6%** | 4.9% | |
| Test 15 | Figure 8 Descender | | 99 | 100 | 100 | | 99.666667 | 2 | **86.2%** | 13.8% | 16.1% | **83.9%** | **72.3%** | **522.9%** | 3.7% | Tested with brake rope parallel to standing part, so indicated friction is less than normal abseiling position. |
| Test 16 | Italian / Munter Hitch on Alloy Krab | | 108 | 108 | | | 108 | 2 | **93.4%** | 6.6% | 7.1% | **92.9%** | **86.7%** | **1308.7%** | 3.6% | |
| Load Calibration Tests | | | 118 | 118 | | | 118 | | **100.0%** | | | | | | | |
| Test17 | Riley RM15A Rescue Pulley | 40.4 | 64 | 64 | 65 | | 64.333333 | 2 | **54.5%** | 45.5% | 83.4% | **16.6%** | **9.0%** | **19.9%** | 3.1% | |
| Test18 | SRT P4Ka Knot Passing Pulley | 77 | 64 | 64 | 65 | | 64.333333 | 2 | **54.5%** | 45.5% | 83.4% | **16.6%** | **9.0%** | **19.9%** | 3.1% | |
| Test 19 | SRT P3a Ball Bearing Pulley | 48.4 | 61 | 62 | 60 | 61 | 61 | 2 | **51.7%** | 48.3% | 93.4% | **6.6%** | **3.4%** | **7.0%** | 3.3% | Compare with Test 5 - Standard P3a Pulley with plain bearing. |
| Test 20 | Anchor 150mm Diameter Snatch Block | 125 | 60 | 61 | 61 | | 60.666667 | 2 | **51.4%** | 48.6% | 94.5% | **5.5%** | **2.8%** | **5.8%** | 3.3% | |
| Test 21 | Petzl P50 Rescue Pulley (used) | 48.2 | 60 | 61 | 61 | 62 | 61 | 2 | **51.7%** | 48.3% | 93.4% | **6.6%** | **3.4%** | **7.0%** | 3.3% | Compare with tests 5, 19 and 22. |

| | | **Sheave Diameter, mm** | **Measured Tight Side Load, kg** | | | | **Average Measured Tight side load, kg** | **Tight Side Load Error, kg +/-** | **% Load Tight Side** | **% Load Slack Side** | **Slack Side / Tight Side** | **Friction / Effort (Tight side tension)** | **Friction / Redirection Load** | **Friction / Load (Slack side tension)** | **% Load Error, +/-** | **Notes** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test 22 | Petzl P50 Rescue Pulley (new) | 48.2 | 61 | 62 | 62 | 63 | 62 | 2 | **52.5%** | 47.5% | 90.3% | **9.7%** | **5.1%** | **10.7%** | 3.2% | Compare with Tests 5, 19 and 21. |
| Test 23 | Petzl Mini Traxion | 18.8 | 68 | 68 | | | 68 | 2 | **57.6%** | 42.4% | 73.5% | **26.5%** | **15.3%** | **36.0%** | 2.9% | |
| Test 24 | Petzl Fixed Cheek Pulley | 18.8 | 69 | 70 | 68 | 69 | 69 | 2 | **58.5%** | 41.5% | 71.0% | **29.0%** | **16.9%** | **40.8%** | 2.9% | |
| Test 25 | Rescue Systems Pulley (Red) | 22.5 | 69 | 70 | 68 | 69 | 69 | 2 | **58.5%** | 41.5% | 71.0% | **29.0%** | **16.9%** | **40.8%** | 2.9% | |
| Test 26 | Rescue Systems Pulley (Black) | 22.5 | 70 | 69 | | | 69.5 | 2 | **58.9%** | 41.1% | 69.8% | **30.2%** | **17.8%** | **43.3%** | 2.9% | Pulley >15 Y.O. |
| Test 27 | Petzl Tandem | 20.9 | 71 | 72 | 72 | | 71.666667 | 2 | **60.7%** | 39.3% | 64.7% | **35.3%** | **21.5%** | **54.7%** | 2.8% | |
| Test 28 | Round Turn on Alloy Krab | | 102 | 103 | 92 | | 99 | 2 | **83.9%** | 16.1% | 19.2% | **80.8%** | **67.8%** | **421.1%** | 2.0% | |
| Test 29 | Kong Choy (Belay plate on alloy krab) | | 81 | 82 | 81 | | 81.333333 | 3 | **68.9%** | 31.1% | 45.1% | **54.9%** | **37.9%** | **121.8%** | 3.7% | |
| Test 30 | SRT Edge Rollers (ladder type - with side friction) | 22.3 | 86 | 87 | | | 86.5 | 4 | **73.3%** | 26.7% | 36.4% | **63.6%** | **46.6%** | **174.6%** | 4.6% | |
| Test 31 | SRT Edge Rollers (ladder type - without side friction) | 22.3 | 76 | 77 | 76 | 77 | 76.5 | 5 | **64.8%** | 35.2% | 54.2% | **45.8%** | **29.7%** | **84.3%** | 6.5% | |
| Test 32 | SRT Edge Roller (pair - some side friction) | 39.8 | 66 | 67 | | | 66.5 | 6 | **56.4%** | 43.6% | 77.4% | **22.6%** | **12.7%** | **29.1%** | 9.0% | |
| Test 33 | SRT Edge Roller (pair - no side friction) | 39.8 | 64 | 64 | | | 64 | 7 | **54.2%** | 45.8% | 84.4% | **15.6%** | **8.5%** | **18.5%** | 10.9% | |

## Appendix II: Actual Mechanical Advantages of Common Vertical Rescue Haul Systems

| friction / effort | Slack Side / Tight Side | 2:1 MA | 3:1 MA | 4:1 XMA | 4:1 HBTMA | 4:1 LBTMA | 5:1 HBTMA | 5:1 LBTMA | 6:1 XMA | 6:1 HBTMA | 6:1 LBTMA | 8:1 XMA | Pulley |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0% | 100% | 200% | 300% | 400% | 400% | 400% | 500% | 500% | 600% | 600% | 600% | 800% | |
| 1% | 99% | 199% | 297% | 396% | 394% | 390% | 490% | 485% | 591% | 585% | 579% | 788% | |
| 2% | 98% | 198% | 294% | 392% | 388% | 380% | 480% | 471% | 582% | 571% | 559% | 776% | |
| 3% | 97% | 197% | 291% | 388% | 382% | 371% | 471% | 457% | 573% | 557% | 540% | 765% | |
| 4% | 96% | 196% | 288% | 384% | 377% | 362% | 462% | 443% | 565% | 543% | 521% | 753% | |
| 5% | 95% | 195% | 285% | 380% | 371% | 352% | 452% | 430% | 556% | 530% | 503% | 741% | Anchor 150mm Diameter Snatch Block |
| 6% | 94% | 194% | 282% | 376% | 365% | 343% | 443% | 417% | 548% | 517% | 486% | 730% | SRT P3a Ball Bearing Pulley, Petzl P50 Rescue Pulley (used) |
| 7% | 93% | 193% | 279% | 372% | 360% | 335% | 435% | 404% | 539% | 504% | 469% | 719% | CMI Plastic Sheave Rescue Pulley - lubricated |
| 8% | 92% | 192% | 277% | 369% | 355% | 326% | 426% | 392% | 531% | 492% | 453% | 708% | |
| 9% | 91% | 191% | 274% | 365% | 349% | 318% | 418% | 380% | 523% | 480% | 437% | 697% | Petzl P50 Rescue Pulley (new) |
| 10% | 90% | 190% | 271% | 361% | 344% | 310% | 410% | 369% | 515% | 469% | 422% | 686% | |
| 11% | 89% | 189% | 268% | 357% | 339% | 301% | 401% | 357% | 507% | 457% | 407% | 675% | |
| 12% | 88% | 188% | 265% | 353% | 334% | 294% | 394% | 346% | 499% | 446% | 393% | 664% | CMI Rescue Pulleys |
| 13% | 87% | 187% | 263% | 350% | 329% | 286% | 386% | 336% | 491% | 436% | 379% | 654% | |
| 14% | 86% | 186% | 260% | 346% | 324% | 278% | 378% | 325% | 484% | 425% | 366% | 643% | SRT P3a Pulley - lubricated |
| 15% | 85% | 185% | 257% | 342% | 319% | 271% | 371% | 315% | 476% | 415% | 353% | 633% | |
| 16% | 84% | 184% | 255% | 339% | 314% | 264% | 364% | 305% | 468% | 405% | 341% | 623% | SRT P3a Pulley, Riley RM15A Rescue Pulley, SRT P4Ka Knot Passing Pulley |
| 17% | 83% | 183% | 252% | 335% | 309% | 257% | 357% | 296% | 461% | 396% | 329% | 613% | |
| 18% | 82% | 182% | 249% | 331% | 304% | 250% | 350% | 287% | 454% | 387% | 317% | 603% | SRT P2Pa Prusik Minding Pulley |
| 19% | 81% | 181% | 247% | 328% | 300% | 243% | 343% | 278% | 446% | 378% | 306% | 593% | SRT P3Ta Pulley (red 16mm) |
| 20% | 80% | 180% | 244% | 324% | 295% | 236% | 336% | 269% | 439% | 369% | 295% | 583% | SRT P2a Pulley, SRT P1a Lubricated |
| 21% | 79% | 179% | 241% | 320% | 291% | 230% | 330% | 260% | 432% | 360% | 285% | 574% | |
| 22% | 78% | 178% | 239% | 317% | 286% | 223% | 323% | 252% | 425% | 352% | 275% | 564% | SRT P1a Pulley |
| 23% | 77% | 177% | 236% | 313% | 282% | 217% | 317% | 244% | 418% | 344% | 265% | 555% | RSI Rescue Pulley |
| 24% | 76% | 176% | 234% | 310% | 278% | 211% | 311% | 236% | 411% | 336% | 256% | 545% | |
| 25% | 75% | 175% | 231% | 306% | 273% | 205% | 305% | 229% | 405% | 329% | 247% | 536% | |
| 26% | 74% | 174% | 229% | 303% | 269% | 199% | 299% | 221% | 398% | 321% | 238% | 527% | Petzl Mini Traxion |

| friction / effort | Slack Side / Tight Side | 2:1 MA | 3:1 MA | 4:1 XMA | 4:1 HBTMA | 4:1 LBTMA | 5:1 HBTMA | 5:1 LBTMA | 6:1 XMA | 6:1 HBTMA | 6:1 LBTMA | 8:1 XMA | Pulley |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27% | 73% | 173% | 226% | 299% | 265% | 194% | 294% | 214% | 391% | 314% | 229% | 518% | |
| 28% | 72% | 172% | 224% | 296% | 261% | 188% | 288% | 207% | 385% | 307% | 221% | 509% | |
| 29% | 71% | 171% | 221% | 292% | 257% | 183% | 283% | 201% | 379% | 301% | 213% | 500% | Petzl Fixed Cheek Pulley |
| 30% | 70% | 170% | 219% | 289% | 253% | 177% | 277% | 194% | 372% | 294% | 206% | 491% | Rescue Systems Pulley |
| 31% | 69% | 169% | 217% | 286% | 249% | 172% | 272% | 188% | 366% | 288% | 199% | 483% | |
| 32% | 68% | 168% | 214% | 282% | 246% | 167% | 267% | 182% | 360% | 282% | 191% | 474% | |
| 33% | 67% | 167% | 212% | 279% | 242% | 162% | 262% | 176% | 354% | 276% | 185% | 466% | |
| 34% | 66% | 166% | 210% | 276% | 238% | 157% | 257% | 170% | 348% | 270% | 178% | 457% | |
| 35% | 65% | 165% | 207% | 272% | 235% | 153% | 253% | 164% | 342% | 264% | 172% | 449% | Petzl P00 Pulley wheel, Petzl Tandem |
| 36% | 64% | 164% | 205% | 269% | 231% | 148% | 248% | 159% | 336% | 259% | 166% | 441% | |
| 37% | 63% | 163% | 203% | 266% | 228% | 143% | 243% | 153% | 330% | 253% | 160% | 433% | |
| 38% | 62% | 162% | 200% | 262% | 224% | 139% | 239% | 148% | 325% | 248% | 154% | 425% | |
| 39% | 61% | 161% | 198% | 259% | 221% | 135% | 235% | 143% | 319% | 243% | 148% | 417% | |
| 40% | 60% | 160% | 196% | 256% | 218% | 131% | 231% | 138% | 314% | 238% | 143% | 410% | |
| 41% | 59% | 159% | 194% | 253% | 214% | 126% | 226% | 134% | 308% | 234% | 138% | 402% | |
| 42% | 58% | 158% | 192% | 250% | 211% | 122% | 222% | 129% | 303% | 229% | 133% | 394% | |
| 43% | 57% | 157% | 189% | 246% | 208% | 119% | 219% | 125% | 297% | 225% | 128% | 387% | |
| 44% | 56% | 156% | 187% | 243% | 205% | 115% | 215% | 120% | 292% | 220% | 123% | 380% | |
| 45% | 55% | 155% | 185% | 240% | 202% | 111% | 211% | 116% | 287% | 216% | 119% | 372% | |
| 46% | 54% | 154% | 183% | 237% | 199% | 107% | 207% | 112% | 282% | 212% | 114% | 365% | |
| 47% | 53% | 153% | 181% | 234% | 196% | 104% | 204% | 108% | 277% | 208% | 110% | 358% | |
| 48% | 52% | 152% | 179% | 231% | 193% | 100% | 200% | 104% | 272% | 204% | 106% | 351% | Steel Karabiner |
| 49% | 51% | 151% | 177% | 228% | 190% | 97% | 197% | 100% | 267% | 200% | 102% | 344% | |
| 50% | 50% | 150% | 175% | 225% | 188% | 94% | 194% | 97% | 263% | 197% | 98% | 338% | Alloy Karabiner (53%) |

**Legend:**

| | |
|---|---|
| MA | Mechanical Advantage. |
| HBTMA | Hauling Block and Tackle Mechanical Advantage. I.e. Haul rope from moving block. |
| LBTMA | Lifting Block and Tackle Mechanical Advantage. I.e. Haul rope from fixed block. |
| XMA | Multiplying Mechanical Advantage (Piggy Back or Compound System). |

# Appendix III: Graph of Actual Mechanical Advantage v Pulley Friction