Gordon Smith has been with Seattle Mountain Rescue for 20 years and has been climbing for over 35 years. He is currently Chairman of Seattle Mountain Rescue, and Rigging Committee Co-Chair. He has been Training Chair and Rescue Chair. He has summited the highest peaks in the U.S., Canada, and Mexico, climbed in the Nepal Himalaya, summited every peak over 9,000’ in Washington State, and summited numerous other peaks in Washington, Alaska, Oregon, California, Wyoming, British Columbia and Alberta. He has first ascents of new climbing routes, including a route on the highest peak in the Chugach Range of Alaska. His paying work focuses on changing land uses in developing countries to make them more sustainable and to reduce greenhouse gas. He tests rescue rigging systems to inform Seattle Mountain Rescue decisions about what practices to use on missions.

Abstract

Pulley Efficiency in a Rescue System

Gordon Smith
Seattle Mountain Rescue

This presentation has two parts. One part examines the amount of force required to raise a rescue load with different types of pulleys. The other part looks at the effect of the type of rope on the amount of force required to raise a rescue load.

Why do we care? As mountain rescuers, we have two goals that often conflict: We want to carry as little weight into the mountains as possible, and, at the same time, we want our gear to make our jobs easy.

We tested a standard 3 to 1 pulley raising system with a 200kg (441 lb.) rescue load, and 11mm (7/16”) low stretch rope. We tested pulleys with sheave diameters ranging from 0.47-2” (12-51mm). In general, pulleys with smaller sheave diameters required more force to raise the load, but the pulley with a larger diameter groove on the sheave required less raising force relative to its sheave diameter.

A pulley with a 1.1” sheave diameter, that was moderately inefficient when tested with the rescue rope, tested as nearly perfectly efficient in a system with a 2.35mm diameter cord, instead of the rescue rope.

We hypothesize that the system would be more efficient if the groove on the pulley sheave were larger in diameter; and we propose a test of this hypothesis.

We recommend that when pulley efficiency is measured for rating the pulley, the procedure should use: (a) a rope of the maximum diameter for which the pulley is rated, (b) a rope of the material for which the pulley is intended to be used (e.g. a pulley sold for mountaineering use should have efficiency measured using a nylon kernmantle climbing rope, not a wire cable), (c) a 180 degree turn of the rope around the pulley, and (d) a load of the typical expected working load, or maximum rated load.

Pulley Efficiency in a Rescue System
October 1, 2014
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Overview

This study examines different pulleys to see how they would perform in a typical mountain rescue 3 to 1 pulley raising system (Figure 1). We want to have pulleys that are small and light but at the same time work efficiently. We find significant differences in the amount of force required to raise a 200kg (441 lb) rescue load using different pulleys, with the same 11.1mm (7/16") diameter low stretch rescue rope. We make conclusions about how pulley efficiency should be measured and reported, and suggest further testing that might result in lighter, more efficient pulleys.

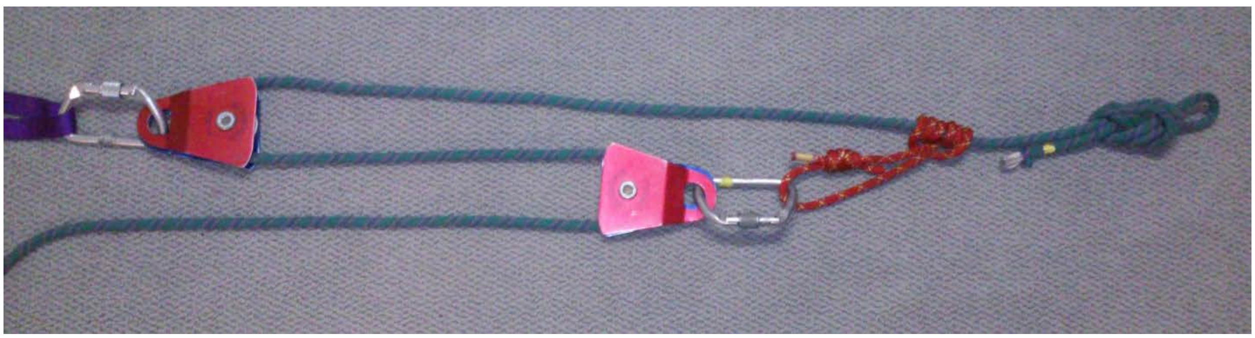

Figure 1. Standard 3-to-1 mechanical advantage raising system.

The Test System

The goal of our test system design was to replicate a standard raise, but control for situation specific variation in slope, edges, and people hauling. We chose a standard simple 3-to1 pulley system, as used by many mountain rescue teams. This system is sometimes called a "Z" pulley. To avoid confounding effects of friction of rope against rock, attendants wiggling, and less than vertical slopes, we rigged the system free hanging in space, using 200 kg (441 lb) of metal weights to simulate the patient, litter and attendant (Figure 2).

An electronic scale was tied into the rope where the pullers would grasp the line. Another pulley at the top of the test system served as a change of direction, and the rope was directed to the floor of the testing room, and a second change of direction changed the rope to horizontal, directing it to an electric winch. Placing the electronic scale between the raising system and change of direction pulleys meant that any friction in the change of directions was excluded from the measurements. An electric winch provided a constant rate of pull.

We performed at least 10 pulls with each configuration of the system. Several different pulleys were tested. We also measured the force required to do a raise without pulleys, with the rope traveling directly over carabiners. One set of pulleys was tested with the standard 11.1mm (7/16") diameter rescue rope and with a 2.35mm diameter cord.

Figure 2. Photograph of 3-to-1 pulley raising test system.

Two winches were tried, with raising speeds of 0.167 and 0.5 feet per second (0.05 and 0.15m/sec). Most of the raises were done with the slower 0.167 foot per second winch. We did not do a statistical analysis but by inspection the different raising speeds appeared to have the same forces for any given system configuration. Approximately 12m (40') of rope was in service between the load and the connection to the winch cable.

As the winch was raising the load, a person watched the readout on the scale, and judged the median force during the raise. Because of rope stretch and the relatively slow winch speeds, the load did not bounce as the raising was started, and within a few centimeters after the load was lifted off the ground the pulling force remained constant within a couple kg's range. The recorded force was the most common reading observed during 5-20 seconds of continuous raising. Initially we had three people reading the values on the scale, with one person reading the low value, one person reading the median value, and one person reading the high value. However, the readings were so constant that we were comfortable with one person reading the median value.

Figure 3. Tested pulleys (selected), left to right: Rock Exotica PMP, SMC Swiftwater, CMC Protech, REI personal rescue; Petzl Attache carabiner above.

Brand new and used ropes were tested. All ropes were Sterling HTP High Tenacity Polyester 7/16" diameter (11.1mm). The small diameter cord was 2.35mm (0.09") diameter Dyneema "Ironwire" that the vendor claimed has a 1000 lb (454kg) breaking strength. We recorded when a new section of rope was placed in service.

Results

If the system was perfectly frictionless, the 3-to-1 mechanical advantage pulley system would reduce the pulling force required to raise the system to 1/3 of the 200kg (441 lb) load weight, which would be 66.7kg (147 lb) raising force. Because there is friction in the system, the actual forces required to raise the load were greater than this theoretical minimum.

Results are reported in both table and graph form. Table 1 presents the force required to raise the test load for each system configuration. The sheave diameter is the diameter of the wheel of the pulley, from the bottom of the groove on one side of the wheel to the bottom of the groove on the other side of the wheel.

The average force required to do the raise was calculated for each configuration. The forces were remarkably consistent, and generally were all within a range of about 2% of the raising force. This consistency of force should not be surprising given the consistency of the rope construction, steady winch pull, inert weight, and finely machined pulleys. The low variation in force across different pulls resulted in very small standard deviations in the amounts of force required in different raises on the same system, and very small uncertainty intervals, despite the relatively low numbers of pulls for each configuration. The uncertainty number is the number that if thousands of iterations were measured and the average raising force calculated, there is a 9 in 10 chance that this “true” average would be within the uncertainty range. For example, the Rock Exotica PMPs had an average raising force of 76.3 kg +/- 0.3 kg. This means that if we did thousands of pulls, there is a 9 in 10 chance that the average we would observe across these thousands of pulls would be between 76 kg and 76.6kg. Figure 4 presents the same average raising force data, by pulley, but presents the information in graphic form.

Pulley	**Sheave Diameter (in)**	**Rope Diameter (mm)**	**Number of Pulls**	**Average Force (kg)**	**+/- Uncertainty (90%, kg)**
Theoretical frictionless	n.a.	n.a.	n.a.	66.7	0
Rock Exotica PMP	2	11.1	20	76.3	0.3
SMC Swiftwater	1.5	11.1	11	78.0	0.2
CMC Protech	1.09	11.1	20	83.3	0.4
Petzl personal rescue	1.01	11.1	10	76.8	0.2
REI personal rescue	0.84	11.1	10	94.4	0.6
Carabiners, Petzl Attache anodized gold	0.47	11.1	10	120.0	0.8
CMC Protech	1.09	2.35	10	68.4	0.1

Table 1. Pull test results, by pulley.

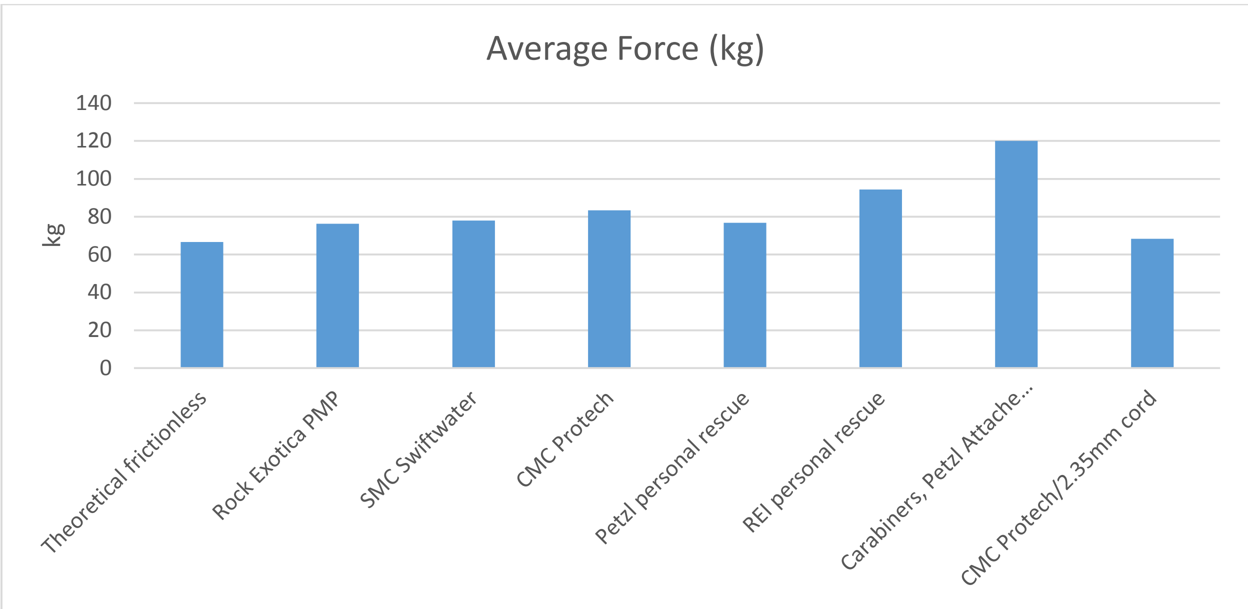

Figure 4. Force to raise a 200kg load using a 3-to-1 raising system, by pulley.

Debate among Seattle Mountain Rescue members as to the cause of the difference between systems revolved around two theories. One theory is that increase force results when the pulley sheave diameter is a smaller multiple of the rope diameter. The other theory is that interaction of the rope and the sides of the groove on the wheel of the pulley adds friction when the rope diameter is about the same as the groove diameter. We were not able to disprove either theory and we suggest a different test that would support or disprove the theory that interaction of the rope a pulley groove adds friction.

Graphing the force required to raise the load as a function of the pulley sheave diameter (Figure 5) shows that the relationship is nonlinear. At pulley sheave diameters less than about 2.5 times the rope diameter the amount of force required to raise the load increase more quickly as sheave diameter decreases, compared to larger sheave diameters. However, these small pulleys may have less efficient bearings; the carabiners are the extreme case, as they have no bearings and the rope slides directly over the metal of the carabiner. The force required to raise the load with carabiners only was 80% more than a perfectly frictionless system.

New ropes required slightly more force to do the raise than ropes that had more than six recent loadings. However, this decrease in force was only about 1%, so it will have minimal effect in practice. The difference between the force required to raise the load on the first four raises on a brand new rope was statistically more than the force require to do the raise on the seventh through tenth raises, at the 90% statistical confidence level. Ropes that had undergone several loadings were stiffer and appeared to be slightly thinner than new ropes, but these diameters were not measured.

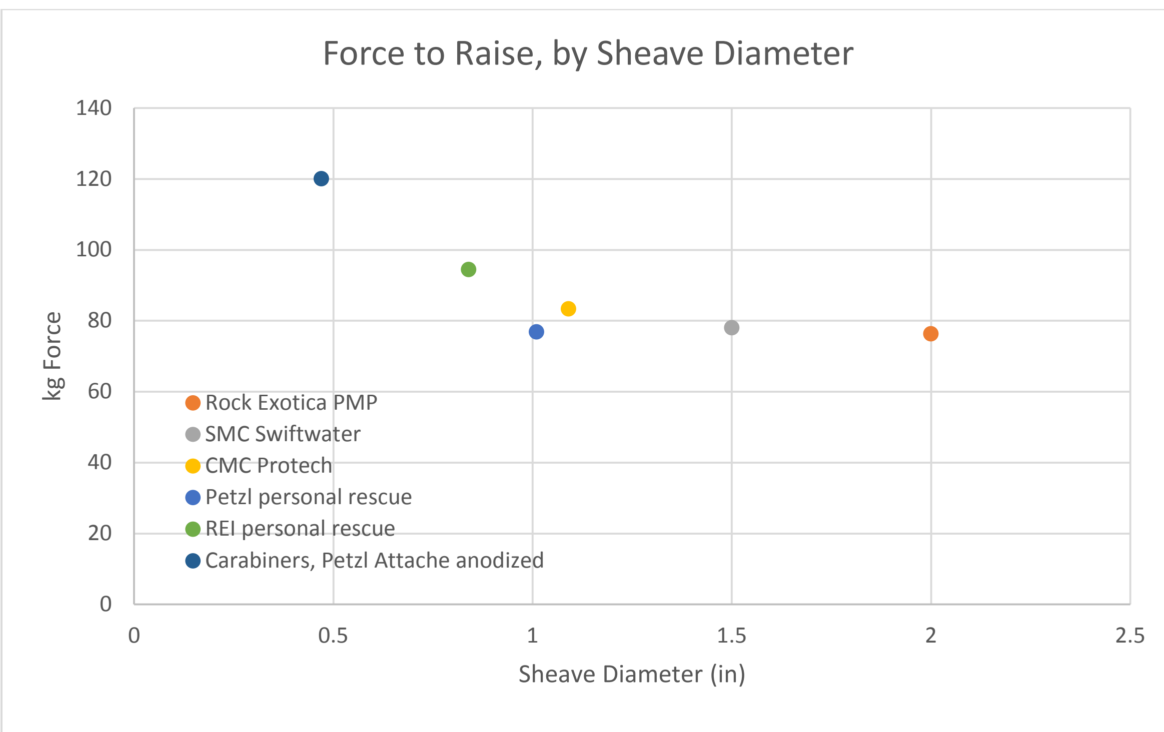

Figure 5. Force required to raise a 200kg load using a 3-to-1 raising system, by pulley sheave diameter.

Discussion

The smaller, lighter pulleys definitely required more force to raise the rescue load. If the system was perfectly frictionless it would require about 67 kg (147 lb) to raise the load. Our CMC and Rock Exotica prusik minding pulleys, with a 2" (50mm) sheave diameter, require about 5% more effort to raise the load than a perfectly frictionless system. This extra resistance is the combined effect of the two pulleys in the raising system, plus any friction in bending the rope, and anything else that causes friction in the operation of the system.

For the same system and load—except replacing the Rock Exotica pulleys with little CMC Protech pulleys with a 1.1" (27mm) sheave diameter—raising the same load required about 10% more effort than the big pulleys, despite the little pulleys having sealed ball bearings that are very efficient. We know the bearings are very efficient because when we test the Protech pulleys with 2.35mm (0.09") diameter cord they tested as almost perfectly efficient (shown in the bottom row of Table 1), with total system inefficiency of 2.5%.

We don't know whether the efficiency fraction remains constant as the load changes. Some of us hypothesize that the efficiency goes down as the load increases, but we did not test this. If the efficiency is constant, if a system has 40% friction from the rope going over a rock edge, the difference in effort required to raise a rescue load using the small CMC Protech pulleys instead of the large Rock Exotica pulleys would be about 10 kg (22 lbs) more force. We are debating whether it is worth it to make our rigging kits 1.2 kg (2.6 lbs) lighter (because we carry five pulleys per rigging kit) at the cost of 6-10kg (13-22lbs) of extra effort required to do a raise with the small pulleys.

We wonder if the small pulleys would give greater efficiency in field operations if they had larger diameter grooves on the pulley wheels. Testing the CMC Protech pulleys with small diameter Dyneema cord and finding high efficiency does not prove that the interaction of rope and groove on the pulley wheel is adding friction. The diameter of the Protech pulley sheave is more than 10 times the diameter of the cord, so if the source of the friction is bending the rope to a bight with a diameter less than 2.5 rope diameters, we have not isolated the effect if the pulley groove diameter.

We have one piece of evidence that supports the hypothesis that the rope interacting with the sides of the groove on the pulley wheel adds friction. The Petzl pulley has groove diameter estimated to be about 0.6" (15mm), which is wider than all of the other pulleys tested in this study. The Petzl pulley has less friction than other pulleys, for its sheave diameter. This suggests that having a larger groove diameter on the pulley might reduce friction. This difference can't be just because of the bearings of the Petzl being more efficient because testing the Protech with a 2.35mm diameter line showed those pulleys to be nearly perfectly efficient. Also, the Protech has a larger sheave diameter than the Petzl, but required more force to raise the same load.

The fact that recently weighted ropes required slightly force to perform the raise might also support the hypothesis that interaction of the rope and groove on the pulley wheel causes friction. Intuitively, one might think that stiffer ropes would have more friction when wrapping around a pulley, but we have no data to support or disprove this hypothesis. This makes us suspect that the decreased diameter of the stretched ropes may have caused the observed decrease in force required to raise the test load after several loadings, because of decreased interaction of the thinner rope and the groove on the pulley sheave.

The way to test the hypothesis that the groove on the edge of the pulley wheel is adding friction is to machine a set of pulley wheels so that they have a larger diameter groove on the sheave, perhaps a 25-35mm diameter groove, while keeping the overall sheave diameter the same. This would also keep the bearings the same. We could use the same test raising system, with the only variation being the diameter of the grooves on the outsides of the pulley wheels. This would definitely distinguish the effect of the groove.

Conclusion

The rated efficiency of pulleys may not be representative of how those pulleys perform in the field. Pulleys with very efficient bearings can be relatively inefficient in rescue systems. This testing was not able to quantify different causes of inefficiency. One hypothesis is that bending a rope at a small multiple of the rope diameter causes friction. Another hypothesis is that when the rope diameter is approximately the diameter of the groove on the edge of a pulley wheel, friction results from the interaction of the groove and rope when the system is weighted and moved. We propose additional research to discern whether the interaction of the pulley wheel groove and rope is a noticeable source of friction. If it is, pulleys could be made more efficient in practice by increasing the diameter of the groove on the sheave.

We recommend that when pulley efficiency is measured for rating the pulley, the procedure should use: (a) a rope of the maximum diameter for which the pulley is rated, (b) a rope of the material for which the pulley is intended to be used (e.g. a pulley sold for mountaineering use should have efficiency measured using a nylon kernmantle climbing rope, not a wire cable), (c) a 180 degree turn of the rope around the pulley, and (d) a load of the typical expected working load or maximum rated load.