Multi-point Pre-Equalized Anchoring Systems

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Abstract:
Background: Building an anchor is one of the most important aspects of any technical rope system. The goal of this research is to obtain a better understanding of load distribution in a pre-equalized anchor system using multiple point configurations. All climbers, mountaineers, technical rescue teams (Mountain Rescue, USAR), guides, or anyone who needs to build an anchor with multiple points in the system does so with little understanding of how a pre-equalized anchor system works.

Methods: A series of slow pull tests were performed to gain a better understanding of the forces generated in a pre-equalized system. The results from these pull tests relate to how the anchor is set up, regarding speed and safety. We evaluated three and four point pre-equalized anchors in both 0º (perpendicular) and 45º (off-axis) configurations with symmetrical and asymmetrical anchor points.

Conclusions:
The standard cordalette is a useful tool when building a multi-point pre-equalized anchor. However, understanding the nuances of how to use it effectively is important.

***INTRODUCTION*:**

In rope rescue, an anchor system with a 20 kN total strength is desirable. Most points in anchors made with rock gear have strengths in the range of 7 to 10 kN. One way of obtaining the needed strength is to build a load-distributing anchor from a series of components, with each component not exceeding a maximum load.

Many recommendations of how to build anchor systems exist. Volumes of books have been published analyzing various systems. Some of these systems have been shown to be better than others based merely on logic alone. The “magic x” was used during the 1980’s but has fallen out of favor for several reasons. It has been shown that a two point equalized anchor does not share a load as equitable as a two point non-equalized anchor[1]. Only a specially anodized figure 8 device showed any reasonable equalization in the “magic x” configuration[2]. Friction affects the load distribution in a self-equalized anchor. Furthermore, the “magic-x” has the ability to be shock loaded to a significant degree should a single anchor point fail[3]. The “magic x” does not defend the anchor against extension should one point fail. If the “magic x” fails, then it cannot significantly shock load the rest of the system. The consequence of any shock load on an anchor system is difficult to ascertain in the real world. The “magic-x” is not necessarily worse at load distributing than a non-equalized anchor.

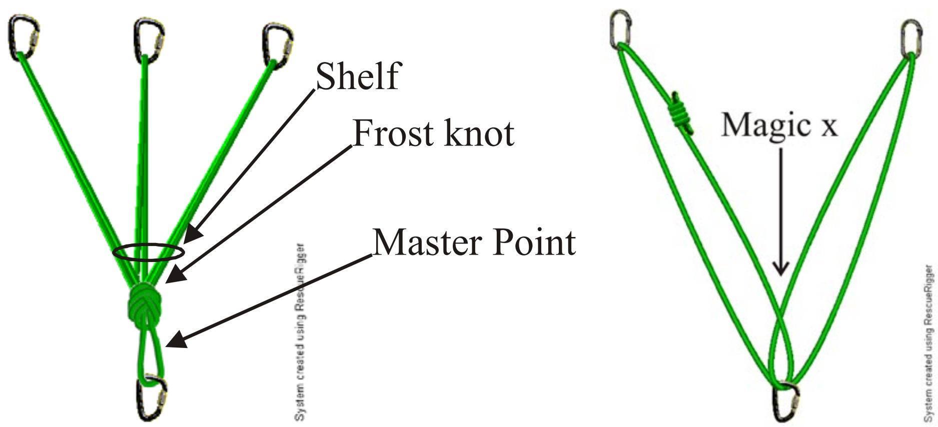


Figure 1**:** (left) A cordalette used in tying a 3 point symmetrical pre-equalized anchor; (right) an "equalized" or "Magic x", shown here with only two points for clarity.

The pre-equalized anchor has several drawbacks, but it has many benefits when compared to the "magic-x." If each point in the anchor system is about equal length, and a big knot is used to create the Master Point, then the loads within each leg have the potential to be balanced. The pre-equalization technique uses an overhand, a "figure 8" knot, a Frost knot or its variant, tied at the point of equalization.

No published data exists for off-axis pre-equalized systems in relationship to an anchor system's strength, the distribution of forces, or possible failure modes. This was alluded to by Moyer[4]: "While the cordalette anchor does not equalize when the belayer shifts position, there is typically enough stretch in each arm that all three will be loaded to varying degrees in a major impact."

Fox[5] showed that the overhand knot is sufficient in the pre-equalized method for a climbing anchor, even if clipped into the shelf, so long as a carabiner is clipped into the master point to prevent a roll-out effect. For this reason we elected to use the overhand Frost knot in our testing. Fox did have an anchor point fail during each test. However, he did not evaluate individual strengths of each anchor point, nor were any leg tensions evaluated during these failure tests.

When a point in a pre-equalized system fails, it can completely change the configuration of the system. The anchor master point may shift as a result of an anchor point failure. We suspect that there are major load shifts. The possibility also exists for successive failures by placing larger forces than anticipated on the other points in the system.

Hypothesis:

The anchor point locations and the relative stiffness of each leg in a pre-equalized anchor system have the potential to create an anchor system that is significantly stronger than the individual strengths of each anchor point. Given a 7 kN limit on each leg, it is possible to build a 20 kN anchor suitable for rescue loads.

Our questions:

1. What are the forces that are exerted on each of a three or four point anchor system?
2. How does the geometry of the anchor points affect the pre-equalized system?
3. How does the stiffness of each leg of the pre-equalized system affect the strength of each leg and the strength of the system?
4. Is the pre-equalized system stronger than the individual anchors, if so by how much?
5. Is a four-point anchor system necessarily better than a three-point anchor system?

The null hypothesis is that pre-equalized anchors do not provide a significant increase in strength over the individual strengths of each anchor leg.

METHODS

A hydraulic ram exceeding 44kN maximum pulling force was mounted to a 10-inch “H” beam (*Figure 2*). At the anchor system master point a NEPA 5000-lb. load cell was used to measure the total force on the system. Load cells were also placed on each individual point in the anchor system. The ram was pulled at a standard rate of ½ inch per second. In addition to measuring the force, the displacement of the master point of the system was also measured. Load cell data was recorded using a V-Link data logger. This system allows variable data logging rates (2 kHz to 32 Hz), having built in signal amplification with 12 bit analog to digital converter.

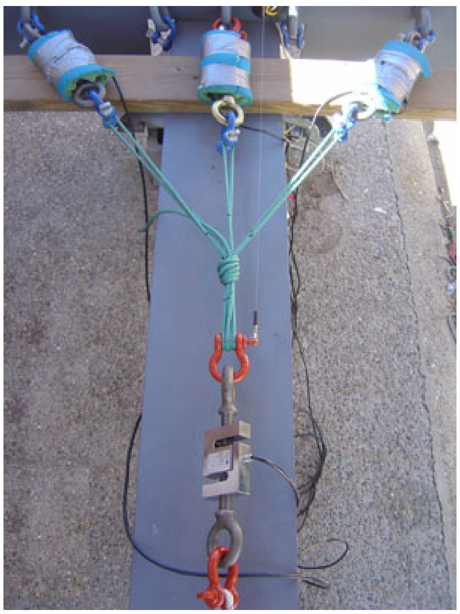


Figure 2: Typical pull testing set-up.

Although slow pull testing does not replicate what happens under dynamic load conditions, such testing provides a starting point to evaluate this type of anchor system. The distribution of forces within the anchor should be similar for both slow pull and dynamic drop tests. Both three and four points anchor systems were tested in a two-dimensional (flat) configuration.

Multi-point Anchors

The forces within a multi-point anchor depend upon the anchor geometry and the stiffness of each leg. For anchors with only two points, the forces can be computed based on the equations of static equilibrium. Each anchor leg intersects at the master point (MP). The requirement of static equilibrium (i.e. no acceleration) dictates that the sum of the forces at the master point equal zero.

The vector sum of the forces at the master point gives:

$$\mathbf{F}_{load} + \sum \mathbf{T}_i = 0 \quad (0.1)$$

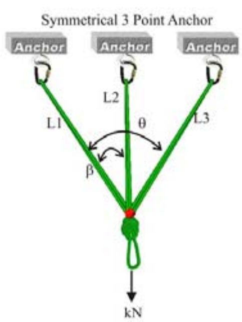
where, the $\vec{\mathbf{F}} = F_x\vec{\mathbf{i}} + F_y\vec{\mathbf{j}} + F_z\vec{\mathbf{k}}$ represents the vector of force with unit vectors in the *x*, *y*, and *z* direction and $\mathbf{T}_i$ is the load in each anchor leg. In the cases considered here, we limited the anchor systems to the z plane, which means that all forces in the z direction will be zero. When the equations of static equilibrium are applied in the *x* and *y* direction at the master point, they give two equilibrium equations that can be used to solve for only two unknowns. This means that if we use the equations of static equilibrium, then we can only solve systems having only two anchor points.

Forces in systems with more than three anchor points will still obey Eq. 1.1; however, the force within each leg cannot be solved using the static equilibrium. The tension, T_i , in each leg will depend on the displacement both at the master point and the leg stiffness. The leg's tension will also depend on the initial slack and the amount of rope that slips though the knot.

In the test that follows, professional rock climbing guides tied the systems attempting to have zero slack in each leg at the test start. In addition, the master point knot was dressed and pulled hand tight before the start of each test. Clearly, uncertainties with the initial lengths and the knot can be quite large and cause variation from test to test. Even with this variation, we feel that clear trends were observable in the testing.

Pre-equalized Three-point Symmetric Anchor

We first looked at loads in a symmetric three-point anchor in a 0º (perpendicular) configuration. *Figure 3* shows the results for this system. If the anchor point in a leg is assumed to fail between 7 to 10 kN, then, based on the measured forces, a three point pre-equalized anchor would not support a rescue load of 20 kN.



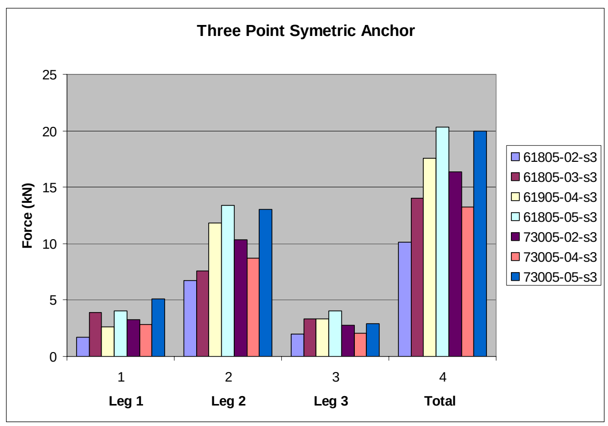
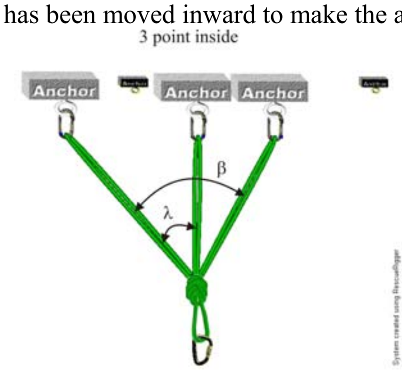


***Figure 3* and *Figure 4*:** Geometry and measured force from seven different symmetric three-point anchors system test.

A variation in the anchor geometry shown in *Figure 3* is shown in *Figure 5*. In this configuration, one leg has been moved inward to make the angles between the legs unequal.



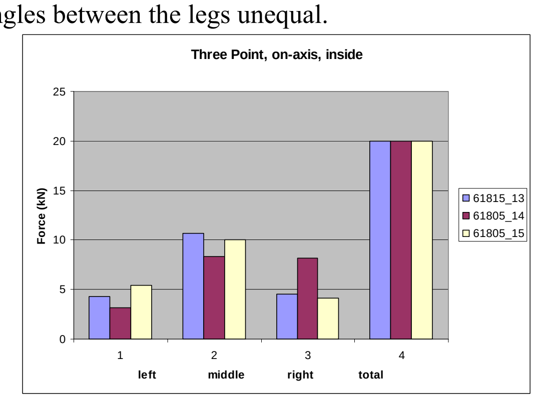


***Figure 5 and* Figure 6:** Geometry and Measured force from three tests of a three point on–axis anchor with one leg moved to the inside.

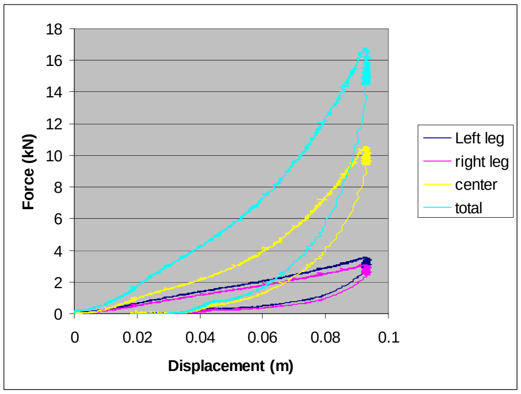
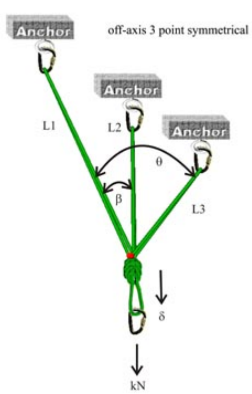


Figure 7: Force displacement relation for a typical symmetric, three-point anchor.

Displacements in the system are also of interest. *Figure 7* shows a plot of the force as a function of displacement for the three-point anchor system shown in *Figure 3*. For this plot, almost 10 cm of stretch was observed when the peak anchor force was 16 kN. For systems with longer legs, even more stretch will be observed.

Three Point Off-Axis Anchors:

A number of anchor systems can be studied in a 45º (off-axis) configuration. ***Figure 8*** through *Figure 12* show measured forces for three variants of three-point 45° off-axis asymmetrical anchor systems. ***Figure 8*** shows an off-axis symmetrical (ß=θ) system; *Figure 10* shows an asymmetrical off-axis outside (ß≠θ); and *Figure 12* shows off-axis asymmetrical inside (ß≠λ) system.



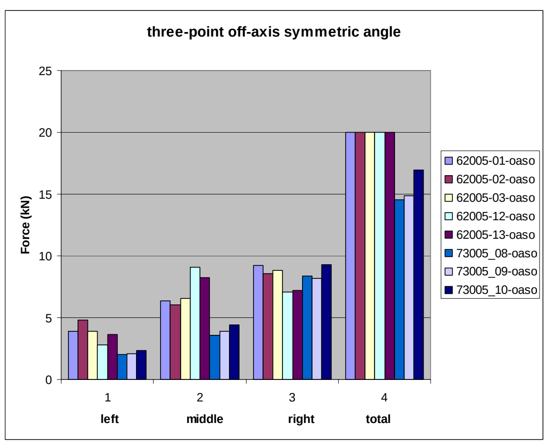
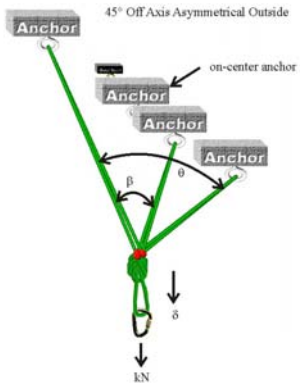


***Figure 8 and Figure 9*:** Geometry and measured leg tension from eight different test of a three-point off-axis, symmetric angle (ß=θ/2) anchor.



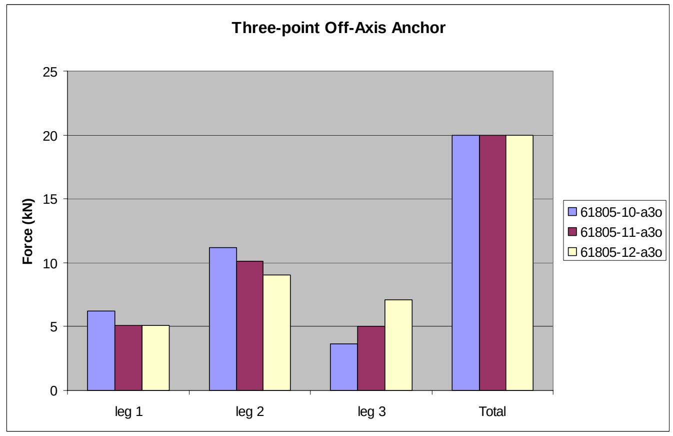
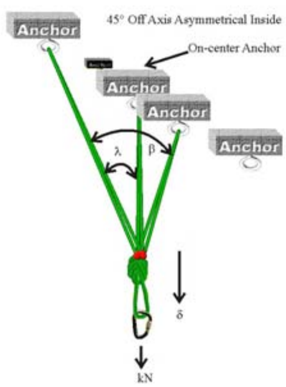


Figure 10 **and** ***Figure 11***: Geometry and measured leg tension in three different test of three-point off-axis asymmetrical off-axis outside (ß≠θ/2) anchor.



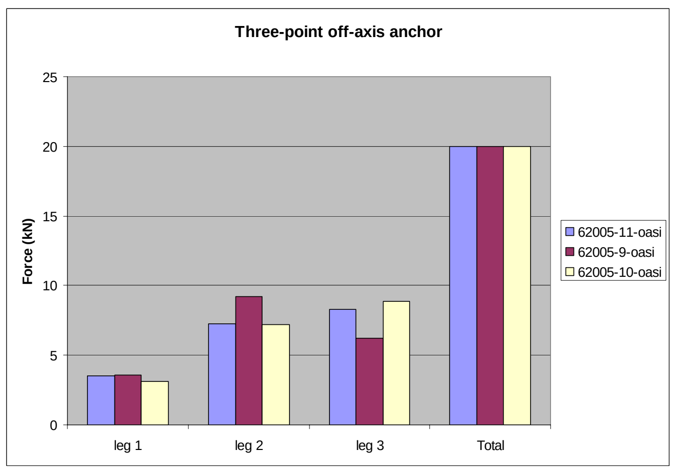


Figure 12 **and** ***Figure 13*****:** Measured tensions in three tests of three-point off-axis asymmetrical inside (ß/2≠λ) anchor.

In all of the configurations tested, the forces in one anchor leg exceeded 7 kN before the total force reached 20 kN. Variations from test to test showed that the distribution had considerable uncertainty. Even with this uncertainty in force distribution, one leg force in each anchor system would exceed 7 kN before the total load reached 20 kN. ***Figure 14*** shows a histogram plot from the above three-point anchor test. Since the peak load in some tests did not reach 20 kN, the individual leg loads were scaled by the ratio of the peak load to 20 kN. This plot suggests that the maximum load in one leg will exceed 8 kN for all configurations, and that, in 6 out of 21 cases, the maximum leg load will exceed 12 kN.

For comparison, a simple two-point equalized anchor with 60 degrees between the anchor legs will generate 11.54 kN when loaded with a total force of 20 kN. Even when the angle between the legs approaches 90 degrees, the maximum anchor load in a two point system will be 14 kN for a 20 kN load.

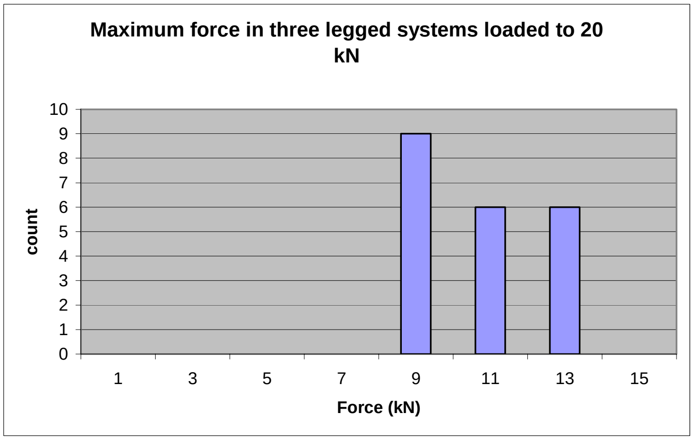
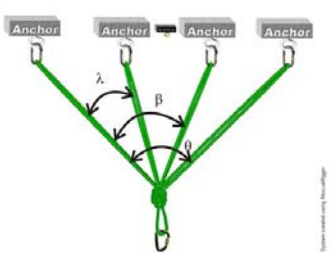
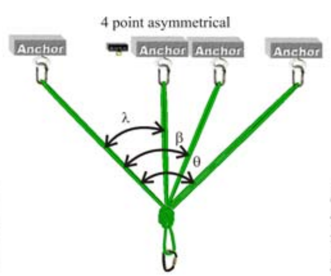


Figure 14: Histogram showing maximum force measured in all three point systems tested.

Four Point Anchors:

Four-point anchors were tested in a 0º (perpendicular) configuration. Both symmetrical and asymmetrical anchor systems were tested. ***Figure 15*** shows the resulting forces for two different four-point anchors when loaded to a total force of 20 kN. The anchor points were located along a horizontal line with two geometric variations in anchor placement. One system was fully symmetric, and one had an inside leg that was centered. This test set showed that at least one leg would exceed 7 kN when the total system load reached 20 kN. In one case, the tension exceeded 10 kN in one of the legs.





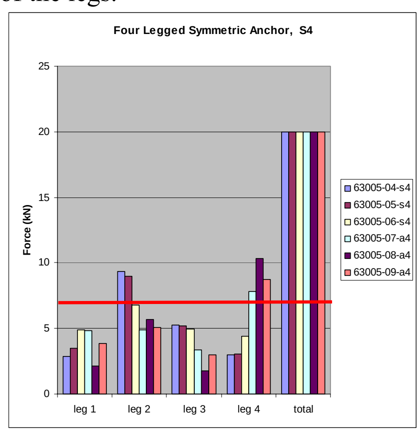
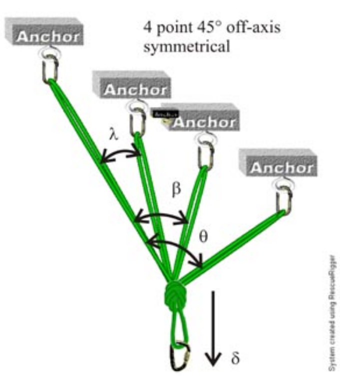


Figure 15, Figure 16, and Figure 17: Geometry and measured forces in a symmetric four-point anchor system. Geometry: symmetric (*left*) and asymmetric (*right)* 4-point anchor. The horizontal red line indicates a 7 kN load.



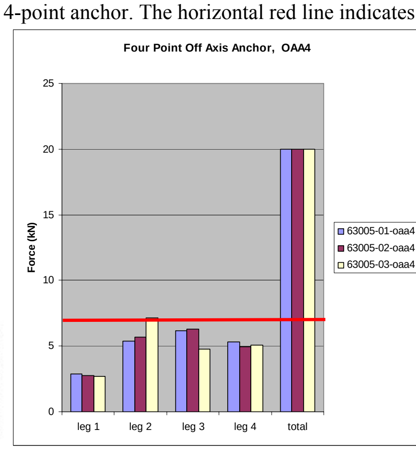


Figure 18 and Figure 19: Geometry and force distribution for off-axis four-point anchor system. The horizontal red line indicates a 7 kN load.

Off-axis Four Point Anchors

The results for the off-axis, four-point anchor system are shown in *Figure 18*. The off-axis, four-point system appears to be the only system meeting the requirement that each leg force be below 7 kN when the total load is at 20 kN. However, one of the legs was equal to 7 kN in one test.

In general, for all anchor system configurations we tested, the shortest leg length experienced the highest forces within the system. This observation is consistent with the idea that the stiffness of any given leg is inversely proportional to its length.

Maximum leg strength

The goal of our testing was to see if a system could reach 20 kN of load before failing. For situations where rock-climbing gear is used as the anchor, the weakest point in the system will likely be the rock climbing protection. (chock, SLCDs, hex, nut, Big Bro, etc.). We assumed that a 7 to 10 kN force acting on rock climbing anchor would be likely to fail. In reality, some climbing protection will be much stronger.

In some anchor systems tested, the systems were pulled until the 7 mm cord failed. A summary of the leg failure force is shown in the graphs in *Figure 20a and b*. The minimum failure force was 15.2. In some tests, a second leg failed just after the first leg failure.

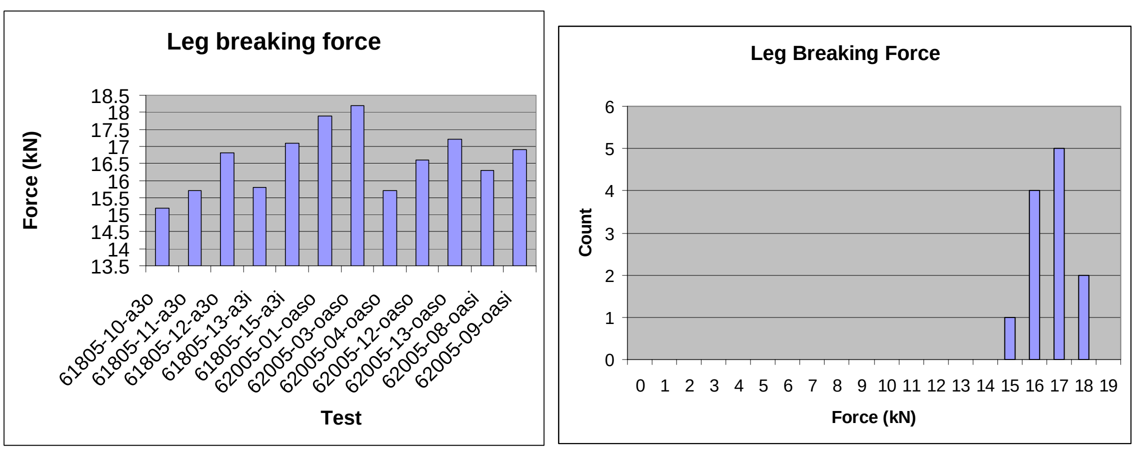


Figure 20: Failure force in a single leg of a three-point system pulled to failure; 20a ***(left)*** by individual test and, 20b ***(right)*** by total count.

Analytical Anchor Model:

In this section of the paper, the forces in a multi-point anchor will be predicted based on an analytical model of the rope system. While the model used here is far from perfect, the goal is to use the model to help us understand how the uncertainties in anchor placement can affect the force distribution in a pre-equalized anchor system. Technical rescue requires an intuitive understanding of the mechanics of rope behavior. The rope technician communities should have an intuitive understanding of how geometric variations and initial rope tension affect the maximum anchor force. Once such knowledge has been gained, risk based decisions can be made.

A second order polynomial fit for tension as a function of rope elongation will be combined with a knot model to simulate pre-equalized multi-point anchor systems. This numerical anchor model will used to consider a wide range of different anchor configurations. From a random sampling of possible anchor leg lengths, angles, and initial slack, a better idea of how likely a given anchor system will support 20 kN of load without exceeding 7 kN of force in any one leg.

The model used here was based on the assumption that the rope stretch could be modeled using a second order polynomial[6]. In this model the force, F, in a rope as a function of stretch, ε, is given by

$$F = a_r \varepsilon + b_r \varepsilon^2 \tag{0.2}$$

Here, a_r and b_r are constants determined with data from the rope pull test and anchor testing reported in this paper. The total displacement of the end of the rope can be computed from the strain and the rope length, L, by:

$$\delta = \varepsilon L \tag{0.3}$$

this gives force as a function of displacement as:

$$F = \frac{a_r}{L}\delta + \frac{b_r}{L^2}\delta^2 \tag{0.4}$$

An anchor system can be viewed as a system of non-linear springs (*Figure 21*), each leg representing a spring with its force governed by the total elongation according to Eq. 1.3.

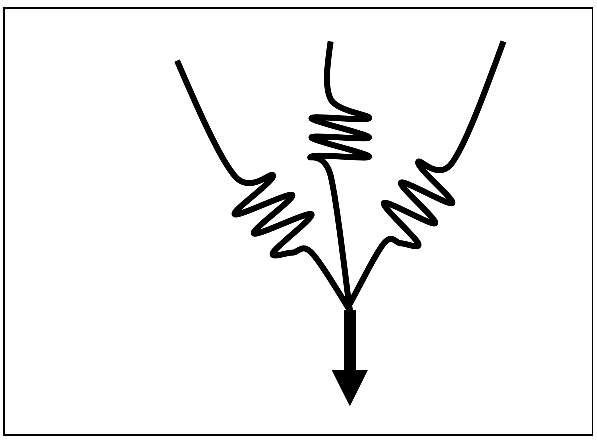


***Figure 21*:** Anchor system viewed as a system of springs.

The force can be computed by directly applying a displacement to the master point. The resulting change in geometry will be used to compute leg tensions and leg directions. A vector sum will then be used to compute the resultant force, F.

A large uncertainty in a pre-equalized system is knot behavior. Modeling the master point knot is difficult. Rope slips from the knot, depending to a first approximation, by the amount of force in the system. The rope slippage was measured during each test and was plotted as a function of leg force, shown in *Figure 22*.

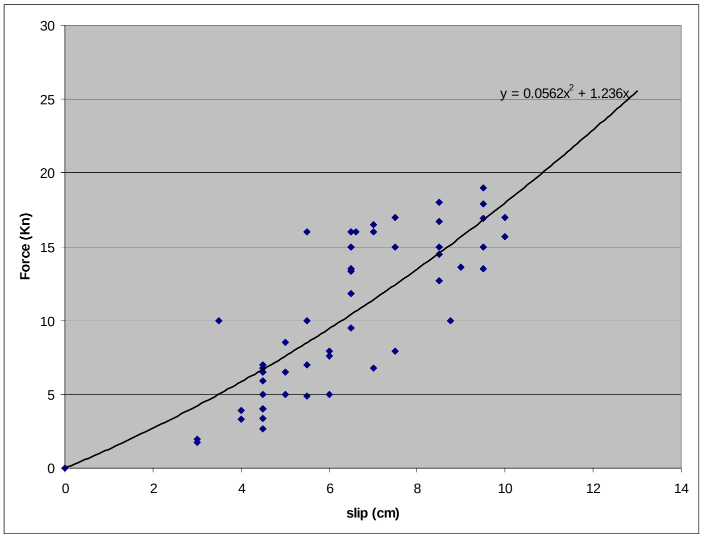


***Figure 22*:** Knot slip as a function of leg tension.

Rope slip physics can be quite messy and depends on, but is not limited to, how well the knot is tied, how much pre-tension is placed on the knot, the day of the week, and many other variables. Here, we are interested in developing a very simple model that might capture some of the effects of rope slip. By using a second order fit for the data in *Figure 22*, we can treat the rope slip as an additional spring in the anchor system.

The knot slip, δ_s, will be assumed to be a function of the tension by:

$$T = a_s\delta_s + b_s\delta_s^{\,2} \tag{0.5}$$

Where a_s and b_s are constants determined from the "best" fit of the data in *Figure 22*.

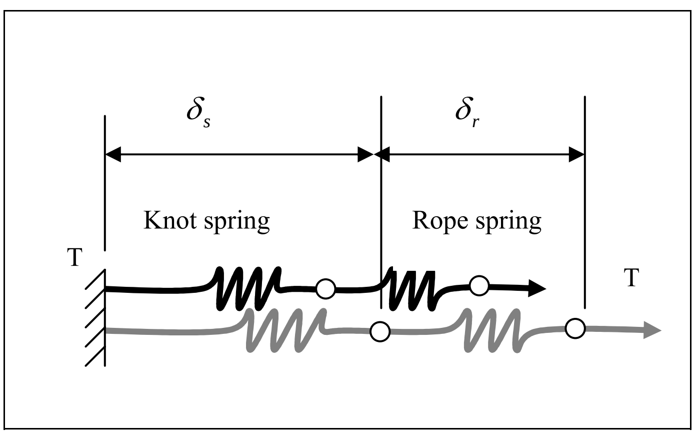


Figure 23: System of springs used to represent an anchor with knot slip.

The force in the two-spring system, one spring representing the knot slip and one representing the cord stretch, can be computed given the total displacement of the two springs. The total displacement of each leg will be given by the displacement of the spring representing the cord stretch, δ_r, and the displacement of the spring representing knot slip, δ_s:

$$\delta_T = \delta_r + \delta_s \tag{0.6}$$

Since the springs are connected in series, the force in each spring will be the same. The length of the cord increases as the material slips from the knot. The cord length in Equation 1.4 must be modified to include this new slipped material. This gives:

$$T = a_s\delta_s + b_s\delta_s^2 = \frac{a_r}{L+\delta_s}\delta_r + \frac{b_r}{(L+\delta_s)^2}\delta_r^2 . \tag{0.7}$$

Equations 1.6 and 1.7 can be combined into a single fourth-order equation for δ_s. Once this equation is solved, the portion of displacement from knot slip and the portion that comes from rope stretch can be computed for a given total displacement. Either the knot slip or the rope stretch can then be used to compute the leg force.

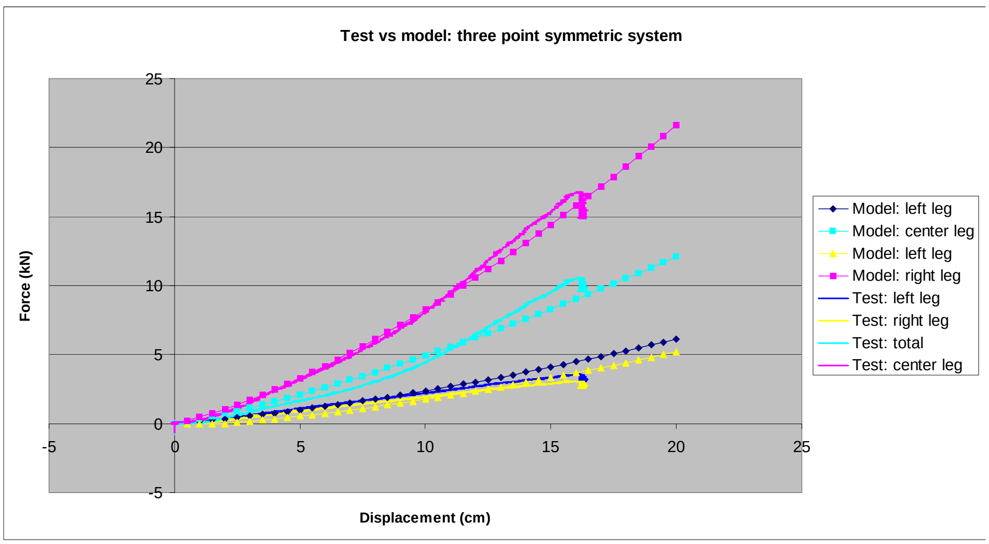


Figure 24: Example of knot slip and rope stretch computed using Equation 1.6 and 1.7. The model closely follows the test results.

The constants used in Eq. 1.7 were based upon a best fit from data measured in this paper. The constants used in Eq. 1.7 were: $a_s = 0.5, b_s = 0.05, a_r = 10, b_s = 60$.

One might have reason to take exception to the pre-equalized anchor model presented here. There are many details of rope and knot mechanics that are omitted from the model[7]. While one could create a more complex model that might be more accurate, let us first explore the current model.

As a point of departure for our model exploration, consider the three-point symmetrical system shown in *Figure 3*. Here, we will assume that the master point is pulled straight down and not allowed to displace from side to side. This constraint may or may not be present in the real world. In our testing, as much as 1.0 to 2.0 cm of lateral movement was observed for the asymmetric system. This modeling constraint simplifies the solution of the equations. Without this assumption, the equilibrium position of the master point must be solved. While this can be done, it was more work than needed for this simple system exploration.

First, we consider the effect of changing leg angles from a nominal of 36º, 0º, 36º by plus or minus 5 degrees. Next, we consider the effect of changing the total length (rope plus load cell) by plus or minus 5 cm. In length variation, each leg is assumed to have no initial slack. The change is only in the initial length of the rope. Lastly, we consider the effects of initial slack in the legs. The slack can be viewed as either poor workmanship in tying the system, or it could be viewed as arising from the uncertainty of the knot slip. Slack could also arise in a system that has the pull direction moved slightly in one direction or the other.

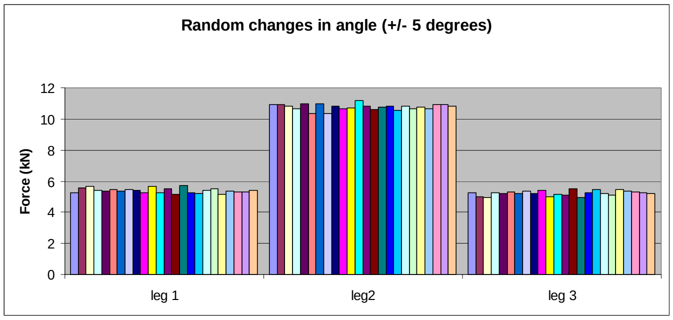


Figure 25**:** Effects on leg forces for a 3-point symmetric system from random changes of +/- 5 degrees in angle.

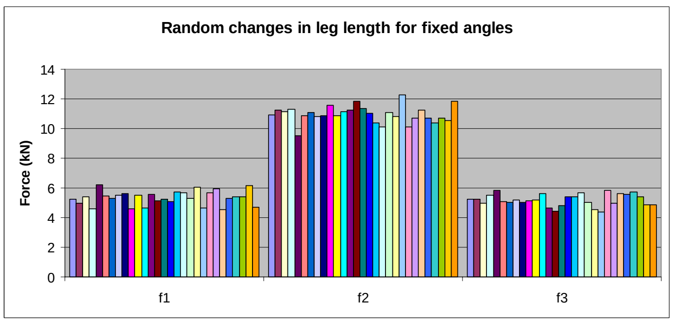


Figure 26**:** Effects on leg forces for a 3 point symmetric system from random changes in length of each leg by +/- 5 cm.

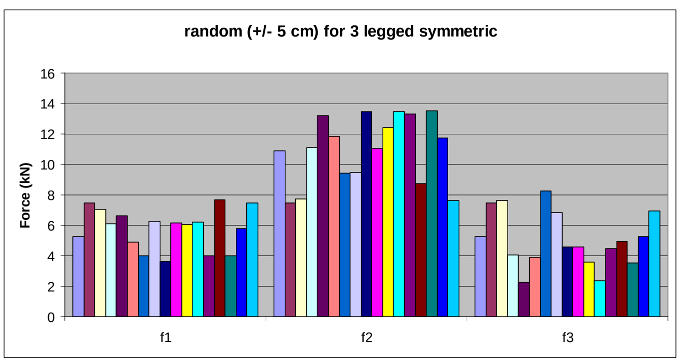


Figure 27**:** Effects on leg forces for a 3 point symmetric system from random changes in the initial slack in each leg (+/- 5 cm).

Figure 25 illustrates that a small change in angle does not have a great effect on the load in each leg. *Figure 26* shows that change in length of a leg is more significant than changes in angle. *Figure 27* shows that the most dramatic variations in leg tension are due to initial slack or uneven knot slippage.

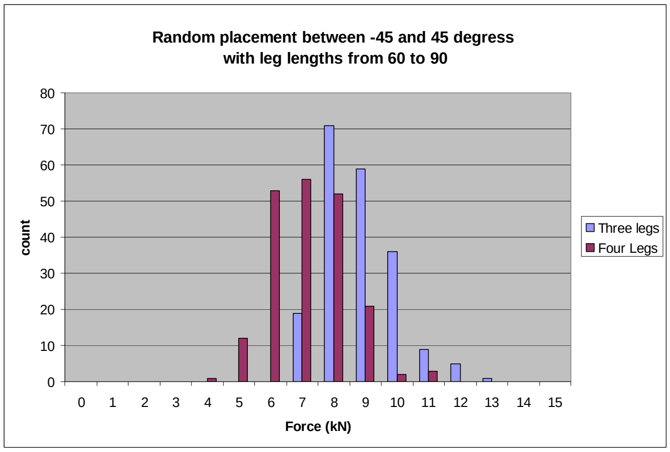


Figure 28: Maximum force in any given leg for a random placement in multi-point system.

All three effects (angle, length, and initial slack) can be varied at once for both the three-point and four-point system. The measure of merit for such a variation would be the peak force in any given leg when the master point tension is 20 kN. *Figure 28* shows histograms for the three and four point systems with the legs randomly placed within a cone of 90°. The leg lengths were varied from 60 cm to 90 cm. Recall that 39 cm of this length are stiff to represent the load cell or the protection slings and carabiners. This plot shows that, in almost every configuration, a leg in the three-point system will exceed 7 kN. This result is consistent with the test data. Adding a fourth point does indeed increase the likelihood that a system can be rigged that satisfies our desired constraints. Even so, more than half of the four-point systems exceeded the 7 kN requirement.

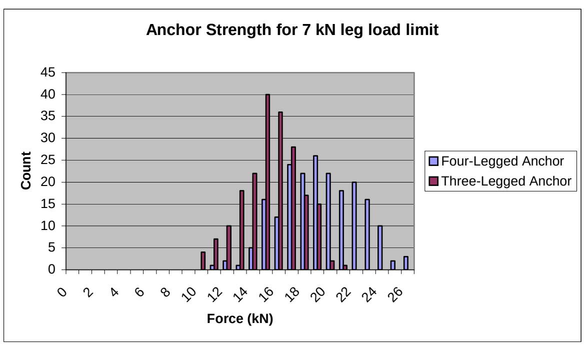


***Figure 29*:** Anchor Strength with a limit of 7 kN in any given leg for 3 and 4 point anchors with random placement with angles between –45 and 45 degrees, leg length between 60 and 90 cm, and +/- 5 cm slack in each leg.

Figure 29 plots the estimated anchor strength for random placements when the load in any given leg is 7 kN. The same conclusions can be drawn in this plot as were drawn from *Figure 28*. When a 7 kN limit was placed on each leg, the average anchor strength for the three-point system was 15.4, and the average strength for the four-point system was 19.2. For comparison, a two point system with a 60 degree angle between the legs would have a 12.1 kN strength when each leg load is limited to 7 kN.

Summary

The three and four-point anchor systems were tested to measure the forces exerted on multi-point anchor systems. These measurements clearly showed that the geometry of the anchor points affected the pre-equalized system. In general, leg length was more of a factor than the leg angle. While the stiffness of each leg of the pre-equalized system is important, slack in a pre-tensioned anchor appears to be a dominant factor.

On average, the three-point pre-equalized system is almost twice as strong as the individual strength of each anchor leg. Numerical modeling of a simple anchor showed that a three-point anchor is always stronger than a single anchor. (i.e., tying a three point anchor is not weaker compared with a single anchor). However, about half the time numerical modeling showed four-point anchor systems are not necessarily better than a three-point anchor system.

If a multi-point pre-equalized anchor is tied at greater than 90°, and even as high as 120°, the outside legs will not have high geometric forces multiplied on them if 7mm nylon cord is used. Knot tightening and stretch of materials will decrease angle substantially, and the longer leg length will cause reduced load angle θ. The short leg in a multi-point anchor will carry a far greater load than its share of the load.

Any time nylon cordalette is used as a primary means for anchor construction, several points should be considered:

1) Angle appears to have little significance in determining the anchor point strength, even when greater than 90° and approaching 120°. Instead, concentrate on the best placements possible and avoid short, stiff legs.

2) It may be beneficial to extend all anchor points to uniform length. A low stretch material like Spectra or one of the high tenacity cords can be used to increase length where needed before pre-equalizing with a nylon cordalette. Should one of the legs be inordinately long, the nylon portion of the anchor should be made the same length as the other legs with the total leg length extended using a low stretch material.

3) Attempt to control the pre-tension while tying a Frost knot, figure 8 knot, overhand, or other knot used in the pre equalization process.

4) More is not always better.

The rescue community, in general, recognizes that rock-climbing anchors may not be strong enough for the higher loads typically seen in rescues. Through testing and analysis, this paper has tried to quantify the strength of one type of anchor system. Our analysis might be considered conservative since we assumed rock-climbing gear fails at a nominal value of 7 kN. This value may be well below what some equipment can achieve in actual placement. Experience and good judgement are key in maximizing strength a multi-point anchor. Hopefully, this paper will help both rock-climbers and rescuers make risk informed decisions when constructing anchors. When in doubt, use bolts.

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