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# Kinematics and Dynamics of Lead Climbing

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by

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**Abstract**

The goal of this research is to gain a better understanding of the kinematics and dynamics involved with lead climbing. Digital accelerometers, load sensors, and slow motion cameras were used to conduct both small and large scale testing of different factors of that might effect a climber and belayer during lead climbing. Rope elasticity and belayer movement were the two factors that were looked at for this research. Small scale testing was done using rigid masses, cords with different levels of elasticity, and a pulley system to simulate anchor points. From the small scale testing it was found that a more elastic rope decreases the force experienced in a fall. After comparing tests of an anchored belayer to a free belayer it was found that there is a 30% and 35% decrease in the maximum average force experienced by the climber and the belayer, respectively.  While both tests show a scenario in which one case is better, in real climbing, the best setup changes on a case by case basis. It is the job of both the climber and belayer to know the risks and come up with a plan to reduce the most amount of risks possible in order to enjoy climbing safely.

**Research Question**

How do~~es~~ different climbing gear and belaying techniques effect the kinematics and dynamics of a falling climber and their belayer?

**Introduction**

Rock climbing is a dangerous sport and requires many technical skills and knowledge of the dangers in order to enjoy the sport safely. While climbing has evolved and grown a lot in recent years, the techniques and safety gear used have not changed much. For example the shape of the carabineers and quick draws have remained relatively similar in the past 20 years. The biggest change to safety devices comes in the form of lighter and stronger materials. The popularity of recreational rock climbing has been on the rise in recent years. With rock climbing now being a part of the 2020 Olympics in Tokyo, there is more potential to grow. With this increase in popularity it is important for people to learn and understand safe climbing practices. In this project I hope to better understand the kinematics and dynamics involved in lead climbing and how we can use that knowledge to improve the safety of rock climbers.

*Figure 1: Illustration of a Lead Climbing Fall*[6]

Rock climbing comes with a lot of different risks and it is everyone's job to ensure that the sport can be enjoyed safely. For this research I will be looking at two possible ways of reducing risks. The first being choosing the right equipment. Specifically I will be looking how rope elasticity effects a falling climber. The second method of reducing risks in climbing that I will be looking at is belayer positioning. I will be comparing the tradeoffs between a belayer being anchored and a belayer being free to be pulled and lifted by the rope.

As a climber moves up a wall, the amount of potential energy they have increases. That is important to understand when rock climbing. When the climber falls ~~a majority of their stored potential energy is about to be transformed into kinetic energy~~their energy can be converted to either kinetic energy or thermal energy (through friction). Lead climbing is a type of rock climbing in which the climber leads the rope as they climb up the wall. The climber is above the rope when they are climbing and they run the risk of falling a potentially dangerous distance. The distance that a lead climber will fall can be calculated using:

$$\Delta x = (2 * x_{clip}) + x_{slack} + x_{stretch} \quad \text{(Equation 1)}$$

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~~When a climber falls while lead climbing they will fall twice the distance from their last anchor point, the amount of slack in the rope when they fell, plus the amount of stretch of the rope.~~In this equation $\Delta x$ is the total change in height, $x_{clip}$ is the distance above the last clip, $x_{slack}$ is the amount of slack in the system, and $x_{stretch}$ is the elongation of the rope due to elasticity. Falling excessive distances can lead to serious or even fatal injuries. Through theoretical modeling, experimentation, and data analysis, a better understanding of what happens when a person falls while climbing can be gained. With that information I can better understand how physics and engineering can help improve the safety of rock climbers.

It is important for both gear designers and rock climbers to understand the physics behind rock climbing. A better understanding of what is happening can help designers create gear that better protects the climbers. When climbers have a better understanding of what is happening, they will be able to adapt to the situation and use specific belay techniques to better catch a falling climber. A study by researchers at the Center for Injury Research and Policy of the Research Institute at the Nationwide Children's Hospital found that there was a 63% increase in number of patients that were treated for rock climbing related injuries between 1990 and 2007. Also in the study they found that over three quarters of the injuries were the result of some kind of fall. This research project aims to decrease the amount of injuries through physics and engineering.

**Prior Research**

A big factor in the forces experienced during a fall have to do with the type of rope being used. Climbing ropes are dynamic which means they stretch as a load is applied. Different ropes have different moduli of elasticity. Max Bigelmayr (2014) conducted a variety of tests that measured the modulus of elasticity of a rope under different fall conditions. He was able to gather information on the oscillations experienced by the "climber" after a drop test. Within this test, Bigelmayr was able to relate the fall factor to the behavior of the rope. A fall factor is a theoretical number to help quantify the severity of a fall. The value of a fall factor can range from a 0 which is an extremely soft fall to a 2 which is a fall that could lead to serious injury or even death. The fall factor is calculated by using the following equation:

$$F_{th} = \frac{Fall\ Length}{Rope\ Length} \quad \text{(Equation 2)}$$

In this equation the fall length is equal to the distance above the last clip times two. The rope length is equal to the amount of rope between the belayer and climber. A fall factor of 2 describes a climber that has climbed without putting any protection. It is important to understand that a fall factor can describe someone falling 1 meter or 30 meters. Rope behavior is very important to understand when conducting research on climbing falls. Each rope can absorb and dissipate different amounts of energy which can help better protect a climber from excessive impact forces.

In another study, Harutyunyan, Milton, Dick, and Boyer (2016) looked at the ideal climbing rope. Their focus was to minimize the maximum force experienced by a climber during a fall. Their study found that one of the most effective materials for a mathematically ideal rope would be a shape memory material. They found that the existing shape memory materials are not suitable for climbing ropes, however they were still able to model and test the effects of different rope properties on the force experienced by a climber.

In depth research has been conducted by the manufacturers that create climbing gear like Petzl and Black Diamond. One particular test conducted by Petzl looked at the forces experienced by the climber, belayer, and top piece of gear during different fall scenarios. They compared the forces when the belayer was free to be moved by the rope to when the belayer was anchored. They observed how each case would help or hinder in catching the falling climber. They found that the climber always experiences the maximum force when nothing is done. From this research I can test to see if the forces experienced can be more evenly distributed within the system to help minimize the maximum force felt.

**Experimental Methods**

During this project I ~~used two different methods to understanding the kinematics and dynamics of lead climbing: theoretical modeling and physical experimentation.~~conducted small scale testing to determine the pros and cons of different climbing equipment and techniques. Both ~~these methods~~of these were tested by simulating a falling climber. ~~were used to analyze a falling climber.~~ There are many factors that may affect a falling climber including: fall height, distance from last clip, number of clips, types of equipment used etc. For this research the rope elasticity and belayer positioning was tested.

~~Theoretical modeling was created using a simple equation of motion to describe the movement of the climber. Different factors such as mass, damping, and spring force were taken into account. The theoretical model was then used to create a graph that was roughly representative of the data collected.~~

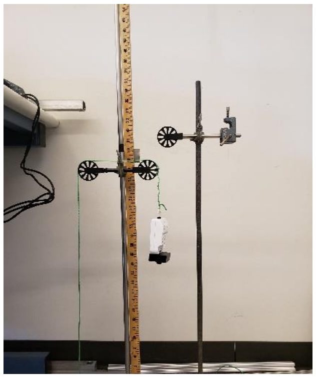

*Figure 2: Picture of Test Apparatus*

To ensure the accuracy of this test set up, a test was conducted recording the data using different methods: video, load sensor, and accelerometer. Each of these collection methods result in kinematic data that can be compared. The accelerometer gives kinematic data directly. With the data from the load sensor, acceleration was calculated using Newton's laws of motion. With the recorded video data I used Tracker, a computer data analysis tool, to track the center of mass. With that tracking data I was able to find the position, velocity, and acceleration of the falling mass. The results from each of the methods was then compared and used to ensure the accuracy of the test system (Figure 3). The data that was found using video and tracker had a lot of noise and didn't produce a clean graph.

Bothe the data calculated using the force sensor and the recorded data from the accelerometer produced smooth graphs. Moving forward the data calculated from the load sensor was used because we were interested in both the kinematics and the dynamics of the system.

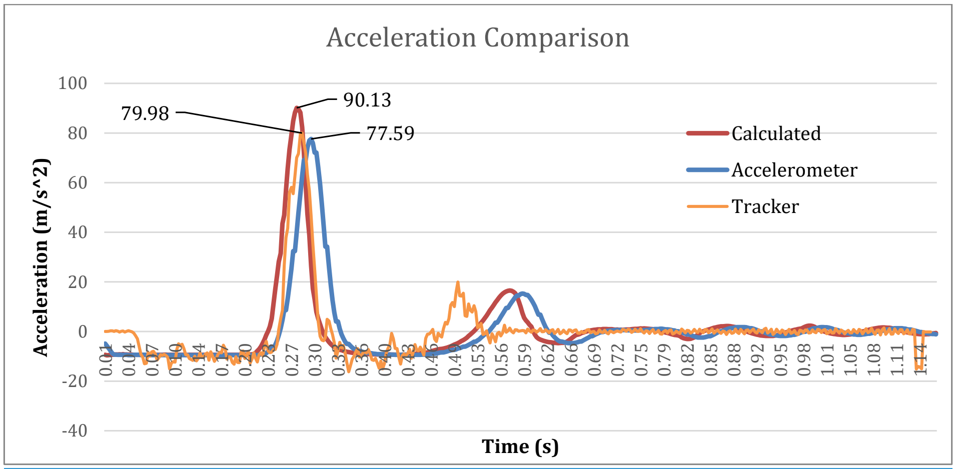


*Figure 3: Graph of Acceleration vs Time comparing anchored belayer tor free belayer*

When testing the effect of rope elasticity on a falling climber two cords with different levels of elasticity were chosen and tested (Figure 4). For these tests one end of the cord was secured to the test fixture and acted as a belayer with a static anchor. The other end was connected to the wireless force and acceleration sensor which would act as the climber. Each cord was cut to the same length, 1.016 m, and was dropped the same distance each time, about 0.1 m. The test procedure (described above) was kept the same for each cord to ensure a valid comparison.

To compare the effect a belayer can have on a falling climber the same test fixture was used with slight adjustments. For the tests the more static cord was used for all tests. In these tests both ends of the rope were attached to force and acceleration sensors. The second sensor was used to record the force and motion experienced by the belayer. A base was constructed so on sensor, the belayer, could be anchored. In order to better understand the relationship between the experiences of the climber vs the experiences of the belayer two different tests were conducted, one test with the belayer anchored to the test fixture and the second with belayer free to be moved. When conducting the tests it was found that friction was an important factor when studying a falling climber. In real rock climbing friction is added to the system mainly through the number of clips a climber has used. The rope moving through each clip adds kinetic friction to the system. To add friction to the system one of the pulleys was prevented from moving in a manner that would force the rope to slide over the pulley as opposed to the pulley turning with the rope.

**Scientific Models**

**Rope Comparison Test Results:**

*Figure 4: Image of Two Cords Tested Green Sting (Top) and Sueded Cord (Bottom)*

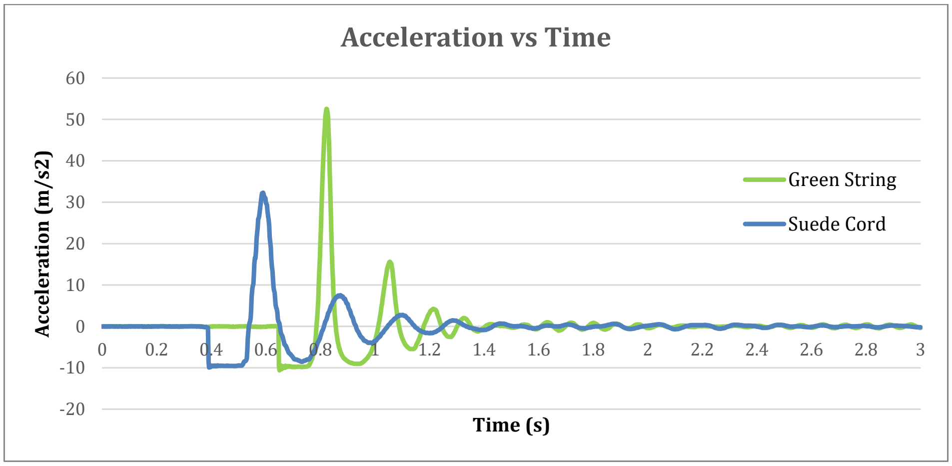


*Figure 5: Graph of Acceleration vs Time of two different cords*

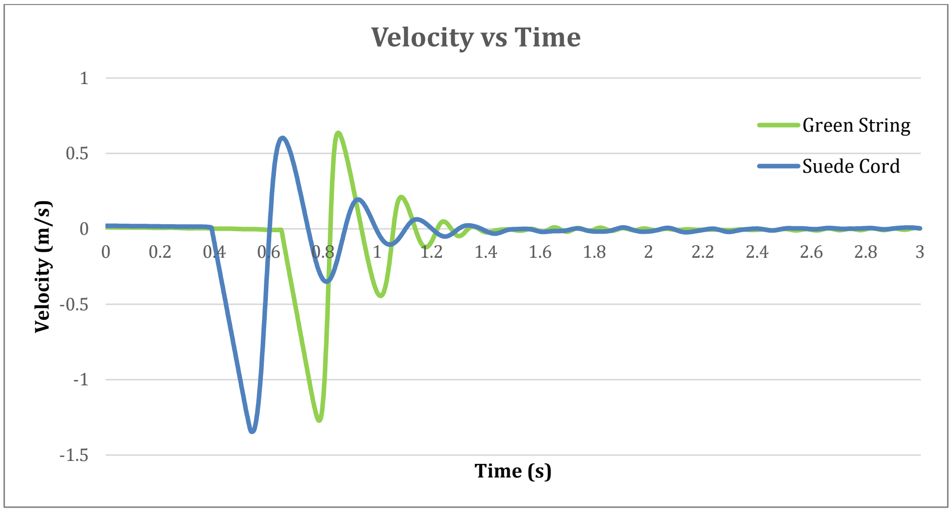


*Figure 6: Graph of Velocity vs Time of two different cords*

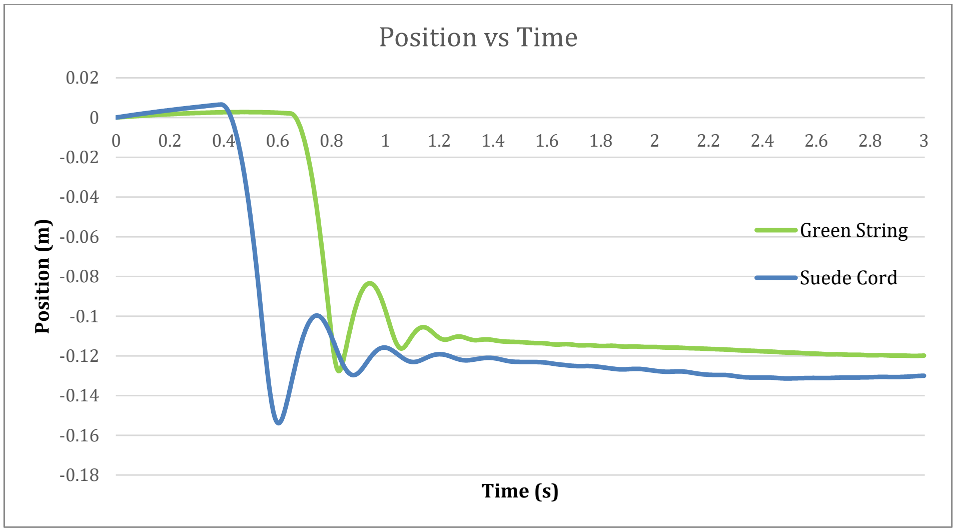


*Figure 7: Graph of Position vs Time of two different cords*

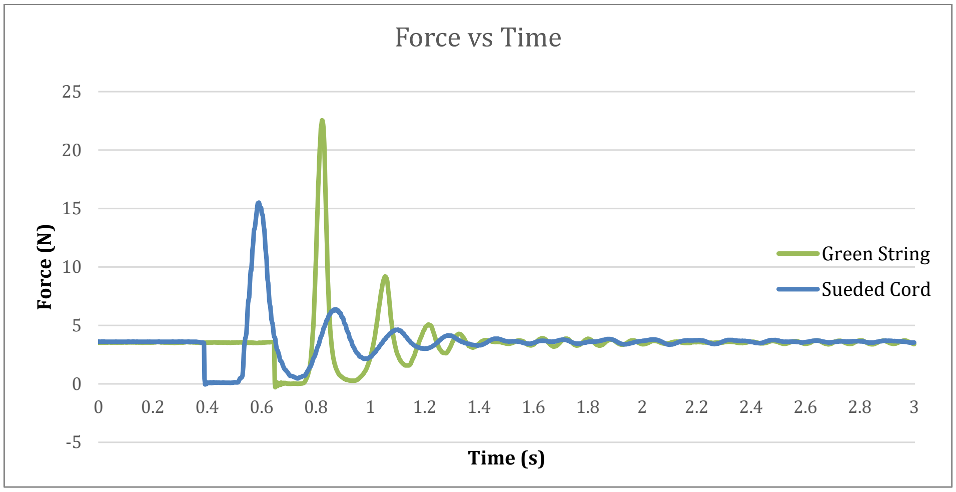


*Figure 8: Graph of Force vs Time of two different cords*

**Anchored Belayer vs Free Belayer Test Results**

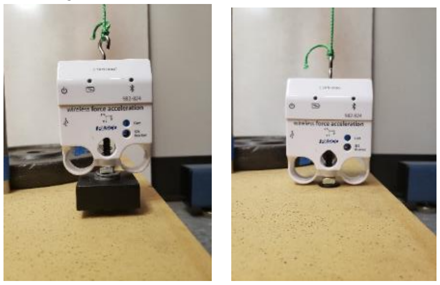

*Figure 9: Image of Free Belayer (Left) and Anchored Belayer (Right)*

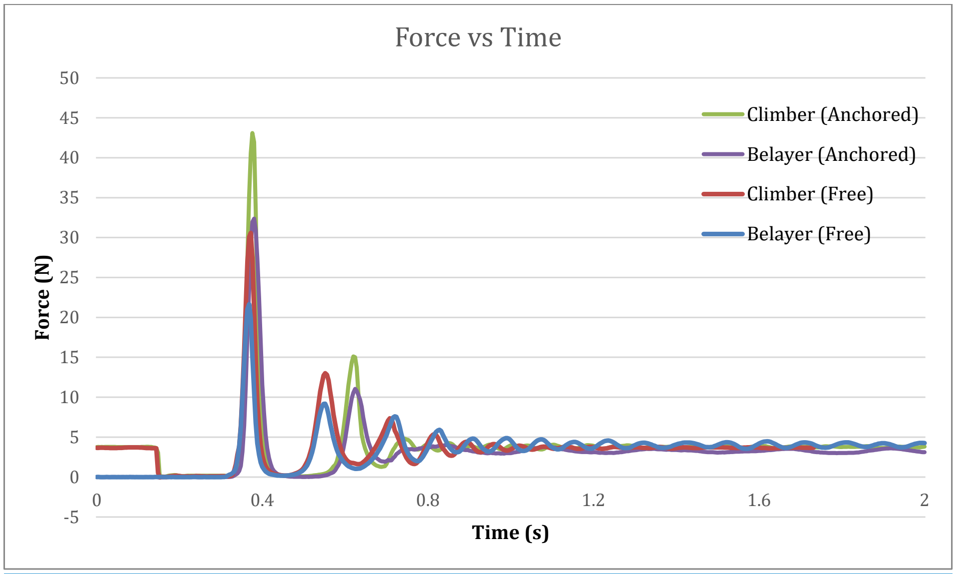


*Figure 10: Graph of Force vs Time comparing anchored belayer to free belayer*

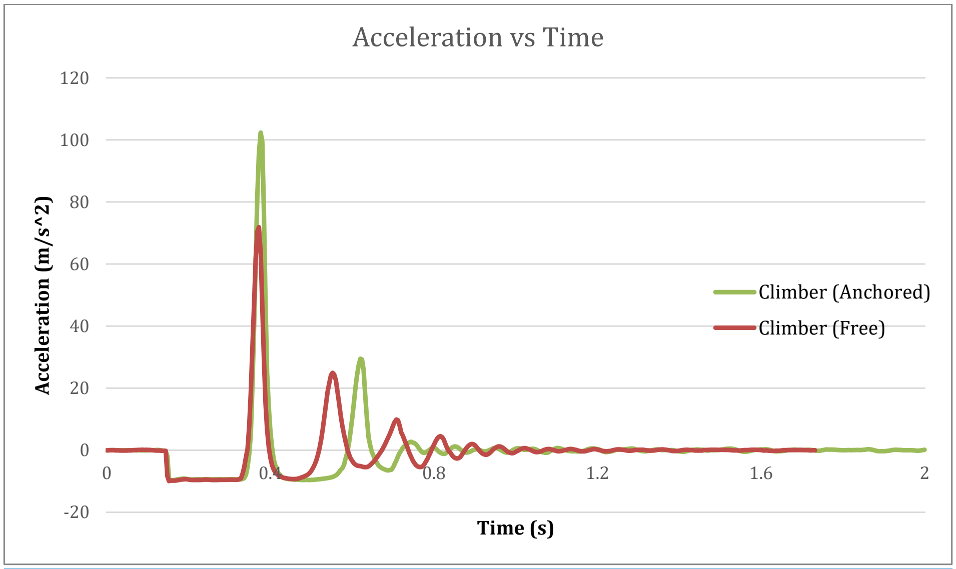


*Figure 11: Graph of Acceleration vs Time comparing anchored belayer to free belayer*

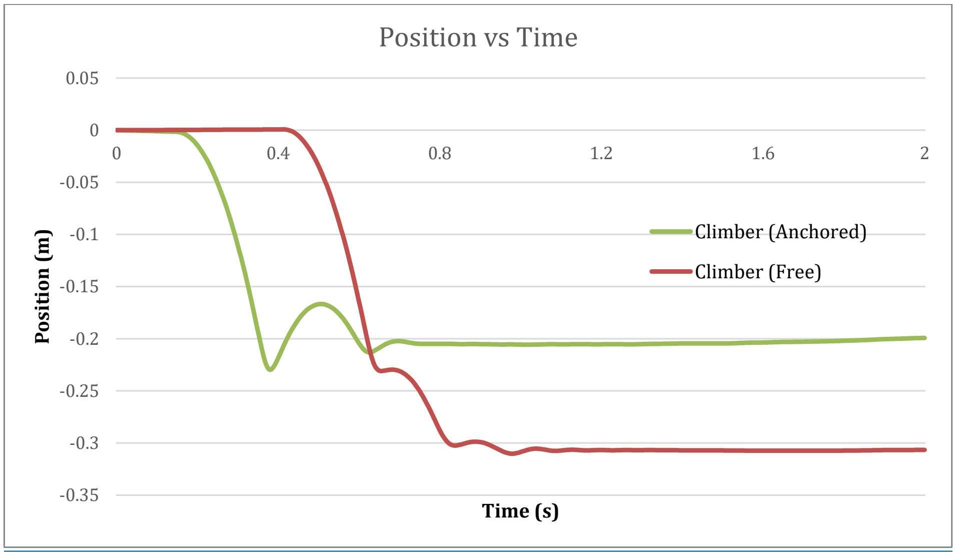


*Figure 12: Graph of Position vs Time comparing anchored belayer to free belayer*

**Analysis**

~~For~~ In the comparison of the elasticity of cords, both cords were tested using the same test apparatus. The data from the load sensor was then used to create graphs of the acceleration, velocity, position, and force (Figure 5, Figure 6, Figure 7, and Figure 8). When using the more elastic cord (sueded cord) the "climber" experienced a maximum force of about 16 N. On the other hand when using the more static cord (green string) the "climber" experienced a maximum force of about 23 N (Figure 8). The climber using the sueded cord experienced less force because the cord absorbed the force through the elastic properties of the cord. The sueded cord may offer the advantage of decreasing the force experienced by a falling climber however it does have some downsides. After a few test the length of the sueded cord had increased by about 0.~~1~~01 m as seen in Figure 7. This is an indication that the cord was experiencing plastic deformation which is permeant as opposed to elastic deformation which is reversible. Depending on the ductility of the cord, continued plastic deformation can eventually lead to rope failure.

~~In real world situations the elasticity of a rope can be a good thing but also it could be a bad thing. For example~~While there is not a rope that will be able to protect climbers in every situation imaginable, there are factors to consider when choosing the right rope for a climb. The tests show that the climber will experience a smaller force when taking a fall on an elastic rope. For the most part choosing a fairly elastic rope will lessen the force and change in acceleration experienced by the climber. However, an elastic rope also comes at a price. The more elastic a rope is, the more stretch and oscillation will occur in the fall. One example of when this might do more harm than good is when climbing a route with a roof section. The big risk here would be when the climber has made it through the roof section and is continuing to climb past the edge. If the last piece of protection was in the roof section and the climber were to take a fall, an over elastic rope may cause the climber to rebound too far after the initial drop and hit the roof. Another situation where it would be beneficial for a less elastic rope is if the route's crux, the most difficult movement, is close to the ground where ground falls are likely. With a more elastic rope the climber will be more likely to hitting the ground instead of bottoming out due to the extra stretch of the rope. When choosing which equipment to use on a route it is important to consider all the risks and choose the equipment that will reduce the most amount of the risks.

Proper equipment choice is one way to reduce risks prior to climbing, but what can be done by the climber or the belayer during the climb that will reduce some of the risks. Tests were conducted that compare the effects of the belayer being anchored and not being anchored. Both the kinematics and the dynamics of this system was looked at in both situations (Figure 10 and Figure 11). In both test the climber was raised 0.2 m from its resting point. The fall factor of this situation was calculated to be 0.156 using equation 2. This fall is equivalent a soft fall from a high distance. When the belayer was anchored it was found that the climber experienced a maximum average force of 43.948 N while the belayer experienced a slightly smaller average maximum force of 33.082 N. When the belayer was free to move the climber experienced a maximum average force of 30.532 N while the belayer experienced a slightly smaller average maximum force of 21.418 N. There was an overall decrease in the force experienced by both the climber and the belayer when the belayer was free to move. There was a 30% and 35% decrease in force experienced by the climber and belayer, respectively. Both the force and the acceleration graphs show that there is a longer period between oscillations when the belayer is anchored (Figure 10 and Figure 11). In Figure 12 it can be seen that when the belayer is free to move the climber falls about 0.3 m which is 0.1 m more than the amount the climber was raised. This is because the belayer was pulled up by the rope and moved up a total of 0.1 m. The belayer's movement is also the reason for the decreased force in the system. When the climber falls the rope slides over the last piece of protection (the pulley) and adds kinetic friction to the system. When the belayer is able to move more rope goes through the pulley adding even more kinetic friction to the system.

This test shows the benefit of allowing the belayer to move during a climb. This set up will decreases the severity of the fall by decreasing both the maximum force and the change of acceleration within the system. However, like equipment choice, it is not always ideal or even possible for the belayer to freely move when a climber falls. In big wall climbing the belayer and the climber are off the ground. In this situation the belayer must be anchored in the wall and it is impossible to allow free movement if a fall were to happen. Another situation where an anchored belayer may prove beneficial is when a falling climber is at risk of hitting the ground. Similar to an overly elastic rope, the belayer's movement increases the maximum change in height of the climber (Figure 7 and Figure 11). One downside of having the belayer move is it adds the risk to the belayer. Depending on the situation a belayer could be dangerously pulled into the wall which may cause them to release the rope. If this were to happen when using a traditional belay device the rope would slide out and the climber and belayer would fall to the ground. Again like choosing the proper climbing equipment, it is important for the climber and belayer be prepared for different situations and be able to employ whichever technique will reduce the most risks.

**Conclusion**

Climbing is dangerous and there are many risks involved but that should not stop people from enjoying the sport. There are different things that can be done in order to reduce some of the risks. This includes choosing the proper equipment and having the technical skills needed to protect the people involved. There is not a single set of gear and proper techniques that will be the best choice in all situations so it is important for the climber and belayer to know the route they are climbing and choose the right equipment and use the proper techniques that will help reduce the risks of the climb.

The results from comparing the two different cords match what was expected. Climbing ropes that are used today are all designed to be dynamic or elastic because of its ability to dissipate forces experienced by the climber. However there must be a balance between the elasticity and rigidity of the rope. When a belayer was able to move there was a decrease in the maximum force experienced by both the climber and belayer. When it comes to reducing the risks in rock climbing it is important that the climber and belayer are knowledgeable of different types of equipment and techniques. The better equipped and trained the pair is the more prepared they will be to reduce the risks of climbing and make sport safer. ~~For example if climbing on an overhang or roof, an elastic rope my decrease the force experienced when bottoming out but could lead to the climber hitting the wall when moving back upward.~~

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## Appendix

### Faith Statement

Christianity and the Church have always been a part of my life; I see myself as a cradle Christian. For as long as I can remember, I have been going to the same church. But even though I have been going to church since I was born, I have never felt any calling toward religion and have never had any big spiritual revelation. Church has just always been in my life, and I have never questioned what it is or why I went to it every weekend. I saw church and school as similar things as I grew up. In both places I felt that I was being spoon fed information on how to act and how I should complete different tasks. I felt like together they provided me with a formula of how to be the person society wants me to be. I have always seen the lessons in church as important not because of religious reasons, but because I saw them as rules and a moral code that I need to follow. Church gave me a list of things to do, and in order to fit in, I would have to check each item off the list. Despite this I still consider myself a Christian even though I still don't completely understand what that means or looks like.

Since coming to SPU I have started to try and engage with the information I am given instead of just accepting that it is true. That applies to both my faith and academic discipline. Up until this point I feel that I have been removed from the decision-making process in my life, and I have just been following the path that has been prescribed to me. I have lived a privileged life in the sense that I have never had to work too hard for anything and everything has always worked out in the end for me. I never really appreciated that God has blessed me in that sense. I have started to see that I am not just living life checking things of a list but I am living the life that God has planned for me. I am still wrestling with the idea that I am where I am today because it is my calling instead of me being pushed and dragged through life.

As an engineer it is easy to think that there is no overlap between faith and what I am working on. I feel like I am called to help people, but it is hard to see how I am doing that as an engineer. The subjects I have been studying in my classes feel like nitty gritty science facts and laws that don't relate to my faith in anyway. Sometimes it is difficult for me to see how completing calculations and analyzing systems helps me fulfill my calling. However, as a Christian engineer I believe that it is my duty to use my God given gifts of technical knowledge and practical abilities to design and create in a way that both glorifies God and improves society. Although I may feel removed from the act of helping people, designing and building products as an engineer allows me to help people and support them with my work. Even though designing and building does not feel like actively serving and helping people, the things I will do as an engineer help people every day. In Mountains Beyond Mountains, Paul Farmer says, "if I had to choose between lib, theo, or any ology, I would go with science as long as service to the poor went along with it. But I don't have to make that choice, do I?" (Kidder, 84). Like Farmer I live in two worlds: faith and scholarship. Farmer did not have to choose one over the other and I am thankful the same can be said about me. I am able to still follow the path of engineering without compromising my values as a Christian, and my Christian values may even inform the work I do as an engineer and will help those in need.

As a steward of God, I believe that I should use my gifts as a way to glorify God. In the bible it says that faith without deeds is dead however I think that deeds without faith are equally forsaken. It is possible to be a good person without being a Christian, but without including our faith our acts may fall short. This distinction is important because it is possible to be good without faith but we can do our best if we do it through God. As a Christian I believe in order to truly engage my faith I need to do things that show my faith instead of saying I have faith. I think that it is equally important to remember my faith when I am doing things that I wouldn't normally associate with God. I see engineering as a very practical major that deals with the physical world. Within the classes there is little to no discussion of how theology or faith relates to the subject matter. As discussed by Marsden, most of STEM is approached from a stance of methodological atheism.  It is easy to forget faith when developing an equation of motions. That being said, when I am working on a practical problem, I look down the line to see how these calculations will eventually help someone.