Study of Breaking Strengths of Selected Progress Capture Devices

Utilized in Rope Rescue Systems

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CERTIFICATION STATEMENT

I hereby certify that this paper constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of others.

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Abstract

Rescuers use the strength of rope system components to determine the static system safety factors (SSSF). This calculation is dependent upon how components interact with one another. The problem was that devices used in haul systems, acting as progress capture devices (PCDs) or ratchets, did not have consistent published rates of failure. There was no widely proliferated information outlining how these PCDs interact with the host rope at the point of failure. As a consequence of this information-gap, field practitioners could not accurately calculate the SSSF in their systems. The purpose of this research was to identify the failure strengths and conditions of common PCDs and publish the information detailing high, low, and average rates of failure as well as the conditions in which this occurs. This project used evaluative research, but placing such in a historical perspective of fire and rescue service's best practices. The primary research was performed using empirical observations of the breaking strengths, behavior, mode of failure, and consequence of eight different progress capture devices on three types of rope. This research answered the following research questions: a) what is the strength of a single Prusik, tandem Prusik, Rescuescender, Grip, Munter Hitch, I'D, and MPD when used on both new and old 12.5mm PMI EZ-Bend kernmantle rope? b) what is the strength of a single Prusik, tandem Prusik, Rescuescender, Grip, Munter Hitch, I'D, Basic, and MPD when used on both new and old 11mm PMI EZ-Bend kernmantle rope? c) what constitutes a failure of a PCD? d) what constitutes a loss of confidence of a PCD?

The research learned the failure rates of various PCDs ranged in SSSF from 2:1 to 25:1 depending on the device and rope. The research also discovered force-limiting conditions deemed the System Operation Limit of haul systems. These SSSFs ranged from 1.2:1 to 10.6:1.

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Introduction

Rope rescue or high-angle rescue is central to many activities performed within technical rescue in modern fire and rescue services. The National Fire Protection Association (NFPA) *1006 Standard for Technical Rescuer Professional Qualifications* (2013) contains 14 separate rescue disciplines in chapters 6-19. Before certifying to any other discipline, 12 fundamental rope rescue skills in chapter 5 are a prerequisite. Most instructors and practitioners familiar with *NFPA 1006* and *NFPA 1670 Standard on Operations and Training for Technical Search and Rescue Incidents* (2014) agree that thorough retention of rope rescue skills is crucial for success in many disciplines. Basic and advanced rope knowledge is required in confined space rescue, water rescue, cave rescue, as well as the other heavy rescue disciplines.

Most firefighters trace their history and origins to Benjamin Franklin and the volunteer fire service. Fire and its danger to people and populations is much older. This is the same with rope. The first rope origins can be traced back to 5,300 years ago when early cave dwellers used hair and natural fibers to descend in and out of cave dwellings in order to avoid predators and threats. Rope has been identified as one of the first tools used by early humans (Padgett & Smith, 1996). These early ropes dating back to 3000 B.C. were also developed by the Egyptians and would prove instrumental in great engineering feats. The early prototypes were made of natural vines, hemp, flax, and grass (Neal, 1990).

Hudson and Vines (2014) discuss how people have engaged in mountaineering and climbing for hundreds of years. These pursuits, fraught with danger, capture the imagination and human spirit. The biggest advances in technology have been made since

World War II. The most significant was the invention of ropes using synthetic fibers. Another influential sport that has yielded advances in technique and technology is vertical cave exploration. Most of the techniques and equipment used in the early days of rope rescue were borrowed and adopted from the recreational climbing and caving community. The modern era of professional rope rescue kicked off in the 1980's as a result of the deaths of two FDNY firefighters and the resulting impetus for change by the NFPA, IAFF, and the ISFSI (Hudson & Vines, 2014).

Most students would be surprised to learn that modern rope rescue is less than 40 years old. The 80's and 90's were formative decades that can be characterized with much debate and the early inception of rope and rescue regulations and standards. Within this time period, many arbitrary safety provisions were established and proliferated as the law-of-the-land. Some of these provisions included the exclusive use of synthetic fiber rope for life safety, one-time use only for life-safety rope, a 300 lb. load for one-person rope, a 600 lb. loads for two-person rope, 15:1 safety ratio for 4,500 and 9,000 lb. rope, and two-rope rescue systems with a tensioned mainline and untensioned belay. These concepts were all derived with the best of intentions. Many have changed or evolved. Some of them have gone away. Some are being challenged at present time.

The last 20 years have seen explosive growth in technology, techniques, training courses, and service delivery. The professional rope recue field has continued to take many lessons from other rope fields, engineering fields, and practical experience. Rope rescue has matured tremendously. Much of this is in thanks to research, testing, empirical observations, and healthy debate. Unfortunately, academic research in technical rescue is a narrow field. This is especially true in the search for published and widely disseminated information. The consequences of this rapid expansion and inadequate research, testing, and publication are assumptions, misinformation, and general gaps in knowledge.

One of these existing gaps in knowledge exists regarding the engineered strength and integrity of common rope rescue systems. This is partially due to dated, incomplete, or unpublished research. The other reason for this gap is the creation and proliferation of new pieces of rescue hardware used in hauling and lowering systems. In both the instructional realm and for field applications, students are taught a rough form of physics and engineering in order to assess the over-all strength of their rigging. Hudson and Vines (2014, p.37) assert that all rope technicians should know the breaking strength of all the equipment in any system they rig. The authors explain that most breaking strengths are published by the manufacturer in the form of *minimum breaking strength (MBS).* The MBS is determined by performing destructive testing and subtracting three standard deviations below the mean of a set of laboratory tests (Hudson & Vines, 2014, p.37).

Using the MBS of the various components of a rescue system, the practitioner can select the weakest component, anticipate the load, and determine the relative *system safety factor (SSF).* Mathews defines the system safety factor as “the ratio of the load compared to the strength of individual components in the rope system (2009, p.20)”. There are many misconceptions and misunderstandings regarding this concept and how it is applied. The concept and its practicality are valid and have origins in engineering that date back many years. Generally structures and systems are designed to hold much more than their anticipated load in order to account for wind, earthquakes, unusual occupancy, shock loading, and similar circumstances. As previously mentioned, manufacturers publish and disclose the MBS of all kinds of products in rescue ranging from soft goods to hardware. One area of knowledge and research that is missing is the MBS or strength of an interface where hardware grips rope, or where software such as a Prusik hitch grips rope. This can be attributed to the great deal of variability between all the different combinations of hardware-on-rope interfaces and software-on-rope interfaces.

One place these interfaces occur is as a rope grab within a haul system. These rope grabs' purpose is to hold the load as the haul system is being reset. Hudson and Vines define the *progress capture device (PCD)* as "a rope grab device, general use ascender, or a hitch placed on the rope in a hauling system to prevent the rope (and the load) from slipping back down as the haul system is reset. Also commonly referred to as a ratchet (2014, p.320)." The National Cave Rescue Commission (NCRC) (2014) discusses the use of software such as Prusik hitches, as well mechanical ascenders such as the Petzl Rescucender in their student manual (p.22.3). This practice is very common depending on the team and jurisdiction. References to using these two main types of PCDs can be found in nearly all literature and manuals from the 1980s to present.

The information that is missing is how these components affect the overall strength of a system. Rescuers strive to pre-plan the strengths of commonly used rescue systems, improvise rigging and perform field calculations as to the over-all integrity of the system. This static system safety factor (SSSF) can only be calculated if all components are known. The problem is that devices used in haul systems, acting as progress capture devices (PCDs) or ratchets, do not have consistent published rates of failure. There is no widely proliferated information outlining how these PCDs interact with the host rope at the point of failure. As a consequence of this information-gap, field practitioners cannot accurately calculate the SSSF in their systems. The researchers feel this likely leads to an over-estimation of system integrity and SSSFs. The purpose of this research is to identify the failure strengths and conditions of common PCDs and publish the information detailing high, low, and average rates of failure as well as the conditions in which this occurs (Walker & McCullar, 2014). This research provides a tool for students and end users to use the missing information to perform field calculations of SSSFs and make the best decisions in rigging applications for their patients and team members.

This project will primarily utilize evaluative research, but placing such in a historical perspective of fire and rescue service's best practices. The primary research will be performed using empirical observations of the breaking strengths, behaviors, modes of failure, and consequences of eight different progress capture devices on three types of rope. The tests will be performed using a calibrated slow-pull hydraulic test bed to pull each device combination. Each combination within the experiment will be performed five times in order to ensure reasonable statistical validity. This research will answer the following research questions: a) what is the strength of a single Prusik, tandem Prusik, Rescuescender, Grip, Munter Hitch, I'D, and MPD when used on both new and old 12.5mm PMI EZ-Bend kernmantle rope? b) what is the strength of a single Prusik, tandem Prusik, Rescuescender, Grip, Munter Hitch, I'D, Basic, and MPD when used on both new and old 11mm PMI EZ-Bend kernmantle rope? c) what constitutes a failure of a PCD? d) what constitutes a loss of confidence of a PCD?

Background and Significance

The Mississippi State Fire Academy began construction in 1974. It is situated on 112 acres outside of Jackson, MS. It is a premier fire service educational institution and its spirit is captured in its mission statement: “To serve the Mississippi fire service community and the world by providing quality education and training in fundamental and advanced skills to save lives and property(Mississippi State Fire Academy, 2014).” The agency employs a staff of 63. Full time instructors comprise 28 positions in various areas of specialization. Nearly 5,000 students attended courses on campus in fiscal year 2014(Mississippi State Fire Academy, 2014, p.14). The Special / Industrial Bureau consists of ten instructors that are responsible for programs in hazardous materials, technical rescue, and industrial firefighting. The researcher manages rescue programs and curriculum both on and off campus. As the mission statement suggests, the Mississippi State Fire Academy does not strive only to be a leader in Mississippi, but also in the greater fire and rescue community.

Need

Students look to the instructional staff for answers. It is widely practiced that if an instructor does not know an answer, rather than bluff or speculate, they will research and deliver the information to the inquiring student. The staff is highly trained and professional in most things dealing with rope rescue. The concept of field calculations, white-board analysis, and static system safety factors (SSSFs) are taught as a part of both intermediate and advanced rigging principles. When a students inquires the breaking strength or SSSF of a progress capture device (PCD), this presents a problem. The PCD is a crucial and critical link in rescue systems. It singularly holds the weight of the patient and the rescuer as they are being hauled while the mechanical advantage pulleys and cam are reset. In the tensioned rope systems, such as a highline, the PCD controls the tension in the tracklines that provide the horizontal rope pathway for rescuers, equipment, and patients.

It is almost inconceivable that after years of study and publication, there is not a clear answer to the following question: How strong is this system while this rope-gripping device or hitch is holding the load? Students and the rescue community at large deserve to have a clear answer and repeatable methods for obtaining their own answers. This is not a totally unexplored concept. Many instructors and rescue groups have contemplated this and performed various “back yard” testing. There is some anecdotal information in obscure self-published rope manuals. Research on Prusik hitches and their holding power is not uncommon, but most tests were in a dynamic setting -testing its merits as a belay hitch. Furthermore, the testing that has been performed, or is often cited, is not published, publicly documented, or subjected to peer review. If you can find anything, it is often in the form of a single breaking strength number in a text without references. This is big problem. This problem hampers the ability of the instructors at the MSFA to answer students’ questions, but it also confounds the greater technical rescue community.

The knowledge that could be gained from answering these questions might constitute a small leap or paradigm shift in the way rescuers view their rigging and equipment. Most teams will purport that their rigging adheres to some safety factor. NASAR’s *Fundamentals of Search and Rescue Manual* (2005) states that many fire and rescue organizations require a 15:1 safety factor for all rope and components. Some wilderness teams will find a 10:1 safety factor acceptable (p.263). In their book, Hudson and Vines (2014) state that some wilderness rescue groups are now using a 7:1 safety factor for many reasons. One of the reasons for lower safety factors is they allow for lighter and smaller equipment (p.37-38). The anecdotal evidence from “backyard testing” suggests that if rescuers were to factor in the breaking strength of these commonly used eight types of PCDs, then their SSSF might be substantially lower. What if one of these components only yielded a 5:1 SSSF with an NFPA two-person load on 12.5mm rope? Would that be a problem? If there is no pile of bodies at the bottom of the pitch after 40 years, what does that say about our SSSFs? Maybe this knowledge can initiate honest discussions about using that smaller carabiner or that skinnier rope. Maybe those strict adherences to 15:1, 10:1, and 7:1 can be re-evaluated.

Another avenue of exploration this research will explore is the concept of PCDs that may not fail. Not all issues are black and white. Some PCDs or ratchets may simply be engineered to slip without damaging the rope or constituting a breakage or “failure.” At the International Technical Rescue Symposium in 2014, Kirk Mauthner presented on the concept of “force-limiting systems.” He alluded to devices similar to those in this study, but spoke to the concept of systems that move beyond a fixed minimum breaking strength (MBS) or SSSF, but rather have a “force-limiting” range. These systems truly can behave as a clutch. This is the beginning of changing the way rescuers view their rigging.

Executive Analysis of Fire Service Operations in Emergency Management Linkage

This project seeks to tackle an issue at several stages of the “Planning Model” found within the *Executive Analysis of Fire Service Operations in Emergency*

Management Manual. The goal of the EAFSOEM course is to prepare senior officers to manage the operational component of a fire department effectively (U. S. Fire Administration, 2014, p. 1-8). The EAFSEOM course manual outlines the trend in the fire service towards technical rescue and special operations. This trend can be traced back to the widespread involvement in the field of emergency medicine. As pre-hospital care was changed, victims of any incident became patients. As fire departments gained ever-greater medical expertise, specialized rescue became a viable core function and a routine responsibility (U. S. Fire Administration, 2014, p. 2-3). Both trends led to greater survivability of patients. Central to this concept is the fact that fire departments were able to evolve and adapt. Also core to patient survivability is the ability of rescuers to make snap-judgments based on sound training and practice. Rescuers must have total faith in their tools and their rigging. Cognitive knowledge of information like MBS and SSSFs really lead to fast action, muscle memory, and recognition-primed decision making (RPDM).

This applied research project seeks to tackle a broad strategic issue and deliver it to the field rescuer as a reliable tactical tool. It is the responsibility of the researcher and his agency to perform research and testing to deliver answers to students. These answers will have a direct impact on policy and tactics used to deliver patient care. The EAFSOEM course discusses how the first response is the job of local emergency services. It also talks at length of the concepts of strategic goals and tactical objectives. The role of the safety officer is highlighted many times in the text. The scope of the EAFSOEM course is very macro-response oriented, but the scope of the research is a very niche area with a micro-response level feel. It is the hope of the researcher that the information learned in this study can be incorporated into the pre-planning part of the Planning “P”, then it can be used in the tactics, the execution stage, and the evaluation stage (U. S. Fire Administration, 2014, p. 8-4)

USFA Linkage

This research project is central to three of the five strategic goals supported by the U.S. Fire Administration. Those three goals are: a) the improvement of local planning and preparedness, b) to improve the fire services capability to respond to and recover from all hazards, and c) to improve the professional status of emergency services (U. S. Fire Administration, 2010). The problem within this research is not one that, once solved, will save an abundance of lives. The problem is academic and philosophical in nature. It leads readers and rescuers to question the status quo and re-think the way they view the rigging world. The research seeks to provide answers in an area where there really are not alternative sources. The strategic goal of the U.S. Fire Administration that most resonates with this research is to improve the professional status of emergency services.

Outside of the International Technical Rescue Symposium (ITRS), a few authors, and loose anecdotal oral tradition; there is scarce academic resources for technical rescue and special operations. The Learning Resource Center at the National Emergency Training Center is indicative of this void. The fire service has a responsibility to research, question, and justify those most extreme tactics and techniques that rescuers are called upon to perform. The tools and techniques, which rescuers risk their lives using, should be vetted by more than a consensus standard and Underwriters Laboratories. Components not only need to be tested individually, but they should be tested in the manner they are used in the rescue system. Tests should be done in-line with field applications. Those tests should be documented, published, and repeatable. Those resources should be centrally located in the LRC. This will elevate the professional status of emergency services.

Literature Review

On June 27, 1980, FDNY firefighters Gerard Frisby and Lawrence Fitzpatrick fell seven stories to their deaths during a rope rescue operation at a working structure fire. While performing search operations Frisby became separated from his crew and was spotted semi-conscious hanging out of the window of a seventh story apartment. Fitzpatrick of Rescue 3 was lowered from the roof on a ½" rescue rope to assist and rescue Frisby. When both men loaded the rope and swung away from the window, the line gave way and they plummeted to the street (Brown, 2000, p.7-9).

This event was the impetus for standardization and regulation of rope rescue equipment and techniques in the modern fire and rescue services. In the years to follow, the National Fire Protection Association would deliberate and deliver the initial *NFPA Standard on Fire Service Life Safety Rope and System Components* on June 6, 1985(Brown, 2000, p.9). Prior to this event and subsequent standard, the primary organizations influencing the rope rescue were the Mountain Rescue Association(MRA), the National Association for Search and Rescue(NASAR), the National Speleological Society Vertical Section, and to a degree the Union of International Alpine Associations(UIAA). Most of the rope market and standards were being driven by volunteer search and rescue organizations and recreational users. It is for this reason that for years, the rope rescue community used tools and techniques primarily grounded in the recreation environment.

After the New York accident, there was a vacuum of information, but a need to push for some kind of standardization while the NFPA was drafting NFPA 1983. The International Association of Firefighters (IAFF) published a white paper entitled *Line to Safety* (1981) that recommended changes and improvements to rope rescue equipment selection and management. This document constitutes one of the earliest references to issues, rules, and management that are often misunderstood or misquoted to this day. The first significant recommendation was to transition from within the fire service from natural fiber manila ropes to synthetic fiber nylon or polyester ropes. It was further recommended that these ropes be “Rescue-Kernmantle” (p.15).

The next broad area in the document deals with rope size, strength, safe working load, and implicitly the issue of safety factors. The document outlines how the Cordage Institute generally recommends safety factors from 7:1 to 10:1 for industrial use. It also states that Civil Defense and IFSTA manuals call for 5:1 and 10:1 safety factors for rescue. It goes on to state that these are considered inadequate for critical rescue use (IAFF, 1981, p.4). The paper contends that a two person working load should be considered 600 lbs. and a 15:1 safety factor should be used. Therefore a rope with a breaking strength of 9000 lbs. should be used in all rescue situations (IAFF, 1981, p.18). In order to meet this requirement, the recommended rope diameters range from 9/16” to ¾”.

One of the last and most controversial parts of this paper and later standards was the assertion that after use, the residual strength of ropes could not be determined, therefore all life safety ropes were limited to one use. This meant, whether it be in an actual rescue or training, once used, the rope should be relegated to utility purposes

(IAFF, 1981, p.20). These issues of strength, safety factor, and one-time use would echo in the impending NFPA 1983 standard to be released four years later.

Rescue historians should understand the context in which these ideas and standards were conceived. These standards were in reaction to a tragic accident. Furthermore it involved the deaths of two large FDNY firefighters during an unusual rope rescue at a high-rise structure fire. When ideas regarding rope standardization were being considered, the thought revolved around two fully ensembled firefighters in structural fire gear and SCBA. It was also under the pretense, that a possible rope rescue mission-profile, take place in the fire environment. Synthetic fiber kernmantle rope was a wholly new concept to the fire service. Little was known about its characteristics or strength retention. These factors almost created the perfect storm for reactionary alarmism. With so many factors and characteristics of the new rope yet unknown, bigger seemed better. This would prove the case with rope strength, rope diameter, potential working loads, and the safety factor.

The reader should understand that since the 1980's, there have probably been less than ten major texts written by authors that really possessed and broad and deep understanding of the rope rescue macro-environment. That is to say only a few widely published authors knew rope craft from creating standards, to manufacturing equipment, to the needs and reality of the end user. Authors that come to mind in this category are Hudson, Vines, Padgett, Smith, and Frank. There are other authors who are strong subject matter experts who made their livelihood as instructors and their works were never widely published. Many educators and institutions write their own manuals that cater to the needs of their customers. This creates a challenge for those thirsty for knowledge because many great works are not publicly available. Some of these authors include Pat Rhodes, Steve Crandall, Rick Weber, and Reed Thorne, just to name a few. Some of the literature within the following pages can be difficult to find, but is rich in value and historical context.

Engineering Origins Factors of Safety

Engineering principles are intrinsic to the manufacturing process. It is logical that early discussions on rope rescue equipment standardization dealt with desired safety factors. Within the engineering field, this concept is also often referred to as factors of safety. In an article on his engineering website, Waqas Ahmad explains safety factors as the structural capacity of a system beyond its expected or actual loads (2011). The author goes on to explain that many systems are engineered much stronger than normal usage to allow for emergency situations, unexpected loads, misuse, or degradation. This reasoning for safety factors seems to translate very well to the needs of emergency services. Firefighters and rescuers face emergency situations, sometimes misuse gear, over burden themselves and their equipment, and keep equipment longer than its recommended service use. Ahmad (2011) goes on to explain there is a near universal push towards conservative calculations of safety factors to ensure systems are able to withstand worse-case loading.

Hanson (2010) discusses the fact that builders have used safety factors for hundreds of years. Builders would over build so there was strength in reserve. The concept is formally documented in Germany in the 1860s for the construction of railroads. Today the use of safety factors is a well-established structural engineering principle. Areas of engineering where predictability is low, but consequence is high have higher safety factors. When the behavior of the material is very predictable, they can be much lower.

In their text, Burr and Cheatham (1995) discuss common safety factors used in engineering, manufacturing, and construction. The biggest surprise to most people would be the fact that aviation engineering is usually on a factor ranging from 1.2-3. This a product of cost and weight. Because of the low safety factors, the aerospace industry has stringent quality controls and strict preventative maintenance. Automobiles are designed on a factor of three, while construction members are built on a 2:1 design factor (Burr and Cheatham, 1995). All of these safety factors are much lower than that of the previously mentioned 15:1 proposed for rope and components.

The U.S. Army Corps of Engineers publishes the *Urban Search & Rescue Structures Specialist Field Operations Guide*. The 2014 version of that document discusses safety factors and their variability in wood shoring. David Hammond (2011) discusses wood shoring and testing in an article in *Fire Engineering*. He notes that wood shores are expected to fail at three times their design load, yielding a 3:1 factor of safety. The US&R FOG (2014) guide specifically cites the safety factors of Paratech Pneumatic shores as 4:1 and 3:1, depending on the needs of the team and the configuration. This is a document, designed by engineers, that is used by responders in emergency and disaster situations. The standard of care for safety factors in shoring, both vertically and horizontally, in 2014 remains in the low single digits.

Fire Service and Safety Factors

The fire service has had a love of lofty safety factors in rope rescue that has been difficult to move beyond. There is no denying the original verbiage in NFPA 1983.

Safety factors of 15:1 were the standard as well as two person loads of 600 lbs. Ropes had to practically be disposed of after each use. The fire service, instructors, and subsequent generations took these principles to be hard-fast guidelines in the field for systems and operations. The standard was actually conceived and is now exclusively represented as a manufacturers' document. Teams and authorities having jurisdiction (AHJs) have the ability to select their equipment and practice rigging to SSSFs that suit their needs.

Much of the problem lies within the oral traditions and resistance to change within the fire service. A young firefighter attends a rope rescue class in the late 1980s and never revisits the topic for the next 20 years. Now, that captain is also inclined to pass along the same lessons and doctrines he once learned to the new recruit. Like all professions driven by technology and innovation, rope rescue has evolved. This creates confusion and sometimes conflict. The same holds true for much of the rope rescue literature within the fire service. There are texts from very reputable authors and publishers that miss the intent of NFPA 1983 and its authors. They also misapply the concept of SSSFs or subscribe to safety factors that cannot be obtained in the field once the first knot is tied. Some of the authors that really understand the engineering and the intent have backgrounds in manufacturing, rescue, and sat on the NFPA 1983 committee most of their careers. Two authors that wrote and spoke well on the matter were James Frank of CMC Rescue and Steve Hudson of Pigeon Mountain Industries.

NFPA 1983

After the tragedy in New York, subsequent meetings, white papers, and deliberations, NFPA 1983 was released on June 6, 1985(Brown, 2000, p.9). *NFPA 1983*

Standard on Fire Service Life Safety Rope, Harnesses, and Hardware (1985) was eight pages and the content was covered on just under four pages. Six versions later, the current 2012 edition is 69 pages in length. The 1985 version explicitly defines a one person load as 300 lbs. and a two person load as 600 lbs. As a result of this working load, rope was categorized as one person and two person life safety rope. The MBS of new rope was to be expressed in pounds (lbs), and the safe working load was to be determined by dividing by a factor of not less then 15. Therefore one person rope had an MBS of 4500 lbs and two person rope an MBS of 9000 lbs. The circumference for two-person rope was to be between 1½” and 2¼” (NFPA, 1985). It is important to note that the rope and rescue industry now measures rope by diameter, not circumference. The standard also had instructions that rope that was used once in an emergency, be destroyed. Rope used in training was to be severely inspected before re-use.

The current version of *NFPA 1983 Life Safety Rope and Equipment for Emergency Services* (2012) is a culmination of the efforts of generations of manufacturers and practitioners. It has been purged of much of the verbiage that led to great confusion. The vast bulk of the document concerns itself with instructions to manufacturers regarding construction, labeling, and third-party testing. Perhaps the most important take away is the language within the sections on scope and application. The document clearly outlines the intent to standardize design, performance, testing, and certification of equipment. There is no mention of SOPs, SOGs, or derived field use of the document. There is no mention of one person loads or two person loads. The words *safety factor* and *15:1* are nowhere in the document. Rope and other equipment can be inspected and re-used per the manufacturers’ recommendations. Performance requirements, or strengths of equipment, is simply stated in an MBS of lbs and kilonewtons (kN).

It is significant to this study that no PCDs are listed in the current edition of NFPA 1983 in a manner consistent with a haul system. Ascenders and descenders are tested for 30 seconds at 5 kN and 11 kN for Technical use and General use respectively. The tests are evaluated for damage or deformation to the device rather than how the device affects the rope or the system. The ascending devices in this study that fall into that category are the PMI Grip and Petzl Rescucender. The descending devices that fall into this category are the Petzl I'D and the CMC MPD.

Literary References of NFPA 1983

Many different variables can affect the overall SSSF. The component to load ratio (CLR) is the most ideal of circumstances, dividing anticipated load into the MBS of a MBS strength of a specific component of a system. This concept is under the assumption that the component is being used properly and retains all of its original strength (Hudson & Vines, 2004). The SSSF encompasses the practical use and application of all components in the system and the manner in which they are loaded. Equipment that is used improperly can weaken the CLR and SSSF. Each part of a system can influence the strength retained by other parts. Hudson and Vines (2004) explain that knots weaken a rope between 15-30%. This is referred to as knot efficiency. Efficiency is the amount of retained strength remaining in each type of knot. A 70% efficient knot tied into a 9,000 lb. rope would yield a retained strength of 6,300 lbs (Hudson & Vines, 2004, p.28). If a 600 lb. load were attached to a 9000 lb. rope with 70% efficient knot, the resulting SSSF would be 10.5:1. This example illustrated why, as a condition of the physical properties of rope, a 15:1 SSSF is nearly impossible to maintain or aspire to retain.

The hypothesis in this research project revolves around the assumption the progress capture devices (PCDs) used in haul systems, may not yield the CLR and subsequent SSSF to which many organizations subscribe. The literary sources that will be explored will attest to various safety factors and SSSFs that authors cite and sometimes advocate. These various safety factors and SSSFs will range from 5:1 to 15:1. The most significant schism in the literature lies within texts that made or make assertions that the fire service and NFPA use or require 15:1 SSSFs and sources that explain otherwise. The literature review will illustrate an evolution or trend that moves away from the concept of 15:1 safety factors. It was demonstrated earlier, that this notion has clear origins and lineage to the IAFF White Paper from 1981 and early versions of NFPA 1983. Many authors in the 1990s, early 2000s, and even today maintain the use or requirement 15:1 safety factors by NFPA and fire service rescue teams. There are also authors from 1987 to present that argue that the only *15:1* was the early CLR for rope construction by manufacturers. Given their understanding of knots and manner of loading, these authors denounce misapplication of unrealistically high SSSFs. Many also warn readers that NFPA 1983 is a manufacturers' standard not a user standard. These two groups of works will be explored separately as those with a strict interpretation and implementation of 15:1 and those with a broad and interpretation of 15:1

Strict Interpretations of 15:1

Naturally, some early texts in the fire service took the words right out of NFPA 1983 when they explained safety factors. John Neal's work, *Line on a Thread: A*

Practical Rope Rescue for the Fire Service (1990) was one of the earliest books on rope rescue truly born out of the fire service. This work came at the close of the most formative decade for rope rescue standardization of equipment and practices. This was also a time where the Neal's work was relatively groundbreaking as the fire service was still breaking ties with natural fiber ropes in some remaining bastions. The author shows a table of rope strengths and sizes of four major manufacturers. Bluewater, Wellington, Pigeon Mountain Industries, and New England were all manufacturing 5/8" or 16mm ropes that had an MBS of 12,700 lbs. to 13,000 lbs. When it came to rope sizes, Neal (1990) reminds the reader that; "safe working load requirements as set forth in the NFPA Standard 1983. . .A safety factor of 15 to 1 should be the minimum any time lifelines are used" (p.7-8). The author states that standard practice dictates that ropes used as lifelines should have a tensile strength of at least 9000 lbs. Neal does acknowledge that a significant disadvantage of the heavier ropes is their weight and their difficulty to tie knots.

One of the most comprehensive works on all things rope is Alan Padgett and Bruce Smith's text *On Rope* (1996). The text covers cave and wilderness rescue as well as many types of vertical movement on rope. This work focuses on most things rope from caving to theatrical rigging, but is not specifically intended for the fire service audience. In describing rope and webbing strength, the text does make mention of safe working loads. The text asserts that per NFPA, a safe working load of $1/15^{th}$ the breaking strength of the rope is necessary. The text also maintains that a safe working load of $1/10^{th}$ the strength of the rope is reasonable and prudent. Using a load example of 2 kN, the text maintains that when a life is at stake, the conservative 15 to 1 formula is recommended. This would require a rope that tests in excess of 30 kN.

Slim Ray's manual, *Swiftwater Rescue: A Manual for the Rescue Professional* (1997) is still widely considered to be the most thorough and comprehensive work on swiftwater rescue. Its use is prevalent as a primary text in courses to this day. When first discussing rope strength, Ray introduces the concept of tensile strength and working load. He goes on to explain that strength can be greatly affected by knots, age, abrasion, and water. Ray then discusses safety factors or safety margins. In the river world, where some loads are not life-safety, a factor of 5:1 is considered adequate. Ray then maintains that lifelines that a person's life depends upon require a higher factor. He asserts that mountain and cave teams use a safety factor 10:1, but the NFPA recommends a 15:1 safety factor. Ray explains that safety factors are very hard to predict given all the variables in the river environment (Ray, 1997, p.53).

In 1998 Ken Brennan penned the text *Rope Rescue for Firefighting* (1998). This text echoes many of the same themes of John Neal's earlier work. The text harkens upon the origins of the modern rope movement and the first three editions of NFPA 1983. Brennan explores more in-depth material construction and history of textiles. At the time, Brennan does state that NFPA 1983 is a baseline for components and that not many firefighters are fully aware of the standard. Brennan makes mention of the FDNY tragedy and the recreational origins of kernmantle rope. Because the newer ropes, with synthetic fibers, were invented by cavers for the use of single rope technique; the ropes were commonly call caving kernmantle. These early static caving kernmantle met many of the requirements for NFPA 1983, but lacked the strength. For this reason, early manufacturers' ropes were 5/8" or 16mm in diameter to attain the necessary strength. Brennan (1998) states that after much debate and deliberation, it was decided life safety rope were to have a breaking strength of 9,000 lbs. and a working-to-breaking safety factor of 15(p.77). The text also makes mention that ropes are qualified as one person ropes or two person ropes based on their respective breaking strengths. Brennan also makes mention of the cumbersome nature of the early large diameter ropes. Hardware price and selection was a subsequent challenge.

In 2003, Phoenix firefighter Pat Rhodes wrote *Technical Rope Systems and Confined Space Rescue* (2003). Today Rhodes is considered a preeminent authority on knots, rescue physics, and safety factors. In this text, written after the fourth edition of NFPA 1983 in 2001, he writes on the early views of the standard. The 2001 edition of the standard states that rope must have a minimum breaking strength of 4500 lbs for single person load of 300 lbs and 9000 lbs for a two person load of 600 lbs (p.13-14). The safety factor is 15:1 for both. Rhodes (2003) does not discuss the SSSFs for ropes or the need to engineer 15:1 SSSFs in rigging. Later in the text he discusses pulley selection and recommends pulleys with a SSSF of 7:1 or higher (p.22). That recommendation is probably more indicative of progressive thinking of the time.

Perhaps the texts that proliferate the most confusion are broad survey texts that are not written by experts in a given field, but only touch on subject matter in broad generalities. One such text is the International Fire Service Training Association (IFSTA) *Fire Service Search and Rescue* (2005) text. There are some redeeming qualities in this text. It makes mention of the change from one-person use to "light use" and two-person called "general use." The authors of 1983 likely never intended for these two descriptions to ever be affiliated. *Light Use's* association with one-person loads and *Gernal Use's* association with two-person loads has continued to perpetuate confusion. The text continues to explain that the safe working load for light use rope is 300 pounds and the safe working loads for general use ropes are 600 lbs. The text then elaborates that these figures are determined by taking the MBS of the rope and dividing by 15. It is in maintaining this ratio that a margin of safety for both victims and rescuers is achieved. Though this text was published in 2005, the 2001 Ed. of NFPA 1983 had eliminated any mention of safety factors and 15:1(NFPA, 2001).

Similarly the National Association of Search and Rescue (NASAR) *Fundamentals of Search and Rescue* (2005) manual lightly touches on rope rescue, MBS, and safety factors. The text begins by introducing the topic of "Static Safety Factors." The text explains that the latest version of NFPA 1983 requires a safety factor of 15:1 for all rope and components. This means that the rope and components should withstand a load 15-times greater than a one or two person load. It also defines a one or two person load as 300 lbs and 600 lbs respectively. It should be noted that in the 2001 Ed. of NFPA 1983, the notion of one and two-person loads being 300 lbs and 600 lbs had been eliminated. The FUNSAR manual (2005) states that many rescue organizations have accepted this 15:1 safety factor (p.263). The following paragraph explains that some wilderness agencies rely on a safety factor of 10:1. The text cites reasons being a higher level of proficiency and the need for lighter equipment. It goes on to state that a 10:1 is acceptable for most situations.

In 2010, Rick Weber edited and authored a narrowly disseminated training manual for wilderness rescue for the Kentucky Division of Emergency Management. The manual is very well written and briefly hits on safety factors and the NFPA. He astutely writes (2010) that nowhere in the NFPA standards can be found a requirement for specific Static System Safety Factor for rope rescue rigging (p.8). Now, in 2010, and since the inception for NFPA, that is a true statement. Weber(2010) goes on to state that fire departments commonly use a SSSF of 15:1 and mountain rescue teams use 10:1.

Tom Briggs authored a voluminous work on rope rescue for the fire service in 2013 entitled *Vertical Academy*. Despite the evolution of NFPA 1983 and current revisions to the document, Briggs advises readers that 1983 requires equipment to have a minimum capacity of supporting 15 times the static working load. The author also mentions the transition from the use of *Light Use* to the use of *Technical Use.* Despite 1983 having no language advising such, Briggs maintains that Light and Technical describes equipment for one-person loads. He states General Use is for two-person loads. This is a modern day example of an author that editorializes and injects his own thinking on 30-year-old body of work that many minds set out to bring out of the dark ages of rope standards of the 1980s. These opinions, that are re-injected into young minds, impede forward progress.

Broad Interpretations of 15:1

There were authors and practitioners that understood the scope on NFPA 1983 and the limitations of high SSSFs from the very onset in the 1980s. Most of the authors that deal with this topic the best, are not products of the fire service. Most have backgrounds in wilderness rescue, engineering, and manufacturing. The earliest such work in this literature review is that of Jim Frank and Jerrold Smith. Frank and Smith (1987) published the first edition of the *California Mountain Company: Rope Rescue*

Manual. In the first edition, Frank does not go as deep into the issue as he would in later editions. He describes what has come to be called safety factors, or component to load ratios, as *margins of safety*. In the text, Frank maintains wilderness teams use a 4:1 margin of safety, but that some members of the fire service have been recommending a 15:1 margin of safety (Frank & Jerrold, 1987, p.9). The authors emphasize that rescuers need to understand the concept and how to apply it during training and rescues.

Other early authors were Jon Olson and Reed Thorne. These authors wrote a course manual intended for the students of Ropes that Rescue Limited. The manual, entitled *Urban and Industrial Rigging for Rescue* had its first edition in 1988 and subsequent ones in 1993-1994. Early on, the text mentions NFPA's use of a 15:1 safety factor for the manufacture of ropes. It also states that the NFPA does not include the whole system in their calculations for safety factors. They further state that bends and twists such as knots weaken the rope. Thorne and Olson continue to elaborate that a 12.7 mm rope, with a 9000 lb MBS, satisfies the 15:1 safety factor of the 1990 Ed. of NFPA 1983. That same rope, however, will only yield a 10:1 Static System Safety Factor (SSSF) (p.8). The text contends that the straight pull on each element yields the safety factor. This SSSF calculates turns, bends, and knots. It is important to note that this interpretation of SSSF would include pinching and squeezing mechanisms of stress affiliated with PCDs in haul systems concurrent with this study.

This relatively early work also contains a four-page appendix on *systems analysis* and *static system safety factors.* The concepts are introduced under the umbrella of *white board analysis.* Thorne and Olson explain white board analysis as taking all components and examining each piece of the system side by side. The good and the bad elements are written out and compared. A significant part of the white board analysis is the calculation of SSSFs. They define SSSF as the weakest link in the rigging system and a relative predictor of where the system is most likely to fail. It is suggested that the ideal condition is to keep the SSSF close to the knotted strength of the rope. For this condition, a 10:1 SSSF is recommended (Olson & Thorne, 1994, p.A-2).

One of the most well versed authors in the rope rescue field is James Frank. Frank is the President of CMC Rescue, Inc., a California based equipment manufacturer. He is also an active wilderness rescuer and sits on several NFPA rescue committees including 1983. In the third edition of his text, *CMC Rope Rescue Manual* (1998) he dives early into static system safety factors and NFPA 1983. Like Hudson (2004), he first introduces *component safety factors* and then moves into the SSSFs where all components of the system are considered. He states that, to date, there is no mandated SSSF. He cites the fact that mountain teams used 4:1 for years, and that 5:1 and 10:1 have been suggested for rescue teams. Some fire service teams use 15:1 SSSF because the NFPA 1983 had specified the strength of life-support line be 15 times the load. Frank emphasizes that the 15:1 ratio within NFPA 1983 was never intended to be applied to the entire rescue system. He also noted that 1983 uses different ratios for different groups of equipment such as harnesses and hardware. Frank urges that whatever ratio or SSSF the user selects, it is important they understand the concept and can apply it to their systems.

Frank's (1998) text spends much time on the materials and construction of rescue equipment. When he revisits the methods that rope strength standardization were derived, he offers the readers a warning. "Their intent(NFPA 1983) was not to standardize a

System Safety Factor, but to provide a margin of safety that would take into account rope wear, rope aging, knots, and the effects of bending rope over edges"(Frank, 1998, p.18).

Like Thorne and Olson (1994), Frank dedicates some time to *white board analysis* and real SSSFs. It is important that strength is determined on each component based on the way it is used in the system. He illustrates that changes in the overall strength of the system can be affected by many variables; such as how anchors are tied and applied, and what types of carabiners are used. In his illustrations, SSSF is not always assuming the worst case load of 600 lbs, but may be represented by 1 kN, 2kN, or 300 lb figures (Frank, 1998, p.102-103).

One of the modern authorities on rope rescue that came out of the fire service is author Mike Brown. When Brown wrote his book *Engineering Practical Rope Rescue Systems*(2000), he spent a significant portion of the text writing on the FDNY tragedy, origins of NFPA 1983, and safety factors. He cites that in the early days of the development of the standard, the American National Safety Institute (ANSI) and much of industry used a 5:1 margin of safety. He states cave and mountain teams used a 7:1 or even a 10:1. For this reason cavers, mountaineers, and industry were stunned when NFPA chose 15:1. Brown also writes about the surprise and frustration of the "use once and destroy" provisions for rope. This was hard to comprehend for many because NFPA 1983 was written as a "minimum manufacturer's recommendations" and not a *user* standard (Brown, 2000, p.11). Most people thought these provisions were ridiculous and they robbed credibility from the standard. The last standard edition referenced is the 1995 edition of NFPA 1983. Brown shares the following insight, "As usual NFPA 1983-95, contrary to what many instructors teach, does not tell rescuers how to engineer their systems, where to place equipment, or what safety margins should be built into what systems"(Brown, 2000, P.12).

Across all disciplines, one of the most preeminent authorities on all things rope and rescue is the late Steve Hudson. He was the co-founder and President of Pigeon Mountain Industries, a leading rope manufacturer. He was a founding member of many rope, fire, and rescue organizations, and also sat on NFPA 1983. Steve was an ardent speaker for the correct use and applications of NFPA 1983 and static system safety factors. He communicates these thoughts in four different documents within this research. The first, third, and fourth editions of Hudson and Vines *High Angle Rescue Techniques* were examined. These were published in 1989, 2004, and 2014 respectively. In the 2004 document, Hudson discusses the concepts in terms of component to load ratios and system safety factor. He summarizes both these concepts in the same terms that have been previously discussed. The CLR is the component divided by the maximum anticipated force and the system safety factor as the ratio between the maximum expected load on a system and its breaking strength (Hudson & Vines, 2004, p.388). In the 2014 update, Hudson discusses the issue in terms of component to load ratio and *system safety ratios.* The definition of system safety factor and system safety ratio is consistent. Hudson provides a depth of insight and information in this section of his works.

The system load ratio (SLR) reflects the relationship between the strength of the weakest point and the highest force to be applied on the system. Hudson contends that a rigging goal should be to achieve the highest system safety ratio that is reasonable given constraints that include equipment and timeliness. In the 2004 edition, Hudson cites mountain and wilderness rescue groups accept a 10:1 safety factor. By the 2014 version, he notes that they accept a 7:1 for several reasons. He notes lighter equipment and the technical proficiency of the riggers being highest among these reasons.

Hudson (2014) discusses the fire service's relationship with 15:1 safety factors. He labels this early 15:1 figure as a component to load ratio and that NFPA 1983 is a manufacturer standard and not a user standard. He explains that just because a 15:1 CLR exists, it does not mean that the finished system will retain a comparably high safety ratio. Hudson then goes on to explain the various current levels of certifications within NFPA 1983. These are *escape use, technical use,* and *general use.* Hudson contends the technical use rope with a MBS of 20 kN is intended for rescuers capable of determining in-depth system strength, and deciding if adequate safety factors are present. The *general use* classification is for general use where higher loads are present, or greater safety factors are needed (Hudson & Vines, 2014, p.38).

Steve Hudson also writes a nearly identical section on the subject in the 2014 *Manual of U.S. Cave Rescue Techniques,* published by the National Cave Rescue Commission (NCRC) section of the National Speleological Society. Much of the same thoughts and examples from his other texts are present in this document. Hudson cleans up the distinction between system safety factor and system load ratio. In this document, he defines a system safety factor as a "system load ratio (SLR) in excess of 1:1, thus providing a calculated margin of safety" (Mirza, 2014, p.2A. 3).

The co-author of *On Rope,* Bruce Smith was the former founder and owner of On Rope 1, a manufacturer of software, harnesses, and rope ascending systems. Smith also taught rope rescue courses and wrote his own course manuals. In his *Level I & II Rope Technician* (2008), Smith briefly touches on safety factors. The cordage institute recommends software is 10 times stronger than what is needed. Smith recommends that good riggers should be able to rig to a specific safety factor and rescuers typically use a 10:1. Smith argues that a 10:1 safety factor is typically enough to cover a variety of foreseeable problems while the system is under operation. These problem include the load, a strength loss of 2% a year, knots that weaken rope by 33%, wet conditions that weaken nylon up to 15%, and dynamic loading that can be up to 3 times the load. Other issues that could affect the safety factor are crossloaded carabiners or a poor piece of webbing. Smith states that any departure lower than a 10:1 safety factor should be an informed decision (Smith, 2008, p.6-7).

Jeff Mathews is another author with a fire service background. His work, *Technical Rescuer: Rope Levels I and II* was published by Delmar in 2009. The text is fairly abbreviated but Mathews is very accurate and to the point. Mathews states that unlike NFPA 1006 and 1670, NFPA 1983 is not a user's standard. Where safety factors are concerned, Mathews quips, "Somehow, somewhere, rope rescuers came up with the notion that NFPA 1983 established a 15:1 *system safety factor* to be used by rescuers. This is 100 percent false" (Mathews, 2009, p.5). Much of the confusing verbiage was removed from NFPA 1983 in the 2000 edition. It was here that one person and two person loads were changed to general use and light use (later *technical).* The references to what constitutes various loads and safety factors were gone.

Mathews (2009) explains system safety factors and safety factors of various components. This is similar to other accurate references on the subject. The author also notes that as of 2009, there are no published standards that require a specific SSF. Most urban fire rope rescue teams maintain a 10:1 SSF. Some departments say they maintain a

15:1 SSF, but this would be impractical if not impossible because rope loses 20% of its strength when the first knot is tied. Therefore he states if a 9,000 lb general use rope lost 20% strength with a knot, the maximum load could only be 479 lb to meet the 15:1 requirement. So Mathews (2009) mentions that cave and mountain rescue teams use 5:1 and 8:1 SSFs. In conclusion, the author mandates that rescuers should understand the concepts of calculating safety factors and using systems efficiently and effectively.

Pat Rhodes authored a new work in 2014 entitled *A Practitioner's Study: About Rope Rescue Rigging.* In this document Rhodes expands on rigging concepts and acknowledges the evolution of NFPA 1983. In contrast to Briggs (2013), Rhodes discusses the fact that gear has become lighter and many have moved away from the "bigger is stronger" and "heavier is better" mindsets (2014, p.27). Rhodes concedes that rescuers often aspire to rig 10:1 safety factors in their systems, but that at times this can be difficult. Rhodes acknowledges that most practical rigging falls in the realm of 6:1 and 7:1 factors of safety.

Progress Capture Device and Strengths

Other authors have considered progress capture devices (PCDs) in their assessment of the SSSF of various systems. The research on this topic is largely incomplete and unpublished. Authors have disclosed rough figures of failure, slipping, and the conditions, but they do not disclose the specific research study. Much of this is due to the fact that many "backyard studies" are performed, then self-published or only very narrowly circulated. As with the myths associated with NFPA 1983 and safety factors, oral tradition and vague anecdotal information is perpetuated regarding Prusiks and rope grab PCDs. This information is usually focused on the force at the point of failure, mode of failure, and the ability to slip or clutch. This reason highlights the need for more documented and comprehensive research into the matter.

Prusik PCDs

Olson and Thorne (1994), in their discussion on SSSF conversions for components cite the average breaking strength in kilonewtons of Prusiks. Kilonewtons (kN) and pounds of force (lbf) are two units of measure used throughout this study. A kN is approximately 224.8 lbf. Many field practitioners round this figure up to 225 lbf. The breaking strength in kN for a single 8mm Prusik hitch on 12.7mm rope is listed as 9.01 kN. The figure for tandem Prusik hitches on the same rope is 10.51 kN. It is notable that with two loops equally tensioned there is only a documented strength increase of 1.5 kN.

Slim Ray (1997) states that a well paired Prusik that is tied with three wraps around the rope will begin to slip at 1200 lbf. He goes on to explain this provides somewhat of a check when loading. This text and many others write with the understanding that Prusiks will consistently clutch or slip when overloaded. Jim Frank (1998) echoes these thoughts on Prusiks. He discusses Prusiks holding when needed, but then slipping when overloaded. As this takes place, the friction creates high heat in the nylon resulting in melting and bonding together. It is interesting to note, that when used as a ratchet or PCD in a haul system, Frank (1998) advocates using tandem Prusiks.

Mike Brown (2000) writes about the Prusik as a clutch device that slips and warns the rescuer if the system is receiving unexpectedly high forces. He explains that a triple-wrap Prusik will slip around 3000-3500 lbf and this is a useful quality for rope system engineers. Brown also indicates that tandem Prusiks will yield slipping forces around

3,500 lbf on 12.7mm rope. He expects a single 8mm Prusik to slip on 11.1 mm rope at a 2,250 lbf.

Pat Rhodes (2003) advocates using an 8mm Prusik with 12.5mm rope. He advises that a slipping haul Prusik is like having a pressure relief device in a system. These typically slip between 800 and 1200 pounds. He advises readers not to add a Prusik loop if a single haul Prusik begins to slip. This decision is likened to replacing a 15-amp fuse with a 30-amp fuse.

In Bruce Smith's course manual (2008), he is adamant that there is little strength gained from adding a second Prusik to the system. He cites a study where single Prusiks slip between 7.0-9.5 kN and tandem Prusiks slip between 7.5-10.5 kN. It is stated that there is all combinations of size, construction, and material and yield various success.

Jeff Mathews (2009) echoes the same sentiments on Prusiks as Mike Brown (2000). Triple wrap Prusiks of 8mm on 12.5mm rope are said to hold nearly 3000 lbf. Once forces exceed this, the Prusik begins to slip and this is a beneficial quality as it indicates system overload or imminent failure.

In an obscure rope manual from the State of Colorado, Prusik strengths in single and tandem are specifically listed. *Rope Rescue: Colorado Technical Rescue* (N.D.) list single Prusiks clutching at 9-13 kN and tandem Prusiks clutching at 10-14 kN. This again indicates that very little is gained by moving from a single Prusik to tandem Prusik configurations.

Hudson and Vines (2014) are fast to state the inconsistency of Prusiks and avoid assigning any numbers or breaking strength range. They state that the most common configuration for a soft rope grab is a triple wrap Prusik. The Prusik will hold until the

Prusik breaks or until the line that it is gripping breaks. They note that slipping under load may cause melting and failure. Prusiks may not hold in icy or muddy conditions. Lastly, performance varies widely based upon the material used and the experience of rescuers. These authors indicate that tandem Prusiks are known for superior energy absorption over many belay devices, and they have more holding power to prevent slippage. The text does not state the exact difference in holding power between singles and tandems.

Hard Cam PCDs

Hard cam progress capture devices are those that are intended for rescue sized loads and involve placing a piece of hardware around the rope. The two types within this study are the PMI / SMC Grip and the Petzl Rescucender. These types of devices also have their origins in caving and recreational use. It was later that they were fine-tuned and tasked with the business of rescue. Many authors discuss the Gibbs Ascender as one of the all-around hard cams. Like the Grip and the Rescucender, the Ascender consists of a metallic sleeve that wraps around the rope on three sides. The fourth side is captured by an axel with a cam that rotates and pinches the rope in the sleeve. Ken Brennan (1998) mentions the listed holding power of a Gibbs Ascender based on published numbers in product catalogs. He states earlier Ascenders held to 1,000 lbs, but the current working load on the new (1998) models is 3,000 lbs.

Frank (1998) says the Rescucender was invented as an improvement over the Gibbs Ascender. The common concern about mechanical ascenders is failure takes place when the ropes break or the ascender breaks. The Gibbs style usually failed with the cam cutting the rope. This took place between 1,900 lbs and 3,000 lbs. With the curved shell of the Rescucender, the working strength is said to be higher, but the figures are not listed. Tests performed by the North American Technical Rescue Symposium suggested the Rescucender would slip rather than cut the rope. This was viewed as a desirable. The text states that more testing is needed, and that the Rescuecender is still capable of cutting the rope.

Brown (2000) concedes that ascenders with ribbed cams (Grip & Rescuecender) still are known to damage the host rope around 2,000 lbf. Brown discusses some of the on-going innovations regarding cam engineering. Some of these include increasing the surface area of the cams. Others involve coating the inside with Teflon. The goal is to let the rope slip through the device and re-grab. Brown also states that some of these efforts have yielded slipping forces that are too low for heavier rescue loads. These forces were between 300-1,000 lbf. Brown expects to see great improvement in the coming years with regard to ropes slipping at predictable tensions in hard cams.

In his manual, Bruce Smith (2008) agrees the Gibbs Ascenders are known to cut rope at 2,000 lbf based on product literature. It goes on to explain Gibbs does make larger cams that perform similarly to the Rescucender. On 11.1mm rope, Smith states the Rescuecender will hold 4 kN at which point it will begin to slip, much like a Prusik, to prevent overloading. Smith also reminds readers that it would be wrong to use a mechanical rope grab on a line that could receive an impact force.

Jeff Mathews discusses mechanical rope grabs in his 2009 text. He spends time differentiating between ascenders with toothed cams and mechanical rope grabs for rescue and hauling application. Mathews mentions that ascenders, such as those with teeth, can desheath a rope at forces as low as 800 lbs. He contends that excellent ascenders usually make poor rope grabs for rescue hauling. Mathews leans towards using soft cams (Prusiks) for loads over 300 lbs. He also recommend using Prusiks as the PCD because of the risk for potential shock loading. In particular, Mathews recommends tandem triple wrapped Prusiks. If the haul team were to let go of the mechanical advantage, the PCD would engage and prevent the load from falling, thus acting as a safety cam (Mathews, 2009).

Hudson and Vines (2014) discuss cams specifically in the context of hauling systems. They divide them into categories of haul cams and progress capture devices, otherwise known as ratchets. The general use or rescue rated cams in their text are the Gibbs Ascender, the PMI / SMC Grip, and the Petzl Rescucender. Their advantages include easy of installment and use, but their disadvantage is their inconsistency in design and performance. The authors state some models are designed to slip when overloaded, while others may cut through the rope. They make the keen observation that “no single rope grab device or technique is perfect for every rescue situation” (Hudson & Vines, 2014, p.371). Each device has advantages and drawbacks, and each device can be made to fail. Some rescue teams prefer to use tandem Prusiks in light of the fact that most mechanical rope grabs can be made to fail with high shock loading.

Hudson and Vines (2014) advise that light-use personal ascenders should not be used in haul systems. Like Mathews (2009) stated, these devices are intended for the weight of once person. Use of lightweight ascenders can result in tearing of the rope or structural failure of the ascender. Both outcomes could result in the failure of the entire system.

CMC Multi Purpose Device (MPD) and Petzl Industrial Descender (I'D)

The Prusik hitch and the Munter hitch have been used in mountaineering for over 100 years and caving for over 50 years. Rescuers have been using them for over 40 years and they still remain under contentious debate. Mechanical rope grabs, like the Grip and the Rescucender, have been in use for several decades. This makes the Petzl I'D and CMC MPD relatively new to the rescue realm. Both devices' potential are still being explored. The I'D came to market in the late 1990s, and the MPD arrived in the later 2000s. Both devices are considered descenders, lowering devices, and belay devices. The I'D does not have a pulley, but can be used as an inefficient PCD or ratchet in a hauling system (Petzl, 2015). An internal rotating cam captures the rope. The MPD improves on this design with a high efficiency pulley, in addition to a rotating cam. This allows the MPD to perform as a high efficiency PCD (MPD, 2015). Both products have two versions for use on different sized ropes. The MPD comes in an 11mm version and a 13mm version (CMC, 2015). The I'D has an I'D S for 10-11.5mm rope and the I'D L for 11.5-13mm rope(Petzl, 2015). The two rope diameters cover ropes widely used by many user groups including cavers, wilderness rescuers, mountaineers, rope access professionals, and fire rescue teams.

There is very little third party research performed on these devices. They are tested to various standards in the U.S. by Underwriters Laboratories (UL). Some of these standards come from NFPA 1983. The larger of both devices is certified as general use as a descender and belay device for NFPA 1983. The MPD is also certified as a general use pulley. Petzl publishes the holding static holding power of the I'D S on their website. The I'D S holds loads up to 6.5 kN using 11mm static rope (Petzl, 2015).

The relatively short time both these devices have been available means there is not only a shortage of testing on these devices, but they are not mentioned in many texts. Hudson and Vines (2014) mention the I'D as an alternate descender option. They also mention the MPD as an alternate belay device that has a pulley with an internal rope grab. There is not much other discussion or illustration of either of these devices used as PCDs in haul systems. Despite this fact, their use in haul systems by modern rescue teams is well established.

Munter Hitch or Italian Hitch

The Munter hitch, also known as the Italian hitch, is formed by wrapping rope around a carabiner. The hitch is commonly used to belay or lower using the internal friction of the hitch. The hitch is capable of travelling both directions by flipping around the carabiner. For this reason the hitch can also be utilized as a PCD in a haul system. In the case of a "ganged" or "piggy backed" haul system, the haul system is attached to a separate main line for hauling. As the load is hauled, the slack generated in the mainline is controlled by pulling rope through the Munter hitch. This fulfills the requirements of a PCD. Munter hitches require little equipment and time. This makes them ideal for light weight and small party rescue (NCRC, 2014).

Summary

This review of relevant literature establishes several key points in relation to this research project. The use and origins of safety factors is a well-established practice in the engineering of rope rescue equipment. The first early editions of NFPA 1983 contained verbiage concerning *one person loads, two person loads,* and *15:1 safety factors.* Modern literature and consensus demonstrates that NFPA 1983 is a manufacturers' standard and not a user document. Modern literature and deductive reasoning also concludes that a 15:1 factor of safety can be a component to load ratio (CLR) for rope, but cannot be carried over to static system safety factors (SSSF). Current editions of NFPA 1983 establish *general use* rope as having an MBS of 40 kN (9,000 lbs). *Technical use* rope has an MBS of at least 20 kN (4,500 lbs). There is very little other discussion in the document on performance and no discussion on user best practices or safety factors.

There are still texts, schools of instruction, and holdouts, that maintain that NFPA requires specific safety factors such as a 15:1. Some of these same individuals believe that a 15:1 SSSF is used by fire service organizations and is routinely attainable in the field. Because of knots, age, water, and bends in rope, this is not the case. Technical use rope and devices are no longer viewed as capable of supporting only one person. General use rope is no longer limited to supporting only two persons. There are a significant number of users that still teach this philosophy and spread these beliefs.

As far back as the 1980s, there are authors and instructors that had a firm grasp on CLR and SSSFs. They understood what was required of the manufacturers and the difference in what SSSFs could be attained in field applications. As far as conservative values, these instructors generally believe that a 10:1 SSSF was attainable and desirable. This seems to be the consensus among Thorne, Olson, Frank, Hudson, Vines, Padgett, Smith, and others. In the lighter weight cave and mountain rescue world, authorities report guidelines toward SSSFs ranging between 7:1 and 10:1. The only mention of lower safety factors are by Jim Frank (1998) discussing 4:1 and 5:1 use among early mountain rescue teams. Most authors believe that a rescuers' ability to perform field calculations and determine SSSFs is an important and key skill for well trained and practiced rescue technicians.

All rescue manuals and courses discuss the use of rope grabs in hauling systems. The rope grab that supports the entire load while the haul system is being reset is referred to as the ratchet or progress capture device (PCD). The Prusiks, Munter, and mechanical rope grabs are well established as PCDs in haul systems. One or all of these are taught in every text and course manual. Many courses and teams have incorporated the CMC MPD and Petzl I'D into their cache. They use these devices in their in-line haul systems as PCDs. This has yet to carry over widely into textbooks. Relatively little is known or publicly available about the over-all strength of these PCDs as they interact with rope. Prusiks and mechanical rope grabs like the Ascender and Rescucender have been the most researched. Most of this information is only available in the form of a raw figure and little is known about the conditions surrounding the tests. Almost no third party research can be found on the I'D and MPD. This presents a potentially large gap in important information to rope rescuers. At multiple instances during a hauling operation the entire load will be supported by one of the PCD hitches or devices in this study. Given a failure, aside from an independent safety line, the rescuers and patients will fall to the deck. Most authors agree on the importance of white board analysis and SSSF calculations. Given the missing body of information, practitioners are only able to venture a guess as to the safety factor or reserve strength in the system.

Procedures

The idea for this research project was first proposed to the researcher by a colleague- Lieutenant DJ Walker, of the Division of Special Operations of the Austin

(TX) Fire Department. Discussions about the project started in 2013 at the International Technical Rescue Symposium (ITRS) and it would take nearly one year to complete the research. This was only possible with the support of a handful of researchers and the manufacturers PMI, CMC, and Petzl. Early ideas centered around slow pull testing of single Prusiks, tandem Prusiks, the Petzl Rescucender, and the Munter hitch. It was proposed that each device or hitch be tested with new rope and Prusiks, as well as old rope and Prusiks. This would establish both a best-case baseline control group and a group or data set that was more representative of field operations.

Both Lieutenant Walker and the researcher work with fire rescue organizations that use ½” (12.5mm) rope, as well as cave rescue and rope access organizations that use 7/16” (11mm) rope. It was determined that both diameters of rope were relevant to fire rescue, wilderness, cave, and rope access organizations. This line of thinking took a seemingly simple and straightforward project and caused it to grow substantially. This would lead to each hitch or device being tested five times on 12.5mm new rope, five times on 12.5mm old rope, five times on 11mm new rope, and five times on 11mm old rope. Now each device was up to 20 pulls to generate adequate data sets.

In early 2014, PMI announced the sale of a new rope technology, Unicore, which was available in 11mm diameter rope line called Extreme Pro. Extreme Pro uses a technology that bonds the inner core of the rope to the outer sheath. This technology creates a stronger rope, reduces sheath bunching, and retains significant strength when cut or abraded. This rope was new to market and only available in the 11mm diameter. It was determined that including the Extreme Pro in the study would prove to be both innovative and beneficial to readers. This added an additional five pulls or data sets to each device that accommodated 11mm rope.

As the dates for the testing drew closer, the two sizes of the Petzl I'D were added, two sizes of the CMC MPD were added, the SMC Grip was included, and the Petzl Basic toothed chest ascender was added. On paper, this would lead to an initial number of tests in excess of 200 pulls. This would prove to be a limiting factor and continue to shape the experimental design.

This applied research project will utilize Evaluative Research. It is important to view these issues in the historical context of conventional thinking regarding SSSFs and breaking strengths within the literature review. The primary research will be performed using empirical observations of the breaking strengths, behavior, mode of failure, and consequence of eight different progress capture devices (PCDs) on three types of rope. Each combination within the experiment will be performed five times in order to ensure reasonable statistical validity.

Each research question will be answered using the following methods. a) What is the strength of a single Prusik, tandem Prusik, Rescuescender, Grip, Munter hitch, I'D, and MPD when used on 12.5mm PMI EZ-Bend? This will be performed at Pigeon Mountain Industries in Lafayette, GA on a slow-pull hydraulic test bed. Each combination will be pulled five times at a rate of 6" per minute until failure or five minutes time has elapsed. Data collected will include peak values, graphical average of pull, values at failure, video, photos, and samples of each significant finding.

b) What is the strength of a single Prusik, tandem Prusik, Rescuescender, Grip, Munter hitch, I'D, and MPD when used on 11mm PMI EZ-Bend? This will be performed at Pigeon Mountain Industries in Lafayette, GA on a slow-pull hydraulic test bed. Each combination will be pulled five times at a rate of 6" per minute until failure or five minutes time has elapsed. Data collected will include peak values, graphical average of pull, values at failure, video, photos, and samples of each significant finding.

c) What constitutes a failure of a PCD? Using empirical observations garnered from testing, sources within the literature review, discussions with engineers (CMC, Petzl USA, PMI) the definition of a failure will be illustrated in terms of the event and subsequent consequence.

d) What constitutes a loss of confidence of a PCD? Using empirical observations from testing, sources within the literature review, panel discussions with engineers, the concept of *loss of confidence* will be explored. These may be explained in circumstances where components are damaged or inoperable, but the consequence does not mean the load has fallen to the ground, but rather the rescuers lose confidence in the rigging.

Calls and Events Leading Up to Testing

11/7/13-11/11/13

At the 2013 International Technical Rescue Symposium (ITRS) in Albuquerque NM, Lieutenant DJ Walker first proposed the idea of testing and establishing a set of static system safety factors (SSSF) for progress capture devices in haul systems. It was proposed that the research be conducted in 2014 and presented the following Fall at the 2014 ITRS in Golden, CO. Ideas for the testing included Munters, Prusiks, and Rescucenders, pulled to failure on a slow-pull test bed. PMI's point of contact at their testing and manufacturing facility in Lafayette, GA was Kim Hunter. As an engineer, Hunter is the quality manager and oversees quality control and testing at the Lafayette facility. It was proposed that the testing process be performed the week of June 30-July 4, 2014. This holiday week accommodated the most participants.

4/28/14-4/30/14

The week of April 28, 2014, consisted of several emails and phone calls leading up to a conference call with the host facility and the testers. Lieutenant Walker discussed the research with PMI CEO Loui McCurley. Lieutenant Walker then emailed the testing group to set up a phone conference. The facility host and contact was Kim Hunter, and she would be handling future on-site logistics.

The conference call took place at 12:00PM CST on June 30, 2014. Kim Hunter, Lieutenant DJ Walker, the researcher, Lieutenant Wayne Morris of the West Lake Fire Dept. (TX), and Instructor Hayes Nix of the Mississippi State Fire Academy were on the line. Items on the agenda included the various devices and hitches to be tested. This call was the first time the testing of the 11mm Extreme Pro was discussed. The testing dates for the week of June 30-July 4, 2014, were finalized. The testing format and the rough cost and amount of materials were discussed on the call.

The format of the testing would mimic earlier tests performed by the staff of CMC Rescue and presented at previous ITRS. Five pulls of each combination would be performed. Force highs, lows, averages, and three-sigma (MBS) values would be recorded and reported. This information would then be translated into relevant system safety ratios to extrapolate various SSSFs.

Early estimates called for testing up to 4000 ft. of rope. Kim Hunter committed to securing all rope, accessory cord, and the hardware from SMC, such as carabiners and the SMC Grips. The researcher would reach out to Petzl and CMC Rescue to secure their support on the project, and I'Ds, MPDs, and Rescucenders. The Gibbs Ascender was also on the list of PCDs to be tested, but would later be scrapped. Lieutenant Walker, also the National Cave Rescue Commission Coordinator for the Central Region, expressed his Central Region would also offset some of the costs associated with the testing.

The researcher would research the manufacturers' testing, product recommendations, and instructions. He would also compile literature pertaining to SSSFs, assumptions, and the history of safety factors and rescue. This would establish a historical baseline with which to compare the testing with past practices and assumptions.

The last and most difficult area of discussion revolved around testing that might not accomplish a failure, but would reside in a grey area when trying to establish a firm and fixed SSSF. Predicted outcomes included the device or hitch slipping continuously without failure or consequence. Another possibility was rope breaking, but device or hitch remaining intact. It was predicted there would be instances of the outer sheath tearing and failing, but the core bundles remaining intact. This might be a failure of some of the materials, but the load would not crash to the ground. An idea for a category of this behavior was *loss in confidence* described by Lieutenant Walker. This constituted a non-failure, but a loss of confidence of the integrity of the system.

5/1/14 & 5/2/14

On May 1 and May 2, 2014, the researcher discussed the testing process and needed materials with Rick Vance, the Technical Director for Petzl America. Vance is an Engineer and spends much time and efforts on testing, quality control, and standards. Rick and Petzl agreed to support the project with any materials necessary and also consult with the testing process and results.

5/17/14-5/24/14

Lieutenant Walker, Lieutenant Morris, and Instructor Nix, and the researcher discussed the testing process and progress during the National Cave Rescue Commission weeklong Seminar in Divide, CO. More in-depth discussions took place regarding anticipated instances of failure versus loss of confidence versus instances in which continual slipping occurs with no failure. Other assignments and roles for the testing were made. Lieutenant Morris would document the testing with video. The Central Region of the NCRC and Austin FD would provide old ropes and Prusiks.

6/2/14

A phone call and email exchange took place between Joe Flachman of CMC Rescue and the researcher. Flachman is the Director of Marketing and agreed to support the project on many levels including the necessary hardware. Flachman also shared the test plans and experimental design with Mark Green, the Engineering Director for CMC Rescue.

6/2/14

A 20-minute phone call took place between the researcher and Rick Vance of Petzl America. The phone call focused on the experimental process and the anticipated results. Vance discouraged the use of the acronym and equation of MBS for the testing. He advised many devices would slip. They would not have a finite breaking strength. He also confirmed the researchers concerns regarding three-sigma values of the testing. This concern came from the anticipation of large statistical variance and the lack of definitive breaking values. He recommended framing slipping as a type of “system failure” rather than MBS. The researcher agreed with this “failure of no great consequence.” Vance also noted the potential variance in the rate of loading each device. The static “slow” pull versus dynamic loading is a significant variable that increases the variance. This also changes the nature of the testing. Lastly, regarding the tests of new versus old rope, Vance recommended reporting the tests separately rather than together. Combining the data for pulls on old rope and new rope would increase the standard deviation.

6/8/14

The researcher and Lieutenant Walker discussed the project in two emails. The researcher summarized discussions with Joe Flachman of CMC and Rick Vance of Petzl America. The concept of *loss of confidence* was agreed upon, but the need for a category of system limit was expressed. It was also reaffirmed that the tests would be static in nature as most testing with similar devices was conducted with dynamic loading.

6/24/14

Lieutenant Walker sent out a final email to the test group in preparation for the testing week. This email included start times, accommodations, and that Wayne Morris would be driving up the old ropes from Texas.

Procedure and Experimental Design

6/30/14-7/3/14

The testing group met at the PMI Factory in Lafayette, GA, on Monday June 30, 2014. They briefly met in a conference room to discuss the tests and facility etiquette. The group then split up for various tasks. Three individuals split off to cut rope sections into 15’ lengths. Lieutenant Walker, Kim Hunter, and the researcher split off to begin the test set-up.

The tests were conducted on an SKV Model TTL-10 horizontal test bed with 25,000 pound capacity. The machine is located in a warehouse area with consistent climate control of approximately 72 degrees and 70% humidity. The hydraulic piston in the test bed had an approximate length of travel of 12’ length. The test bollards were changed and adjusted for the experiment. The PCDs were attached to a SMC Light Steel Carabiner clipped to a pin on the fixed end of the machine. The rope was wrapped in a four-wrap tensionless configuration around a large bollard. This method retained full strength of the rope and is consistent with similar tests. The force applied to the PCD came from the traveling rope rather than a traveling PCD. This manner of pull and loading seemed most consistent with hauling configurations in the field.

The machine was capable of two speeds. One speed, consistent with other NFPA tests was at a rate of 6” per minute. The machine also featured a “fast-forward” speed of 59” per minute. The initial test was of a Petzl Rescucender applied to new 12.5mm rope. The device slipped continuously at a force of 10-12 kN for the entire duration of the pull. There was some bunching of the sheath, but no damage. The time for change-out and slow nature of the pull took over nearly 15 minutes per set for the first series. This time factor sent up red flags. The experiments were limited to four 8-hour days. There were over 200 test sets to be performed. With continuous testing, confined to a 40-hour workweek, each pull had to be limited to 12 minutes with no room for error. In order to create a comfortable buffer, the pulls needed to be less than 10 minutes each.

It was in this early stage of the process that the experimental design was modified. If a hitch or device was pulled, and the rope traveled through the unit with no significant damage or signs of impending failure, then the test would be arbitrarily stopped five minutes after movement was first observed. The rope was marked with a Sharpie pen where they came in and out of the device or hitch. Once movement was observed a five-minute stopwatch would be initiated. The measurement of travel distance was taken after these type pulls. Most rope travel was 30” which is indicative of the 6” per minute machine speed.

A second timesaving and real world simulating experimental modification involved the rate of loading. Concurrent with the field loading of a PCD, the machine would be accelerated in “fast-forward” mode at a rate of 59” per minute until the device was loaded to a force of 1 kN. This not only saved time, but simulated a haul team suddenly slacking the haul rope and rapidly transitioning the load to the PCD cam. Both experimental adjustments greatly enhanced the flow of the experimental process.

Once all the rope was cut, Prusik loops tied, and components were placed in staging, the test group consisted of the five primary individuals. This group included Kim Hunter, DJ Walker, Wayne Morris, Hayes Nix, and the researcher. Each test, preparation, and change-out, was similar to a racecar pit crew. Each person knew their role and little time was wasted. The devices were inspected and cleaned between pulls. A finishing material, similar to a lubricant, is applied to rope to aid in the manufacturing process. This rope finish was sometimes visible on devices. Devices were cleaned with alcohol between pulls to preclude any build-up of rope finish and skewing of the data.

Each device or hitch combination was pulled at least five times. The machine was advanced in “fast-forward” speed and loaded to a force of 1 kN. If a device slipped, the pull was terminated after five minutes of observed rope travel. Devices and hitches that resulted in complete failure were stopped at the point of failure. Devices and hitches that stripped the sheath and resulted in a perceived *loss of confidence* were stopped. In each series where losses of confidence were observed, at least one test was pulled to total failure. Due to large degrees of variance and some anomalies, some combinations were pulled more than five times. This became the case with old Prusik combinations, the I'D L and the ½"MPD.

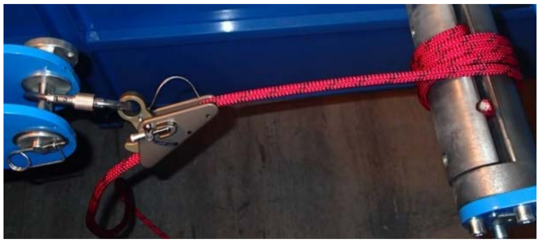

Figure 1. Rescucender 11mm New EZ

Figure 2. Single Prusik 11mm New EZ

Data collected included peak values, values during slipping, distance slipped, graphical representations of each slip, temperature, humidity, and observations of the circumstances surrounding failure. Pulls were documented with photographs and videos. Notes were taken about all relevant findings within the sample sets. Physical samples of all relevant findings were retained.

The researchers who initiated this study most commonly use PMI EZ-Bend rope. In the interest of focusing efforts and resources, the tests were performed on PMI EZ-Bend rope. Diameters tested were 11mm and 12.5mm rope. Both new rope and old rope was used. The new rope was cut directly off a spool that never left the PMI factory. The "old rope" came from three different training caches and was considered "in service" up until the day it was used for testing. The 11mm rope was approximately 10 years old and saw service about 15-days per year. The older 12.5mm rope was 7 years old and saw service approximately 50 days per year. The second "old" 12.5mm rope was manufactured in 2011, in service for one year, and saw 24 days of use (Walker and McCullar, 2014).

The cordage used for Prusiks was 8mm accessory cord. It also consisted of new and old, all manufactured by PMI. The new accessory cord was cut directly off a spool that never left the PMI factory. The "old Prusiks" came from the same respective training caches as the rope and varied in age from 2004-2010(Walker and McCullar, 2014).

Towards the end of the test week, additional decisions about testing were made. Teams within Europe and the cave rescue community sometimes use their personal ascenders as rope grabs in haul systems. With some extra time, experiments were performed using a new style Petzl Basic Ascender on the 11mm rope types. This device is a toothed cam ascender and normally worn as a chest ascender in caving and rope access. The 11mm series were new EZ Bend, old EZ Bend, and Extreme Pro. The only Petzl Basic device failure was on the 11th pull of the series, which was the first pull on the Extreme Pro with Unicore technology. More testing would be required at a later date to finish the series.

Among the old 12.5mm EZ Bend rope, a high rate of desheath was noted among devices that often were inclined to slip on the rope with minimal damage. The term desheath is used to describe the condition where the outer mantle or sheath of the rope is torn away and the white core bundles are exposed. During the five-run series of old 12.5mm EZ Bend in the MPD, the last pull resulted in a partially failed sheath with what appears to be herniated core bundles and strands. This if often referred to as a "core shot." Due to this singular core shot anomaly, an additional five pulls were performed the following day. Several of the additional pulls on old 12.5 in the MPD resulted in a desheath and loss of confidence.

Additionally, the 12.5mm I'D L performed very poorly when combined with old 12.5mm rope. All pulls within this series resulted in a desheath and no pulls with the same device on new rope showed damage. Because of the poor performance of the well-used 10-year-old rope, it was decided that more testing on a younger moderately used rope would be prudent. Another day would be scheduled to finish testing on the 12.5mm MPD, I'D L, and Basic Ascender.

8/15/14

The researcher and Lieutenant Walker returned to PMI in Lafayette, GA, for one additional day of tests. These tests focused on the CMC MPD and Petzl I'D L on a three-year-old 12.5mm rope. The rope had seen approximately 24 days of use in training at the Mississippi State Fire Academy. This rope seemed to correct earlier issues and no desheaths took place. The testers also finished the test series on the Petzl Basic Ascender on 11 mm Extreme Pro.

Limitations

Time and budgetary constraints prohibited all possible PCD and rope combinations from being tested. Relevant devices that could be tested might include ratcheting pulleys, Gibbs Ascenders, and other cam-actuated PCDs. These results may not necessarily be extrapolated to ropes with a differing number of sheath carriers or handling characteristics. The experimental design reflects PCD characteristics only on PMI EZ Bend and Extreme Pro rope. This study may not reflect user experiences with Sterling Rope, Bluewater Rope, and other brands.

The sample sizes were limited to five tests per combination, in an initial attempt to gain 3-sigma values. Three-sigma reporting was later considered to be a poor fit for the scope of the study. This was in part due to large variances and the propensity of many combinations to slip continuously. As with all research, however, larger sample sizes would likely yield even more accurate averages and reduce standard deviations.

The speed or rate of pull only demonstrates behavior in those exact conditions. Hudson and Vines (2014) note the speed of pull brings much to bear on the experiment. Rope pulled apart more slowly will yield stronger values than rope pulled apart more quickly. NFPA 1983(2012), under the direction of the Cordage Institute's 1801(2007) standard on testing rope, use a rate of pull between 1.5" and 6" per minute. The results of this study may not apply to faster or slower rates of pull.

Another limitation encountered was the variability of the loading of PCDs while the machine was in "fast forward." The intent was to load each device to 1 kN, but was limited by the researchers' and operators reaction time. Due to time constraints, an adjustment to the experimental design was made in the test lab. For time-saving purposes, devices clearly exhibiting what came to be known as System Operation Limits(SOL), were given an arbitrary five minutes of testing once the rope began travelling through the device. This typically resulted in 30" of travel, but it cannot be absolutely concluded what may have occurred if the hitch or device was pulled indefinitely.

The Munter Hitch would likely have tested more favorably in a working position, rather than tied-off. This may not reflect true field values based on the best practices users employ when using a Munter hitch to capture haul progress. The test machine cage and experimental design did not allow researchers to explore this avenue. Perhaps utilizing a hand or mechanical grip may have resulted in a potential SOL behavior (Walker & McCullar, 2014).

Calls and Events After Testing

After both test dates in July and August, the engineers, sponsors, and manufacturers were consulted and the observations were discussed and deliberated upon. Petzl America's Technical Director, Rick Vance, offered his insights on the results. A group at CMC Rescue would do the same. Additionally, CMC Rescue offered the services of a statistician to analyze the data.

7/10/14

On July 10, 2014, after a series of emails disclosing the testing results with CMC Rescue a conference call was scheduled. Director of Engineering Mark Green, CMC Engineer Cedric Smith, CMC Training Director John McKently, Lieutenant Walker, and the researcher were on the call. The core shot and old 12.5mm rope in the MPD was discussed. The CMC team expressed satisfaction in the fact that the core strands remained intact and no loads were totally severed. Sheath carriers and their relevance were discussed. CMC asked the researchers for an untested sample of the 12.5mm rope to repeat the tests themselves. The CMC team offered the services of their statistician, Steve Fowler, and offered to fund the consultation. The CMC team felt positive about the results and the experimental process.

7/10/14-7/11/14

After a series of emails disclosing the results of the testing, a conference call was set with Rick Vance of Petzl America on July 11, 2014. The results very closely correlated with Rick's expectations. He expressed interest in the Basic Ascender on Extreme Pro shattering and offered more Basics to finish out the experiments.

8/15/14

Lieutenant Walker and the researcher met in Lafayette, GA, for the last runs of the experiments. They performed an additional 20 pulls with the I'D L, MPD, and Basic Ascender.

9/3014

Kim Hunter sent the researchers information in an email regarding the speed of the test bed. The slow pull speed of 6" per minute was confirmed. The "fast forward" speed of 59" per minute was finally disclosed.

11/7/14

The researchers presented their findings at the 2014 International Technical Rescue Symposium in Golden, CO. This included the publication of a 14 page paper and a 90-minute presentation to peers in the field of technical rescue.

Results

This applied research project ended up becoming a nearly organic, changing, and growing, process. Nothing was ever set in stone and very few of the results were black and white or right and wrong. Having examined the lack of statistical data on this particular topic, the best method of disclosing the results of the testing is to show the tests in their raw form. From that point, one can explain how values of SSSFs and deductive decisions and recommendations can be made.

One reader may look at videos and data within this project and walk away with vastly different conclusions. It is important to the researchers to be completely transparent and forthcoming regarding the experimental process and the data gained. Much of what was disclosed in the literature review reflects a single number or safety factor with no citation or explanation. The results section will disclose the data and the way the data is interpreted into SSSFs. The concept of System Operation Limit (SOL) will also be explained and applied to the data. The pages that follow represent a statistical answer to the first two research questions concerning PCD strength on various rope. The data is extrapolated into a field-friendly SSSF chart in Figure 11.

SMC Grip

PMI/SMC Grip

New Rope, 11mm	Peak KN	Peak Lbf	Comments
11mm #1	8.03	1805.14	little to no slip then desheathes rope at 8.03kN
11mm #2	8.99	2020.95	little to no slip then desheathes rope at 8.99kN
11mm #3	9.07	2038.94	little to no slip then desheathes rope at 9.07kN
11mm #4	7.67	1724.22	little to no slip then desheathes rope at 7.67kN
11mm #5	7.06	1587.09	little to no slip then desheathes rope at 7.06kN
Average	8.16	1835.27	
StandDev	0.864	194.16	

PMI/SMC Grip

New Rope, 12.5mm			
12.5mm #1	9.89	2223.27	little to no slip then desheathes rope at 9.89kN; bent the Grip axle (exposed to 5 pulls)
12.5mm #2	9.81	2205.29	little to no slip then desheathes rope at 9.81kN;
12.5mm #3	10.33	2322.18	little to no slip then desheathes rope at 10.33kN;
12.5mm #4	11.21	2520.01	little to no slip then desheathes rope at 11.21kN;
12.5mm #5	10.91	2452.57	little to no slip then desheathes rope at 10.91kN;
Average	10.43	2344.66	
StandDev	0.617	138.79	

PMI/SMC Grip

New Rope, 11mm ExPro			
11mm ExPro #1	6.72	1510.66	little to no slip then desheathes rope at 6.72kN
11mm ExPro #2	7.3	1641.04	little to no slip then desheathes rope at 7.3kN, continued pull, stayed steady about 3kN bunching the sheath up behind the Grip
11mm ExPro #3	7.4	1663.52	little to no slip then desheathes rope at 7.4kN
11mm ExPro #4	7.82	1757.94	little to no slip then desheathes rope at 7.82kN
11mm ExPro #5	6.88	1546.62	little to no slip then desheathes rope at 6.88kN
Average	7.22	1623.96	
StandDev	0.437	98.27	

Note: 2 of the 3 grips axel pins bent.

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 1. SMC Grip Data

Petzl Rescucender

Rescucender

New Rope, 11mm	Peak KN	Peak Lbf	Comments
11mm #1	4.57	1027.34	Continuous slip, very smooth, Some sheath bunching
11mm #2	3.91	878.97	Continuous slip, very smooth, Some sheath bunching
11mm #3	4.08	917.18	Continuous slip, very smooth, Some sheath bunching
11mm #4	3.46	777.81	Continuous slip, very smooth, Some sheath bunching
11mm #5	3.42	768.82	Continuous slip, very smooth, Some sheath bunching
Average	3.888	874.02	
StandDev	0.476	106.91	

Rescucender

Old Rope, 11mm- (Rope was put in service around 2004)

11mm #1	3.12	701.38	Continuous slip, very smooth, Some sheath bunching
11mm #2	3.30	741.84	Continuous slip, very smooth, Some sheath bunching
11mm #3	4.07	914.94	Continuous slip, very smooth, Some sheath bunching
11mm #4	4.85	1090.28	Continuous slip, very smooth, Some sheath bunching
11mm #5	3.01	676.65	Continuous slip, very smooth, Some sheath bunching
Average	3.670	825.02	
StandDev	0.779	175.12	

Rescucender

New Rope, 12.5mm

12.5mm #1	11.48	2580.70	As the sheath bunched, cam "skipped" several times
12.5mm #2	12.38	2783.02	Continuous slip, very smooth, Some sheath bunching, some "skips" after bunching
12.5mm #3	10.68	2400.86	Continuous slip, very smooth, Some sheath bunching, some "skips" after bunching
12.5mm #4	11.89	2672.87	Continuous slip, very smooth, Some sheath bunching, some "skips" after bunching
12.5mm #5	11.26	2531.25	Continuous slip, very smooth, Some sheath bunching, some "skips" after bunching
Average	11.54	2593.74	
StandDev	0.64	144.37	

Rescucender

Old Rope, 12.5mm- (Rope was put in service around 2007)

12.5mm #1	11.95	2686.36	Desheathed the rope
12.5mm #2	9.92	2230.02	Desheath the rope at 9.92, Continued pull until total failure 10.89
12.5mm #3	11.00	2472.80	Desheath the rope
12.5mm #4	9.79	2200.79	Desheath the rope
12.5mm #5	10.21	2295.21	Desheath the rope
Average	10.574	2377.04	
StandDev	0.901	202.62	

Rescucender

ExPro New Rope, 11mm

11mm ExPro #1	4.69	1054.31	Peaked at 4.69 and continuously slipped at about 4.3 for five minutes
11mm ExPro #2	4.73	1063.30	Started slipping at 2kN, continuously slipped at about 4.3 for five minutes
11mm ExPro #3	4.19	941.91	Peaked at 4.19 and continuously slipped at about 4 for five minute
11mm ExPro #4	4.08	917.18	Peaked at 4.08 and continuously slipped at about 4 for five minute
11mm ExPro #5	4.19	941.91	Peaked at 4.08 and continuously slipped at about 4 for five minute
Average	4.38	983.72	
StandDev	0.309	69.35	

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 2. Petzl Rescucender Data

Munter Hitch (Tied-off with a half hitch followed by an overhand)

Munter Hitch

New Rope, 11mm	Peak KN	Peak Lbf	Comments
11mm #1	17.78	3996.94	Rope Broke where the loaded strand ran through the half hitch of the tieoff
11mm #2	17.28	3884.54	Rope Broke where the loaded strand ran through the half hitch of the tieoff
11mm #3	16.06	3610.29	Rope Broke where the loaded strand ran through the half hitch of the tieoff
11mm #4	15.72	3533.86	Major "Slip" through the hitch 15.72kN (likely the core breaking), then final break at about 6kN (likely the sheath breaking)
11mm #5	17.12	3848.58	Rope Broke where the loaded strand ran through the half hitch of the tieoff
Average	16.79	3774.84	
StandDev	0.867	194.91	

Munter Hitch

Old Rope, 11mm- (Rope was put in service around 2004)

11mm #1	12.44	2796.51	Rope Broke where the loaded strand ran through the half hitch of the tieoff
11mm #2	13.26	2980.85	Rope Broke where the loaded strand ran through the half hitch of the tieoff
11mm #3	13.29	2987.59	Rope Broke where the loaded strand ran through the half hitch of the tieoff
11mm #4	12.59	2830.23	Rope Broke where the loaded strand ran through the half hitch of the tieoff
11mm #5	14.41	3239.37	Rope Broke where the loaded strand ran through the half hitch of the tieoff
Average	13.20	2966.91	
StandDev	0.779	175.05	

Munter Hitch

New Rope, 12.5mm

12.5mm #1	21.44	4819.71	Rope Broke where the loaded strand ran through the half hitch of the tieoff
12.5mm #2	22.5	5058.00	Rope Broke where the loaded strand ran through the half hitch of the tieoff
12.5mm #3	21.97	4938.86	Rope Broke where the loaded strand ran through the half hitch of the tieoff
12.5mm #4	25.53	5739.14	Rope Broke where the loaded strand ran through the half hitch of the tieoff
12.5mm #5	22.75	5114.20	Rope Broke where the loaded strand ran through the half hitch of the tieoff
Average	22.838	5133.98	
StandDev	1.587	356.80	

Munter Hitch

Old Rope, 12.5mm- (Rope was put in service around 2007)

12.5mm #1	14.26	3205.65	Rope Broke where the loaded strand ran through the half hitch of the tieoff
12.5mm #2	14.53	3266.34	Major "Slip" through the hitch 14.5kN (likely the core breaking), then final break at about 5.5kN (likely the sheath breaking)
12.5mm #3	15.42	3466.42	Rope Broke where the loaded strand ran through the half hitch of the tieoff
12.5mm #4	16.19	3639.51	Rope Broke where the loaded strand ran through the half hitch of the tieoff
12.5mm #5	14.39	3234.87	Rope Broke where the loaded strand ran through the half hitch of the tieoff
Average	14.958	3362.56	
StandDev	0.825	185.52	

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 3. Munter Hitch Data

CMC MPD

MPD

New Rope, 11mm	Peak KN	Peak Lbf	Comments
11mm #1	4.15	932.92	continuous slippage at about 4kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
11mm #2	4.45	1000.36	continuous slippage at about 4.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
11mm #3	4.1	921.68	continuous slippage at about 3.9kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping (28" travel)
11mm #4	4.53	1018.34	continuous slippage at about 4.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping (30" travel)
11mm #5	4.33	973.38	continuous slippage at about 4kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
Average	4.31	969.34	
StandDev	0.186	41.77	
11mm #6A	4.61	1036.33	Parking break is set. Continuous slippage at about 4.2kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping

MPD

Old Rope, 11mm- (Rope was put in service around 2004)			
11mm #1	7.16	1609.57	continuous slippage (w/ some "skipping") at about 6.7kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
11mm #2	7.24	1627.55	continuous slippage at about 6.25-7.2kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
11mm #3	7.52	1690.50	continuous slippage at about 6.25-7.2kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
11mm #4	7.9	1775.92	continuous slippage at about 7-7.9kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
11mm #5	7.99	1796.15	continuous slippage (w/ some "skipping") at about 7.6-7.9kN, then quit "skipping" and slipped about 6.5-7.4kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping
Average	7.56	1699.94	
StandDev	0.376	84.45	
11mm #6A	7.55	1697.24	Parking break is set. continuous slippage at about 6-7kNkN. Some bunching of the rope beyond the device. Rope still in good shape after slipping

MPD

New Rope, 12.5mm			
12.5mm #1	9.4	2113.12	continuous slippage at about 8.5-8.75kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping (minor fuzzing)
12.5mm #2	8.67	1949.02	continuous slippage at about 8-8.4kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping (minor fuzzing) (30")
12.5mm #3	8.64	1942.27	continuous slippage at about 7.9-8.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping (minor fuzzing)
12.5mm #4	8.37	1881.58	continuous slippage at about 7.9-8.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping (minor fuzzing) (30.5")
12.5mm #5	8.44	1897.31	continuous slippage at about 7.7-8.5kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping (minor fuzzing)
Average	8.704	1956.66	
StandDev	0.410	92.07	

MPD

Old Rope, 12.5mm- (test 1-10 rope was put in service around 2007; test 11-12 rope was in service 1 year)			
12.5mm #1	10.65	2394.12	continuous slippage at about 8.5-10.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. Some "skipping"
12.5mm #2	9.74	2189.55	continuous slippage at about 9-9.6kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. Some "skipping"
12.5mm #3	11.47	2578.46	continuous slippage at about 10-11.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. Some "skipping"
12.5mm #4	10.98	2468.30	continuous slippage at about 9.5-10.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. Some "skipping"
12.5mm #5	13.28	2985.34	Slipped for short distance (Approx. 12"), Desheathed the rope were the rope is "pinched" in the cam.
12.5mm #6	16.24	3650.75	Slipped for short distance (Approx. 12"), Desheathed the rope were the rope is "pinched" in the cam.
12.5mm #7	13.78	3097.74	continuous slippage at about 9.5-10.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. Some "skipping"
12.5mm #8	13.5	3034.80	Slipped for short distance (Approx. 8"), Desheathed the rope were the rope is "pinched" in the cam.
12.5mm #9	11.09	2493.03	continuous slippage at about 10-10.5kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. Some "skipping"
12.5mm #10	**10.95**	**2461.56**	**On application of force it bit down and caused some moderate sheath damage(core shot) and then began to slip. Continuous slippage at about 9-10.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. Some "skipping"**
12.5mm #11 ***	8.73	1962.504	continuous slippage at about 7.9-8.8kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. No Skipping
12.5mm #12 ***	8.31	1868.088	continuous slippage at about 7.5-8kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. No Skipping (30" slip)
12.5mm #13 ***	8.83	1984.984	continuous slippage at about 8-8.75kN. Small "pop" and then the slipping started. Some bunching of the rope beyond the device. Rope still in good shape after slipping. No Skipping (34" Slip)
12.5mm #14 ***	7.66	1721.968	continuous slippage at about 7-7.6kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. No Skipping (30" slip)
12.5mm #15 ***	8.40	1888.32	continuous slippage at about 8-8.4kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping. No Skipping
Average	10.907	2451.97	
StandDev	2.442	548.88	

*** Denotes that this is a different rope from previous tests. This rope was in service for 1 year.

MPD

New Rope, 11mm			
11mm ExPro #1	6.24	1402.75	continuous slippage at about 6kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping.
11mm ExPro #2	6.82	1533.14	continuous slippage at about 6.5-6.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping.
11mm ExPro #3	6.24	1402.75	continuous slippage at about 6-5.8kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping.
11mm ExPro #4	6.42	1443.22	continuous slippage at about 6.25kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping.
11mm ExPro #5	6.07	1364.54	continuous slippage at about 6-5.8kN. Some bunching of the rope beyond the device. Rope still in good shape after slipping.
Average	6.36	1429.28	
StandDev	0.286	64.38	

Note: Tensioned end of rope exiting the device takes on flat shape at cam (inside), then V or (triangle) when running through deep pulley sheave upon exiting

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 4. CMC MPD Data

Petzl I'D

Petzl ID

New Rope, 11mm	Peak KN	Peak Lbf	Comments
11mm #1	4.63	1040.82	Continuous slipping around 4-4.2kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping. (30")
11mm #2	4.47	1004.86	Continuous slipping around 3.8-4.2kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
11mm #3	4.86	1092.53	Continuous slipping around 4.25-4.75kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
11mm #4	4.65	1045.32	Continuous slipping around 4-4.25kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
11mm #5	4.78	1074.54	Continuous slipping around 4.25-4.75kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
Average	4.68	1051.61	
StandDev	0.150	33.70	

Petzl ID

Old Rope, 11mm- (Rope was put in service around 2004)

11mm #1	7.16	1609.57	Continuous slipping around 6-7kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
11mm #2	6.66	1497.17	Continuous slipping around 5-6.5kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
11mm #3	8.00	1798.40	Continuous slipping around 6-7kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
11mm #4	6.34	1425.23	Continuous slipping around 5.8-6.1kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
11mm #5	7.35	1652.28	Continuous slipping around 6.2-7kN. Some bunching of the rope sheath beyond the device. Rope still in fair shape after slipping.
Average	7.10	1596.53	
StandDev	0.642	144.26	

Petzl ID

New Rope, 12.5mm

12.5mm #1	5.6	1258.88	Continuous slipping around 5-5.25kN. Bunching of the rope sheath beyond the device. Rope still in fair shape after slipping. (31" of slip) No noticeable rope treatment in device
12.5mm #2	5.82	1308.34	Continuous slipping around 5-5.25kN. Bunching of the rope sheath beyond the device. Rope still in fair shape after slipping. No noticeable rope treatment in device
12.5mm #3	5.64	1267.87	Continuous slipping around 5.5-5.75kN. Bunching of the rope sheath beyond the device. Rope still in fair shape after slipping. No noticeable rope treatment in device
12.5mm #4	5.79	1301.59	Continuous slipping around 5-5.75kN. Bunching of the rope sheath beyond the device. Rope still in fair shape after slipping. No noticeable rope treatment in device
12.5mm #5	5.72	1285.86	Continuous slipping around 5-5.75kN. Bunching of the rope sheath beyond the device. Rope still in fair shape after slipping. No noticeable rope treatment in device
Average	5.714	1284.51	
StandDev	0.094	21.18	

Petzl ID

Old Rope, 12.5mm

12.5mm #1	8.11	1823.13	Desheathed the rope at 8.11kN where the rope is pinched by the cam. Little to no slipping
12.5mm #2	6.88	1546.62	Desheathed the rope at 6.88kN where the rope is pinched by the cam. Little to no slipping
12.5mm #3	6.70	1506.16	Desheathed the rope at 6.7kN where the rope is pinched by the cam. Little to no slipping. Continued pulling, and it continued to pop core bundles. Saw an additional peak of 8.05kN
12.5mm #4	8.01	1800.65	Desheathed the rope at 8.01kN where the rope is pinched by the cam. There was 4-6" inches of slip prior to biting down.
12.5mm #5	6.29	1413.99	Desheathed the rope at 6.29kN where the rope is pinched by the cam. There was 4-6" inches of slip prior to biting down.
12.5mm #6 ***	5.95	1337.56	continuous slippage at about 5.2-6kN. Some bunching of the rope beyond the device. Moderate amount of sheath picks after pull (coming from "V" of new cam). No Skipping
12.5mm #7 ***	6.25	1405	continuous slippage at about 5.5-6kN. Some bunching of the rope beyond the device. Moderate amount of sheath picks after pull (coming from "V" of new cam). No Skipping
12.5mm #8 ***	5.47	1229.656	continuous slippage at about 4.8-5.4kN. Some bunching of the rope beyond the device. Moderate amount of sheath picks after pull (coming from "V" of new cam). No Skipping
12.5mm #9 ***	5.71	1283.608	continuous slippage at about 5-5.6kN. Some bunching of the rope beyond the device. Moderate amount of sheath picks after pull (coming from "V" of new cam). No Skipping
12.5mm #10 ***	5.64	1267.872	continuous slippage at about 5-5.2kN. Some bunching of the rope beyond the device. Moderate amount of sheath picks after pull (coming from "V" of new cam). No Skipping
Average	7.198	1618.11	
StandDev	0.816	183.48	

*** Denotes that this is a different rope from previous tests. This rope was in service for 1 year.

Petzl ID

New Rope, 11mm ExPro

11mm ExPro #1	**7.15**	**1607.32**	**There was an initial peak that significantly damaged part of the sheath where the cam pinches the rope, then it continuously slipped 6-6.25kN with no further damage. Some bunching of the rope sheath beyond the device**
11mm ExPro #2	7.38	1659.02	Continuous slipping around 6kN. Some bunching of the rope sheath beyond the device. Some "lumps" in the rope where it traveled through the device.
11mm ExPro #3	7.04	1582.59	On the application of force the device bit down and significantly damaged the sheath where the cam pinches the rope, then continuously slipped 6-6.5kN with no further damage.
11mm ExPro #4	7.73	1737.70	On application of force the device bit down and damaged the sheath. Device then allowed rope to slide through (12-14") until 3 min into the slipping it bit down and desheathed the rope where the cam pinches the rope.
11mm ExPro #5	7.17	1611.82	Continuous slipping around 6kN. Some bunching of the rope sheath beyond the device. Some "lumps" in the rope where it traveled through the device. Noticeable glue on sheathe and device
Average	7.29	1639.69	
StandDev	0.273	61.37	

Note: Appears to be small specks of glue on the rope sheath and in the device after test.

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 5. Petzl I'D Data

Petzl Basic

Petzl Basic

New Rope, 11mm	Peak KN	Peak Lbf	Comments
11mm #1	5.67	1274.62	Desheathed the rope at 5.67kN
11mm #2	5.35	1202.68	Desheathed the rope at 5.35kN
11mm #3	5.66	1272.37	Desheathed the rope at 5.66kN
11mm #4	5.85	1315.08	Desheathed the rope at 5.85kN
11mm #5	5.45	1225.16	Desheathed the rope at 5.45kN
Average	5.60	1257.98	
StandDev	0.197	44.38	

Petzl Basic

Old Rope, 11mm- (Rope was put in service around 2004)

11mm #1	5.66	1272.37	Desheathed the rope at 5.66kN
11mm #2	5.97	1342.06	Desheathed the rope at 5.97kN
11mm #3	5.52	1240.90	Desheathed the rope at 5.52kN
11mm #4	5.26	1182.45	Desheathed the rope at 5.26kN
11mm #5	5.68	1276.86	Desheathed the rope at 5.68kN
Average	5.62	1262.93	
StandDev	0.258	58.11	

Note: Same device for all above tests. After last test, device was still usable but cam was binding slightly.

Petzl Basic

New Rope, 11mm

11mm ExPro #1	**5.37**	**1207.18**	**Basic broke at 5.37kN. Rope has little to no sheath damage. (This was the 11th test with this device).**
11mm ExPro #2	6.16	1384.77	Desheathed rope @6.16kN (Device 2)
11mm ExPro #3	**5.98**	**1344.30**	**Basic broke at 5.98kN. Rope has little to no sheath damage. (Device 2, 2nd pull).**
11mm ExPro #4	6.43	1445.46	Desheathed the rope at 6.43kN (Device 3).
11mm ExPro #5	6.19	1391.51	Desheathed the rope at 6.19kN. (Device 4).
11mm ExPro #6	6.26	1407.25	Desheathed the rope at 6.26kN. (Device 6).
11mm ExPro #7	5.81	1306.09	Desheathed the rope at 5.81kN. (Device 6). Continued pull until Rope sheath bunched and jammed in the device. Basic Broke at 9.10kN after 5.5 feet of slipping
11mm ExPro #8	**5.61**	**1261.13**	**Basic broke at 5.61kN. Rope has little to no sheath damage. (Device 4, 2nd pull.**
11mm ExPro #9	**5.6**	**1258.88**	**Basic broke at 5.37kN. Rope has little to no sheath damage. (Device 3, 2nd pull).**
11mm ExPro #10	**5.25**	**1180.20**	**Basic broke at 5.37kN. Rope has little to no sheath damage. (Device 5, 2nd pull).**
Average	5.87	1318.68	
StandDev	0.400	90.00	

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 6. Petzl Basic Data

Single Prusik

8mm Single Prusik

New Rope,11mm	Peak KN	Peak Lbf	Comments
11mm #1	14.69	3302.31	Prusik broke in the strand under the bridge
11mm #2	13.74	3088.75	Desheathed the rope, Several incremental slips prior to failure, large slip just under 9kN, big slips @ 13 kN
11mm #3	13.88	3120.22	Desheathed the rope, Several incremental slips prior to failure, large slip just under ?, big slips @ ? kN
11mm #4	13.85	3113.48	Prusik broke at the hitch, under the bridge, but further into the wraps
11mm #5	14.47	3252.86	Prusik broke in the strand under the bridge
Average	14.13	3175.52	
StandDev	0.425	95.51	

8mm Single Prusik (Old)

Old Rope, 11mm- (Rope was put in service around 2004. Prusiks vary in age 2004-2008)

11mm #1	12.47	2803.26	very little slip(3-4"), desheathed the rope at 12.47kN (a short slip bonds and bights, followed by sheath strip at a slightly lower value)
11mm #2	12.08	2715.58	very little slip(3-4"), desheathed the rope at 12.08kN(slipped two times, second bonds and bights, followed by sheath strip at a slightly lower value)
11mm #3	11.61	2609.93	Slipped for several inches (6"-8"), then bit down and desheathed the rope at 11.61kN
11mm #4	9.41	2115.37	very little slip(2-3"), Prusik broke at the bridge at 9.41kN
11mm #5	8.12	1825.38	very little slip(2-3"), Prusik broke at the bridge at 8.12kN (prusik-2005)
11mm #6	11.35	2551.48	very little slip(2-3"), Prusik broke at the bridge at 11.35kN
11mm #7	10.67	2398.62	very little slip(2-3"), Prusik broke at the Carabiner bight at 10.67kN
11mm #8	10.88	2445.82	very little slip(2-3"), Slip at 10.2, then grabbed fast, Prusik broke at the Carabiner bight at 10.88kN
11mm #9	12.84	2886.43	Very little slip (2-3"), Slipped at 12.84, then bit down and desheathed the rope at 10.2kN
11mm #10	9.42	2117.62	very little slip(2-3"), Prusik broke at the Carabiner bight at 9.42kN
Average	10.89	2446.95	
StandDev	1.510	339.42	

8mm Single Prusik

New Rope, 12.5mm

12.5mm #1	13.87	3117.98	Prusik broke in the strand under the bridge
12.5mm #2	16.59	3729.43	Prusik broke in the strand under the bridge
12.5mm #3	14.72	3309.06	Prusik broke in the strand under the bridge
12.5mm #4	14.12	3174.18	Prusik broke in the strand under the bridge
12.5mm #5	14.82	3331.54	Prusik broke in the strand under the bridge
Average	14.82	3332.44	
StandDev	1.065	239.37	

8mm Single Prusik (Old)

Old Rope, 12.5mm- (Rope was put in service around 2007. Prusiks vary in age 2006-2013)

12.5mm #1	13.35	3001.08	very little slip (mainly as prusik tightened down), Prusik broke at the carabiner bight at 13.35kN
12.5mm #2	14.09	3167.43	very little slip (mainly as prusik tightened down), Prusik broke at the carabiner bight at 14.09kN
12.5mm #3	8.94	2009.71	very little slip (mainly as prusik tightened down), Prusik broke at the bridge at 8.94kN (prusik 2007)
12.5mm #4	8.34	1874.83	very little slip (mainly as prusik tightend down), Prusik broke at the carabiner bight at 8.34kN
12.5mm #5	11.19	2515.51	Slipped 3.5", prusik broke ar the carabiner bight at 11.19kN (prusik 2006)
Average	11.18	2513.71	
StandDev	2.562	575.99	

Single Prusik

New Rope, 11mm ExPro

11mm ExPro #1	10.73	2412.10	Desheathed the rope at 10.73. Rope desheathed 4.5" from starting point
11mm ExPro #2	9.7	2180.56	Continuiously "skipped" down the rope, would build to 9.5-9.7 and "skip". 21" of slip from the starting point
11mm ExPro #3	10.95	2461.56	Desheathed the rope at 10.95. Rope desheathed 3.5" from starting point
11mm ExPro #4	10.2	2292.96	Continuious smooth slide between 6-7kN for five minutes. Peaked at 10.2 kN, then began slip for 21"
11mm ExPro #5	11.49	2582.95	Detheathed the rope at about 8kN, peak force was 11.49, 4.25" from the starting point
Average	10.61	2386.03	
StandDev	0.689	154.95	

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 7. Single Prusik Data

Tandem Prusiks

8mm Tandem Prusik (New)

New Rope, 11mm	Peak KN	Peak Lbf	Comments
11mm #1	25.88	5817.82	desheathed rope in front of short prusik at 25.88 kN- 6.5" of slip from starting point (long prusik)
11mm #2	23.47	5276.06	desheathed rope in front of short prusik at 23.47 kN- 7.5" of slip from starting point (long prusik)
11mm #3	23.89	5370.47	desheathed rope in front of short prusik at 23.89 kN- continued to pull, desheathed in front of long prusik at 20.5ish
11mm #4	24.18	5435.66	Short prusik broke at 24.18 under the bridge, continued the pull, long prusik broke at 14.72
11mm #5	23.86	5363.73	Short prusik broke at 23.86 under the bridge, continued the pull, Long prusik desheathed the rope at 12.88
Average	24.26	5452.75	
StandDev	0.942	211.83	
11mm Anom1	26.290		Machine started pulling at a much faster rate unexpectedly. Pulled fast with desheathing in front of short prusik at 26.29

8mm Tandem Prusik (Old)

Old Rope, 11mm- (Rope was put in service around 2004. Prusiks vary in age 2004-2008)

11mm #1	18.43	4143.06	Some slipping (3.5"), Large slip around 18 kN, then Short prusik desheathed the rope at 18.43kN
11mm #2	15.87	3567.58	13-14" of slippage, then bit down and desheathed the rope at 15.87kN
11mm #3	19.65	4417.32	Some slipping (3.5"), Large slip at 19.65 kN, reducing loading, then Short prusik bit down and desheathed the rope at 15.8kN
11mm #4	16.35	3675.48	10-12" of slippage of slip, 16.34 kN Short prusik broke at the bridge, Continued pull, long prusik slipped an additional 2-3" and then desheathed the rope at about 10kN
11mm #5	15.85	3563.08	12-13" of slippage, short prusik desheathed the rope at 15.85kN
Average	17.23	3873.30	
StandDev	1.719	386.51	

8mm Tandem Prusik (New)

New Rope, 12.5mm

12.5mm #1	26.02	5849.30	desheathed rope in front of long prusik at 26.02
12.5mm #2	27.75	6238.20	desheathed rope in front of long prusik at 27.75
12.5mm #3	25.14	5651.47	Short Prusik Broke at 25.14 under the bridge; continued pull and long prusik broke at an unknown value
12.5mm #4	27.66	6217.97	Both prusiks broke at the same time under the bridges (4.5" of slippage from start to stopping point in front of the long prusik
12.5mm #5	28.32	6366.34	Short Prusik Broke at 28.32 under the bridge; continued pull and long prusik desheathed the rope at 14.24
Average	26.978	6064.65	
StandDev	1.338	300.72	

8mm Tandem Prusik (Old)

Old Rope, 12.5mm- (Rope was put in service around 2007. Prusiks vary in age 2006-2013)

12.5mm #1	24.96	5611.01	3-4" of slippage, desheathed the rope in front of long prusik at 24.96kN
12.5mm #2	18.45	4147.56	2-3" of slip, short prusik broke at the bridge 18.45kN, continued pull, long prusik broke at the bridge 12.8kN
12.5mm #3	16.67	3747.42	3-4" of slip, short prusik broke at the carabiner 16.67kN, continued pull, long prusik broke at bridge 8.59kN
12.5mm #4	21.4	4810.72	4-5" of slippage, desheathed the rope in front of the long prusik at 21.4kN
12.5mm #5	19.21	4318.41	5.5" of slippage, short prusik broke at carabiner 19.21kN, continued pull, long prusik broke at bridge 11.5kN
12.5mm#6	16.35	3675.48	2-3" of slip, short prusik broke at the bridge 16.35kN, continued pull, long prusik broke at the carabiner bight 10.2kN
12.5mm#7	17.69	3976.71	Short Prusik broke @ 17.69 kN, then long slipped and bites down and broke @ 14.1, Slipped 3"
12.5mm#8	24.8	5575.04	Short Prusik broke @ 24.80 kN, then long slipped and bites down and desheathed @ 15.9, Slipped 4-6"
Average	19.941	4482.79	
StandDev	3.430	771.03	

Tandem Prusik (New)

New Rope, 11mm Ex Pro

11mm ExPro #1	10.4	2337.92	Short prusik elongated and bumped against the long prusik, both continuously slipped down the rope at about 6.1 kN for five minutes
11mm ExPro #2	10.1	2270.48	Short prusik elongated and bumped against the long prusik, both continuously slipped down the rope at about 6.1 kN for five minutes
11mm ExPro #3	10.2	2292.96	Short prusik elongated and bumped against the long prusik, both continuously slipped down the rope at about 5.9-6.1 kN for five minutes
11mm ExPro #4	14.28	3210.14	Desheathed rope in front of Short prusik at 14.28kN
11mm ExPro #5	11.28	2535.74	Short prusik elongated and bumped against the long prusik, both continuously slipped down the rope at about 6.5-7 kN for five minutes
Average	11.25	2529.45	
StandDev	1.756	394.67	

XX	XXXX	Grey cells represent a "Fail"
XX	XXXX	White cells represent "System Operation Limit"
XX	**XXXX**	**Bold text represent an abnormal result**

Table 8. Tandem Prusik Data

Failure of a PCD

One of the most significant observations of the project involved two distinct types of behavior. One type was the breaking strengths of some combinations the study initially set out to determine. Over the course of the research, conventional failure was considered to be an outcome where the PCD broke or the rope became severed, and the result would have allowed the load to release and fall to the ground. Failure and loss of confidence were discussed at length with the researchers and participating manufacturer engineers. This answer to the third research question was determined using both empirical observation and expert consensus. Failure took place when the load was lost to a fall from a failing PCD or rope. Failures occurred most commonly among the Munter, single Prusik, tandem Prusik, Grip, and Basic.

Loss of Confidence of a PCD

The other damaging result that was ultimately categorized as a failure was any significant damage to the PCD device or the rope. This would answer the fourth research question and constitute a new concept or description. When the rope's sheath became severed and peeled back around the core strands, this occurrence was considered a *Loss of Confidence*. A loss of confidence describes the rescuers perception of the compromised integrity of system to continue to function normally as a haul system or support the load. Rope desheaths were the most frequently observed losses of confidence in the PCDs. This loss of confidence was also in their ability to perform their function. Though the load is still supported, the haul system is most often defunct and the rescuers cannot ascertain how much strength and integrity remain in the system. *Loss of confidence* was ultimately categorized by the researchers as a sub-category under failure. The devices that desheathed the rope, resulting in a loss of confidence, included the single Prusik, tandem Prusik, Grip, and Basic. Primarily in the older 12.5mm rope, losses of confidence were also observed in the series involving the MPD, I'D, and Rescucender.

System Operation Limit

Another prominent behavior involved the rope slipping and traveling through the PCD without damaging the rope. It was in these instances that the rope would pull through the PCD for an elapsed time of five minutes, and then the test would be stopped. As a PCD, its job is to hold fast the load, while the hauling pulleys are reset. This constituted a failure of the PCD to perform in the system in the manner, which it was intended. When this took place, the PCD had reached its *System Operation Limit* (SOL). The system operation limit (SOL) category became a frequent occurrence among several rope and PCD combinations. From this point forward, total failure and desheaths were categorized as failures with breaking strengths. Combinations that slipped were considered instances of *System Operation Limits*. There were some combinations that exhibited both categories. Usually, the devices trended towards either *failure* or *SOL* conditions.

Early discussions on the project involved deriving three-sigma breaking strengths resulting in a industry standard minimum breaking strength (MBS). The benefit of this process is that it can be used to predict outcomes to a 99.7% level of confidence. This is achieved by determining the mean, and using the data to determine the variance and standard deviation. Three standard deviations are subtracted from the mean in the series. This will yield an MBS with a high level of confidence. This statistical model can be cast a negative shadow on otherwise strong strength values when sample sizes are low, but the variance or standard deviation is high. Statistical outliers that are not only low, but unusually high, can throw off the data set and cause high standard deviations.

Steve Fowler, the consulting statistician ran numerous statistical models on the data and results. Ultimately, he generated a 70-page report on the statistical outcome of the study. This report can be made available upon request, but the depth and scope exceed this paper. Some of the notable conclusions Fowler made were that the statistics seemed valid and the tests seem repeatable and would likely yield the same results. This conclusion affirmed statistical validity of the research. Fowler also categorized devices into categories of *SOL* devices and *fail* devices.

The researchers wanted to produce field usable SSSF tools for users. Three-sigma MBS models yielded safety factors that were too low and likely too conservative. Using the mean breaking strength could overlook half the outcomes and skew safety factors too high. For this reason, the component safety factors were determined using the lowest value of breaking strength or SOL. This seemed the most conservative and responsible course of action. If readers wish to use averages, three-sigma, or any other method to calculate their SSSFs; the data is available for them to do so.

Figure 11. is intended to represent a field applicable reference for deriving component safety factors and ultimately SSSFs for haul system PCDs. It is the culmination of this ARP, and the ultimate goal of this project. Lieutenant Walker came up with the idea to present the data using a field-friendly chart. The SSSF values presented can be referenced and lends itself to easy memorization. The figures represent the lowest SSSF of each given combination. Wilderness oriented teams tend to use 1 kN and 2 kN loads for field calculations. Fire rescue personnel still lean towards 300 lb and 600 lb loads. The researchers felt it prudent to publish both methods for field application using either accepted value for a one or two-person load.

PCD Safety Factors

1 kN= 1 Person

SOL	11mm New			12.5mm New		
		Safety Factor			Safety Factor	
Device	**SOL Min.**	**1 Person**	**2 Person**	**SOL Min.**	**1 Person**	**2 Person**
MPD	4.10 kN	4:1	2:1	8.37 kN	8.3:1	4.1:1
ID	4.47 kN	4.4:1	2.2:1	5.60 kN	5.6:1	2.8:1
Rescucender	3.42 kN	3.4:1	1.7:1	10.68 kN	10.6:1	5.3:1

Fail	11mm New			12.5mm New		
		Safety Factor			Safety Factor	
Device	**MBS Min.**	**1 Person**	**2 Person**	**MBS Min.**	**1 Person**	**2 Person**
Munter	15.72 kN	15.7:1	7.8:1	21.44 kN	21.4:1	10.7:1
Single Prusik	13.74 kN	13.7:1	6.8:1	13.87 kN	13.8:1	6.9:1
Tandem Prusik	23.47 kN	23.4:1	11.7:1	25.14 kN	25:1	12.5:1
Grip	7.06 kN	7:1	**3.5:1**	9.81 kN	9.8:1	**4.9:1**
Basic	5.35 kN	5.3:1	**2.6:1**	NA	NA	NA

300 lb= 1 Person

SOL	11mm New			12.5mm New		
		Safety Factor			Safety Factor	
Device	**SOL Min.**	**1 Person**	**2 Person**	**SOL Min.**	**1 Person**	**2 Person**
MPD	921.68 lb	3:1	1.5:1	1895.72 lb	6.3:1	3.1:1
ID	1004.86 lb	3.3:1	1.6:1	1258.88 lb	4.2:1	2.1:1
Rescucender	768.82 lb	2.5:1	**1.2:1**	2400.86 lb	8:1	4:1

Fail	11mm New			12.5mm New		
		Safety Factor			Safety Factor	
Device	**MBS Min.**	**1 Person**	**2 Person**	**MBS Min.**	**1 Person**	**2 Person**
Munter	3533.86 lb	11.7:1	5.8:1	4819.71 lb	16:1	8:1
Single Prusik	3088.75 lb	10.2:1	5.1:1	3167.91 lb	10.5:1	5.2:1
Tandem Prusik	5276.06 lb	17.5:1	8.7:1	5651.47 lb	18.8:1	9.4:1
Grip	1587.09 lb	5.3:1	**2.6:1**	2205.29 lb	7.3:1	**3.7:1**
Basic	1202.68 lb	**4:1**	**2:1**	NA	NA	NA

* Lowest System Operations Limit/Minimum Breaking Strength of selected PCD

** Walker & McCullar, (2014). *Slow Pull Testing of Progress Capture Device* s, International Technical Rescue Sypossium.

Table 9. Safety Factor Chart

Discussion

Within the scope of this research, no perfect PCD was observed or found. The same sentiments were later echoed in the 2014 edition of Hudson and Vines' *High Angle Rescue Techniques Volume 4.* Over the course of hundreds of tests, every device or hitch revealed strengths and weaknesses. Some yielded values much higher and more robust than the researchers' predictions, others proved weaker than expected. The answers that the researchers were seeking were calculated into a document that categorizes strengths into areas of *failure* and *system operation limits*. Some of the most important lessons learned were tangent to the intent of the study. Failure of a system can no longer be confined absolutely by a breaking strength. The system can fail to operate, but not necessarily fail the rope or hardware. Another element of extreme importance was the effect that rope and Prusik age had on performance.

The device types that have the most historical longevity are the Prusiks, the hard-cammed Petzl Rescucender, and the SMC Grip. Devices such as these have a historical prevalence as haul cams and PCDs dating back to the 1980s. In the earliest days of NFPA 1983 and fire service 15:1 safety factors, these were the workhorse implements in haul systems. Frank and Smith's first edition *CMC Rope Rescue Manual* (1987) discusses the advantage of such hard cams and illustrates their use in most haul systems as both haul cams and ratchet cams (PCD). This is also later reinforced in Hudson and Vines' first manual (1989). Hudson and Vines use Prusiks and hard cam ascenders interchangeably in the haul systems they present. In one of the early texts written for the fire service, Neal (1990) is on the same page as his contemporaries when it comes to rope grabs. He discusses the use of both Prusiks and Gibbs Ascenders in his text. By 1998, in a later text for the fire service, Brennan (1998) adds the Rescucender in amongst the Gibbs and the Prusiks as ratchet cam options.

The works mentioned above are a sampling of texts written during a confusing and contentious time in rope rescue, when safety proponents were advocating high safety factors such as 15:1 and less often 10:1. For the fire service, these factors were calculated using two person loads of 600 lbs. The research confirms that component safety factors of the PCDs in this study are nowhere near 15:1 when used with two person loads. The strongest PCD, the tandem Prusik, has a CLR that averages 10:1. One can conclude that when using any type of soft cam or hard cam PCD in a haul system, at no time in our history could one achieve a SSSF of 15:1. There is an overwhelming volume of literature that purports mandated safety factors of 10:1 and 15:1 throughout rescue history. The same literature demonstrated Prusik and hard came PCDs. These two philosophies mutually exclude one another.

Rescue has required technicians to tie knots, lower, and haul for a hundred years. This was true on June 27, 1980, when Frisby and Fitzpatrick fell to their deaths. Both knots and rope grabs have weakened rope for all history. For this reason, it is irrational to assume that manufactured strength will be retained when components are integrated and used in systems preferred by rescuers. This study will indicate that the only way to maintain the integrity of both the rope and the PCD is to use an engineered device that will slip or clutch when overloaded.

The highest factors of safety took place when calculating a one kN load on a given PCD using 12.5mm new rope. This approximately 225 lbf load is one of the smaller loads used in rescue calculations and the new 12.5mm rope is some of the strongest rope commonly utilized by rescuers. Only in this category and the instance of the tied Munter hitch and the tandem Prusiks do safety factors approach 15:1. If the author's intent years ago was to advocate or spread the message that 15:1 safety factors were applied to the raw manufactured rope alone, then they would have been correct. But authors that took this further and advised a 15:1 SSSF on rope systems that included haul systems, got it wrong. The group within this literature review that took this position in their works include Neal (1990), Padgett and Smith (1996), Ray (1997), IFSTA (2005), the NASAR FUNSAR Manual (2005), and Briggs (2013).

Some authors were in a position where their texts were written for a more wilderness oriented audience, but they reported the efforts and intent of the fire service during this time. Some authors' works clearly evolve with the prevailing research and best practices over time. This evolution can be seen in the works of James Frank, Hudson and Vines, and Bruce Smith. None of these authors ever fully seemed to embrace to the concept of 15:1 beyond a CLR, but their works reflect progressive research and exploration into this great misunderstanding within the industry.

A more currently and widely accepted SSSF for the fire service in modern literature seems to be 10:1. A 10:1 SSSF seems to be the upper reasonable limit for systems according to Smith's later course manual (2008), James Frank's *CMC Rope Rescue Manual 3rd Ed.* (1998), and Mathews' (2009) fire service oriented manual. This work has affirmed that even a 10:1 SSSF is difficult to attain as the SOL limits and CLRs range from 2:1 to 9.4:1 when used with assumed 600 lb two person loads. Despite this discrepancy, there does not seem to be a fundamental problem with the systems and techniques used by rescuers. There is no pile of bodies, or scrutinized manufacturer, because of weak rope or inadequate PCDs. What rescue teams and the fire service have been using for years seems to work. Some of these hitches and devices used for capturing progress span decades. Most teams also use a wholly independent back-up or safety line system. What people have been doing works, but a chain is only as strong as its weakest link. It seems at no time in modern rescue systems, did haul systems maintain a 10:1 or 15:1 SSSF. If a single Prusik hitch works fine as a haul system PCD with a 5.2:1 factor of safety, then why does the fire service gravitate towards 9000 lb 12.5mm rope rather than lighter 6400 lb 11mm rope that would yield a 7:1 factor of safety when knotted?

Interpretation of the Results

Each device or hitch had distinctly different behaviors. Some of them really shook the foundation of preconceived notions that many rescuers hold dear. These preconceived notions that have been passed down over generations include high SSSFs, the clutching ability or Prusiks, and the holding power of single versus tandem Prusiks. The age of accessory cord and rope also proved to be a major contributing factor in the study.

Single Prusiks

As a single unit PCD, the Prusik demonstrated very high holding power in the mid-teen kNs. Several modes of failure were observed. Older Prusiks had a tendency to suddenly break in the bend of the rope at the SMC Light Steel carabiner. New Prusiks failed primarily in two ways. They either desheathed the rope, resulting in a loss of confidence (LOC), or they suddenly broke in the loaded strand under the Prusik bridge that was closer to the anchor. Though at high force values; of the three types of breaks, two modes occurred with little warning and would result in the load falling to the ground. The loss of confidence failure involved the Prusik marginally slipping and stripping the outer sheath off the rope. Of the slips that were observed, most were only 2-3”. There were two instances of slips up to 4” and one close to 8”. These behaviors were not interpreted as positive clutching behaviors, but rather an indication of preeminent catastrophic failure. The old Prusik cord ranged in age from four to ten years. The newer Prusiks had a slight tendency to break under the bridge. The older cord seemed to break at the bend in the carabiner.

Some clutching behavior was observed in two of five instances pulling single Prusiks on 11mm Extreme Pro with Unicore technology. This was the rope with sheath bonded to core. It is unknown if this behavior was attributed to nylon Prusiks pulling on a polyester sheath, or the Unicore technology. Either way, these two instances were anomalies from the nylon Prusiks pulling on nylon EZ-Bend rope.

Tandem Prusiks

Contrary to much literature and anecdotal, the tandem Prusiks exhibited very high holding power. This combination was the strongest of the study and nearly increased strength over singles two-fold. In most instances, the shorter Pusik, closer to the load, took more of the load. Failures occurred in similar modes to the singles. Prusiks broke in the loaded stranded under the bridge. They broke in the bend around the carabiner and they desheathed the rope. Often there would be combination of the two behaviors such as one Prusik breaking and the second desheathing the rope. Desheathing occurred in instances on both the long and short Prusiks. Any perceived slipping, only ranged most often from 2” to 4”. The combination of old Prusiks on 11mm rope produced some longer slips in the 1 ft. range. Some of the distance attributed to slipping was also believed to be stretching of the rope, tightening of the Prusiks, and the Prusik “knuckles” “wringing” and tightening around the rope. The common fire service combination of 8mm tandem Prusiks on 12.5mm rope yielded very limited ability to clutch and slip distances of 4”to 6”.

Smith’s (2008) course manual advises there is little difference in the slip rate between single and tandem Prusiks. The range cites is 7-9 kN for singles and 7.5-10.5 for tandems (p.8). Thorne and Olson’s manual (1994) shows the breaks as 9.01 kN for singles and 10.51 for tandems (p.A-5). An obscure Colorado rope manual retrieved from the web in 2015 cites singles clutching at 9-13 kN and tandems clutching at 10-14 kN. Due to lack of information from where these figures were derived, it is unknown if these numbers were produced with slow static pulls or through dynamic testing. In each work, however, they are being cited as a breaking strength and incorporated into SSSF analysis. The findings of this research indicate that adding a Prusik almost doubles the holding power in slow pull applications of 6” per minute.

Mike Brown’s (2000) manual discusses at length Prusiks slipping and clutching as a positive and useful tool for rescuers. Clutching is portrayed as an indicator of overloading the system. There are many authors over the years that have discussed Prusiks ability to clutch in this context. Discussions on Prusik behavior should definitely be divided into instances of dynamic testing and static tests. Any mixing of the two types of tests leads to confusion. Hudson and Vines (2014) state that Prusiks are if anything unpredictable. This seems to be consistent with the findings of this study. A fire service author, Jeff Mathews (2009), argues that when a Prusik begins to slip on a host rope it is an indication of extreme overload. Mathews does advocate using tandems over single where concern or overloading is possible. In this study, Prusiks were just as likely to break without warning as slip a small amount then fail. Having lives hanging in the balance, counting on the clutching behavior of Prusiks opposed to failure, seems imprudent given the results of this testing.

The tandem Prusiks on Extreme Pro 11mm yielded odd behavior once more. In four of five pulls, the tandem Prusiks would stretch until the long and the short would bump against each other. They then slid down the rope for a duration of five minutes. This was the closest instance of clutching or force-limiting behavior seen in Prusiks.

Petzl Rescucender

The Rescucender is a front-runner in the category of hard cams that have a shell that wraps around the rope and a cam that rotates on an axel pinching the rope. A similar cam action can be found in the SMC Grip and various models of the Gibbs Ascender. The Rescucender is a “one model fits both rope sizes” device. Statistically, the Rescucender emerged as a device that displayed a system operation limit (SOL). The Rescucender slipped on all host ropes with the exception of the well used seven year old 12.5mm rope. The standard deviations were very small, indicating very predictable behavior. This behavior seemed consistent with Bruce Smith’s (2008) text where he discusses Rescucenders slipping on 11mm rope at 4 kN. With a 2 kN or a 600 lb two person load, the SOL safety factors with this device are very low ranging from 1.2:1 to 1.7:1. The Rescucender would be an unfavorable option in hauling extremely heavy loads that must be held such as US&R concrete loads. It does demonstrate the exceptional ability to slip and clutch, with the exception of older rope. The holding power of the Rescucender nearly triples when applied to 12.5mm rope as opposed to 11mm. The Extreme Pro had values that were between the 11mm and 12.5mm EZ Bend.

This test series was one of several indicators of the fatigue or stress of the older rope. The new12.5mm rope, which fills in more surface area of the Rescucender held to 11.5 kN and slipped continually. The same size old rope desheathed 100% of the time at an average lower of 10.5 kN. This makes a strong case for software management and rotating ropes and accessory cord. It also makes a case that some failures are caused by the device or hitch, while other failures can be attributed to the host rope.

SMC Grip

The SMC Grip is similar in function to the Rescucender. The Grip desheathed all new rope samples. Given the limited supply of aged rope, further testing on the Grip with aged rope was scuttled. The Grip held higher values in the 11mm category than the Rescucender, but was categorized as a fail device. Two of three units were deformed during testing as the axel pin was bent. Despite the similarities to the Rescucender, the peak values of the 11mm and 12.5mm were much closer. It is noteworthy that the lowest desheath values of the Grip to place on the 11mm Extreme Pro.

Munter Hitch

The Munter hitch was very limited in its testing and application due to the nature of the tie-off. When used as a PCD, the Munter is held with two hands and operated in the open and untied position. One of the areas that illuminates other parts of the research involve the strength loss due to age. When tied off, the Munter's failures are similar to that of knotted rope. When the old samples are compared to the new, a significant strength reduction can be observed. The 11mm old broke 21% lower than the new. The 12.5mm old broke 35% lower than the new. This helps explain the poor behavior of the older ropes, especially the 12.5mm in camming devices. As a side note, the strength and manner of failure between a slipped half hitch tie-off and a Munter mule tie-off yielded equally comparable strengths and modes of failure.

CMC MPD

The MPD was the newest device tested. It is touted as a PCD, belay device, and lowering / descending device. The MPD tested very favorably as an SOL device. The device exhibited high SOL values and low standard deviations. The MPD comes in two models- one for 11mm and one for 12.5mm rope. During the last run of five on old 12.5mm rope a desheath was observed. An additional five runs were performed with old 12.5mm rope resulting in two desheaths and one core shot. This would lead researchers to revisit the MPD and Petzl I'D with more moderately used 12.5mm rope. Later 12.5mm runs would yield five more pulls none of which resulted in a desheath.

There was no difference in observed values with the MPD's parking break on or off. Similar to the Rescucender, values of the 11mm Extreme Pro fell in between the 11mm and 12.5mm EZ Bend. When contrasting the MPD and the I'D, the gap in values between the 11mm and 12.5.mm rope was larger in the MPD. Also the values resulting in the three instances of desheating in the MPD were higher than those of the same rope in the 12.5mm I'D.

Petzl I'D

The Petzl I'D proved to be another SOL device. It too, comes in two models for 11mm and 12.5mm rope respectively. The I'D proved more aggressive than the MPD on the old 12.5mm rope. The tests resulted in 100% desheathing of the old 12.5mm rope. The SOL values fell in between the two other SOL devices, the Rescucender and the

MPD. The holding values between the 11mm and 12.5mm variations were much narrower than the I'D. The Extreme Pro held the highest SOL values in the I'D.

The failures of the old 12.5mm rope in the I'D was another indicator of the consequences of older used rope. It is important to note here that all the old rope was in service and passed inspection immediately up to the testing. There were no physical or visual indicators the rope should be retired. The three year old 12.5mm rope that had been subjected to one season of training use tested more favorably in both the I'D and the MPD.

Petzl Basic

The Petzl Basic was an impromptu bonus at the late stages of testing. The device is a toothed cam chest ascender that is very rarely used in taught rescue systems. There is product literature from Petzl that shows the device being used as a PCD. This practice is more common with one person loads in cave and mountain rescue in Europe. Each climber or caver has this type of device on their person, so it is a natural option for minimalist rescue techniques. The new model device is made for 11mm ropes. It tested consistently near 5.5 kN, and all pulls on EZ Bend resulted in a desheath. Though not a common practice, the CLR of a Basic with a 1 kN load is higher than the CLR of a single Prusik with a 600 lb load.

One unusual aspect of the testing with the Basic occurred when paired with the Extreme Pro. The first Basic unit lasted 10 pulls on the new and old 11mm EZ Bend. When this unit was pulled the first time on 11mm Extreme Pro, the unit shattered. Without units, the last pulls of the Extreme Pro would be performed on the second test date. With new units, each initial pull would result in a desheath on the Extreme Pro. The second time Basics were tested resulted in failure every time. The devices passed visual and tactile inspection before reuse. This illustrates that sometimes, compromised integrity in a piece of hardware shows little signs of impending failure.

Age of Software

The age of the rope and software provided another area of interest and concern. Disparate instances between new and old were seen in nearly all series of tests. They revealed themselves in the Prusiks, camming devices, and tied-off Munter hitches. Figure 12 shows the strength losses in the Prusik series. The manufacturers recommend retiring

11mm Rope		
8mm Single Prusik	**Peak KN**	**Peak Lbf**
New Rope Average	14.13	3175.52
Old Rope Average	10.89	2446.95
	-23%	
8mm Tandem Prusik	**Peak KN**	**Peak Lbf**
New Rope Average	24.26	5452.75
Old Rope Average	17.23	3873.30
	-29%	

12.5mm Rope		
8mm Single Prusik	**Peak KN**	**Peak Lbf**
New Rope Average	14.82	3332.44
Old Rope Average	11.18	2513.71
	-25%	
8mm Tandem Prusik	**Peak KN**	**Peak Lbf**
New Rope Average	26.98	6064.65
Old Rope Average	19.94	4482.79
	-26%	

Table 10. Strength Loss Due to Age

Software regardless of use after 10 years from the date of manufacture. This information can be found on PMI's website along with other rope manufacturers. Hudson and Vines (2014) explain nylon's preference in rope making because it is resilient and relatively inexpensive. In their 1989 work, they also make mention that rope is a relatively inexpensive tool and should be readily replaced when in doubt. In his course text, Bruce Smith (2008) suggests that as a rule of thumb, nylon ropes lose 2% of their original strength per year. This number seems consistent with this study. The variability on this topic is extreme because each rope is used and treated differently over its lifespan.

It is important to note that 8mm accessory cord used to form Prusiks is woven very differently than its host kernmantle rope. The sheath on accessory cord is woven very loosely to create a supple hand. Life safety rope's sheath is woven tightly and keeps foreign objects out of the core. This trait offers more internal protection for life safety rope than for accessory cord or Prusiks.

PMI 11mm Extreme Pro

There was too much extreme behavior to make any broad generalizations about the Extreme Pro. More testing is required. It does not behave in the same manner as conventional kernmatle ropes. Despite its Unicore technology, it can be desheathed. In holding values, it tends to hold higher than 11mm EZ Bend and sometimes higher than the 12.5mm. It typically held to higher values in SOL type devices. It typically failed lower in the devices prone to failure. It is unknown whether some of the differences of behavior should be attributed to the Unicore construction or the polyester outer sheath. One of the most notable properties of this 11mm rope, which was outside the context of the study, was that the manufacturers' published MBS is over 8400 lbf. This means the rope is small, but has nearly the strength of the 12.5mm rope favored for so long by the fire service. It is worth noting, the statistician's report and researchers anecdotal observations both confirmed the PCDs in this study performed most desirably in all the 11mm rope. The 11mm rope performed better in the hardware devices that fit both rope sizes and the hardware that was sized specifically for the rope.

Organizational Implications

This research project proved very influential in both reshaping and validating the several of the researchers' preconceived beliefs. The goal was certainly achieved. The body of work gives instructors a tool to explain to students exactly how a PCDs' component to load ratio (CLR) affects the SSSF of the haul system. The chart in Figure 11 has been made into a 3"x5" laminated tool for field evaluations. The literature review within this body of work, contrasted with the results of the research, gives instructors context to explain the evolution and use or misuse of SSSFs in rescue. To understand the course and direction of a discipline such as rope rescue, instructors must understand appreciate the history of the field.

The Mississippi State Fire Academy (MSFA) will increase its attentiveness to the age of software, especially Prusiks. MSFA training rope typically is used up and retired well before it reaches ten years of age. More attention will be given to cycling Prusiks in and out of service at more frequent intervals.

The merits and disadvantages of PCDs is also ready to be put to use. The researchers' agencies would definitely use tandem Prusik PCDs for heavy rigging and US&R applications. In applications where early, but safe overload warning is warranted, the researchers' agencies will be inclined to use one of the SOL type devices.

For the MSFA and others, this research should constitute a paradigm shift away from SSSF in contexts of absolute breaking strength values. Now systems can be rigged and engineered with true force-limiting characteristics that lie within a safe range of values rather than a single figure leading to catastrophic failure. This type of rigging with intent, is a relatively new frontier in high-angle rescue. With readily available devices that can provide these type of predictable clutch behaviors, the need to rely on the unreliable clutching behavior of Prusiks is mitigated. This line of thinking will continue to be woven into the instructional methodologies and philosophies of the MSFA. Concepts such as this can safely alter and adjust the ways that tensioned rope systems, such as highlines, are tensioned and managed. The tension in conventional highlines, over the last 30 years, has been held by Prusik PCDs. Today the results of this research may inspire teams to consider transitioning to I'D and MPD PCDs.

Recommendations

Clutching Prusiks

Under the test conditions given a static pull of 6" per minute, the results of this research strongly indicates that Prusiks cannot be predictably or reliably counted upon to slip and regrab in a manner consistent with "clutching." There were some tests where Prusiks would slip incrementally and regrab in keeping with literature such as Brown (2000) and Mathews (2009). More than half of the test series involving new Prusiks on new rope resulted in sudden catastrophic breaks in the Prusik loop under the bridge of the Prusik hitch. These breaks often took place with little of no warning and no behavior that could be associated with "clutching."

The Prusiks did display remarkable holding power in both single and tandem configuration. It was the observation of the researchers, that Prusiks that appear to be slipping is a strong indication of imminent failure and not a desirable instance of "clutching" or "force limiting." Instructors and users that heavily rely on this "clutching" or "force limiting" behavior of Prusiks should use extreme caution and consider further investigation or even suspension of this ideology. This rings especially true in a world where more reliable, engineered, clutch PCDs are readily available.

Safety Factors

In PCDs that have a tendency to fail, it is recommended that users use a 5:1 or higher safety factor. It is possible to engineer other parts of the rope system to a higher safety factor. The PCD may be allowed to have a lower safety factor due to the nature of its use and its temporary tasking on the rope when resetting haul systems. This consideration also takes into account the fact that the PCD, once loaded, is under a static load and not likely to be subjected to any shock-loading.

In the case of PCDs that have a tendency to reach a system operation limit (SOL), it is recommended that the SOL be at least 1.5-2 times the anticipated static load. This margin is enough to account from minor dynamic factors that could lead to small increases in system force. The SOL devices are ideal in applications where true clutching behavior is needed. Such applications include tensioned rope systems.

Software Age and Retirement

The impact of the age of nylon software ended up bearing a significant role in the performance of the PCDs in this study. Importance of the age of rope, accessory cord, and software management proved to be one of the biggest lessons of this research. Older Prusiks had a notable lower breaking strength than new Prusiks. In light of this study, it is recommended that Prusiks be changed out and retired regularly, based on use patterns. If Prusiks are well used and see more than just a few days of service a year, users should consider annual replacement cycles. Organizations such as trainers that see even more use in austere and soiled conditions may even consider bi-annual replacement of Prusiks.

The age of rope also proved an important factor. Most manufacturers of nylon software instruct buyers to retire rope, webbing, and accessory cord products ten years after date of manufacture. This is regardless of use. This information is readily available within product instructions on manufacturers' websites such as PMI. The oldest rope in the testing was a 12.5mm rope that was seven years old. The rope had seen significant use and service every year, but passed inspection and appeared ready for use. This rope did not perform well in many PCDs. Even PCDs that statistically proved to be SOL devices performed poorly on this seven year old rope. The rope desheathed in the I'D and the Rescucender in 100% of the pulls. The rope had three desheaths and one core-shot in the MPD during ten pulls. In later testing, a three-year-old rope with one year of moderate use performed well and achieved clutching SOL behavior in the I'D and MPD.

The fire service is notorious for holding on to tools too long and skirting manufacturers' recommendations. It is essential that organizations implement proactive gear management systems and protocols. Ropes that are seeing heavy use in institutions, such as training organizations, should evaluate replacing ropes on shorter intervals. It is very possible that ropes that see a significant amount of use should be replaced on intervals every five years.

Recommendations for Further Research

With every question this study answered, several more questions and areas for future research were discovered. The testing was limited by time and the budgeted amount of rope. It was easy to obtain new rope from manufacturers, but difficult to supply the needed amount of used rope. One area of future research is the expansion of the devices tested within this study. These devices could include ratcheting pulleys, Gibbs Ascenders, and smaller Prusiks on smaller ropes. These small 5mm Prusiks on 8mm lines are often found in small 4:1 block and tackle systems referred to as sets of fours.

Feedback from several users, as well as CMC and Petzl, suggested testing ropes with a higher carrier sheath construction. The higher carrier sheaths are typically less abrasion resistant, but are more supple and have a softer hand. This would also open up testing to more varied rope manufacturers.

One of the most eye-opening areas of the study revolved around the age and degradation of Prusiks, nylon rope, and potentially webbing. This should focus on heavy use organizations that provide training such as those represented by the researchers. Ten-year life cycles may certainly be too long for high use ropes. The events that lead to the degradation should be explored. It would be beneficial to understand of the degradation of strength were due to steel, knot, and aluminum use, cyclic soiling, exposure to sunlight, washing, or other variables.

One last area of examination worth studying is the relationship between the PCDs and the polyester sheath of ropes such as the Extreme Pro. The Extreme Pro demonstrated very different behavior than the nylon EZ Bend. Experiments could be performed to discern the behavior of nylon Prusiks on polyester rope versus nylon Prusiks on nylon rope. The two materials have different physical properties including melting point. More practitioners are using polyester ropes for specialized applications.

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