

SCIENCE VERSUS THE MOUNTAIN
AN ANTHOLOGY OF CLIMBING EQUIPMENT

by
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On a warm, June afternoon my partner and I crested the top of Crescent Crack, a gorgeous granite rock climb in Little Cottonwood Canyon. We gazed above us at the next formation. The Coffin loomed above, aptly named not because of a grim history, but because of the six-sided rock roof above that assumed the shape of its namesake. An inviting hand and finger crack spanned vertically the mottled granite face that stretched out below the coffin-shaped roof. Neither my partner nor I wanted to stop for the day, and we soon concurred to continue climbing, rather than to take the available descent route. The weather was great, and having climbed the Coffin before, I knew it was a superb route. Soon we were on our way up. I rhythmically secured my hands and feet in the solid, beautiful crack, absorbed in the movement and nuances of the climb. I had climbed numerous times before with my partner, who was down below belaying me (passing a rope through a device ready to hold a fall). I had complete trust in her attentiveness and ability to hold my weight should I fall. The climb was sustained and enjoyably challenging. Soon I reached the base of the roof, and while hunching over, I underclinged the crack between the roof and the wall. I lackadaisically fumbled with my equipment, aiming to secure a new point of protection at the roof. What came next took me by complete surprise.

On another route, about twenty feet to my right, was another climber finishing his climb. I enjoyed a few words with him as I selected my next piece of gear, and together we admired the qualities of the wall. I thought about my previous visit to the Coffin, which yielded no surprises or undue difficulties, except for the mountain goat that met us on the way down (which had intimidating horns, and would not leave us alone). I felt comfortable on my last visit, and perhaps this next time I grew too comfortable. Just as I was about to place my gear, my foot lost its purchase below me, and I pitched off the top of the route. I had no time to think about anything, no scenes from my life flashed before me. All I experienced was an adrenaline reaction, and I subverted to a then-instinctive response to falling. I pulled into a cat-like stance to avoid injury on the way down. A few seconds later, and over 30 feet lower, the rope pulled tight and my downward progress came to a firm, but not wrenching halt.

What caught me? What mechanical system ended my flight toward the ground? Why was I not concerned about falling? I was not concerned about falling for the same reason that other climbers around the world have not worried much about falling lately. Falling safely has actually become a frequent occurrence in climbing. Some climbers have even advanced the standards of technical difficulty due to this confidence. Climbers and engineers have applied modern technology to the realm of mountaineering, and in the last century the sport, dare I call it just a sport, has been revolutionized. The technology introduced to climbing has profoundly changed climbing in ways supremely beneficial to the climber, to the environment, and to the sport itself without removing any of the subtle, intrinsic qualities that make the sport what it is. Risk is still inherently tied to climbing, but modern equipment enables climbers to manage their risk to acceptable levels, and has freed climbers to focus on difficult moves and to push their physical limits, rather than troubling over whether they are safe or not. When my fall came to a stop that June afternoon, my appreciation for modern gear grew to a new level. After a moment of rest, I brushed myself off and resumed climbing. No harm done.

This paper will explore technical developments of a few select categories of climbing gear. To begin to appreciate these advances in climbing equipment, one first must understand the fundamental physics principles relating to the mechanical climbing belay system. The purpose of this system is to non-destructively halt the descent of a falling climber. Before a climber falls, he/she has potential energy by nature of vertical position. As the climber falls, this potential energy is converted to both kinetic energy (due to downward velocity), and to heat (due to air resistance). A mechanical climbing belay system must absorb this remaining kinetic energy. To find its magnitude, we begin with Newton's second law so we can find a falling climber's velocity as a function of the distance fallen. Then, with this velocity, we can calculate the kinetic energy possessed by the climber after falling a particular distance.

Two forces act on a falling climber: his/her weight pulls down and the drag force due to air resistance pushes up. Summing these forces, we find:

$$\sum F = ma = F_{weight} - F_{drag} = mg - \frac{1}{2} \rho AC_D V^2$$

Then by the chain rule, we find that the distance fallen is expressed by this integral:

$$X = \int_0^{V_f} \frac{V dV}{2mg - \rho AC_D V^2}$$

After evaluating this integral and solving for V_f , the climber's velocity after falling a distance X , we arrive at:

$$V_f = \sqrt{\frac{\left(1 - \exp\left(-\frac{\rho AC_D X}{m}\right)\right) 2mg}{\rho AC_D}}$$

Where:

$g = 9.81 \text{ m/s}^2$ (the acceleration of gravity)

$m = 80 \text{ Kg}$ (the mass of an average climber, also the value used with most gear testing methods)

$C_D = 2.2405$ (the drag coefficient for an 80Kg climber in a random posture, calculated using 54 m/s as terminal velocity)

$\rho = 1.20 \text{ Kg/m}^3$ (the density of air at STP)

$A = 0.20 \text{ m}^2$ (the cross sectional area of the climber's body)

X = the distance fallen in meters (the independent variable)

Thus, we can calculate that the climber, at the end of a longish fall of about 12.0 meters, has a velocity of 15.0 meters per second. Therefore, his/her kinetic energy is given by:

$$U = \frac{1}{2} m V_f^2 = 9.0 \text{ kJ}$$

This is a rather large amount of energy. If we take the climber's fallen position to be the zero of potential energy, the potential energy before the fall is given by:

$$V_{PE} = mg\Delta X = 9.4kJ$$

We account for the 0.4 kJ discrepancy with the energy converted to heat due to air resistance.

In this case, some mechanical system, or "belay" system, must absorb 9.0 kJ in a way that limits the force on a climber. The maximum force that the human body can withstand without sustaining internal organ injury is 12kN. This value was determined through research done by the U.S. military in the 1940's (Harmston). The maximum impulse force relates directly to the portion of the energy that must be absorbed by the rope. This energy value is the difference between the kinetic energy of the falling climber, and the energy absorbed by the rest of the belay system. If we plot the force on the rope as a function of its elongation, the area under the force curve is the energy absorbed by the rope. If we know the energy the rope must absorb, we can then relate it to the force on the rope by this expression:

$$\int_0^{l_{max}} F(l)dl = U_{climber} - U_{system}$$

If the F(l) curve is steep, i.e. the rope is stiff, then the maximum force the falling climber experiences is high. If the F(l) curve has a small slope, i.e. the rope is stretchy, then the maximum force is smaller. We can also examine this force in terms of momentum. Force, by Newton's second law, is the time rate of change of momentum. If the climber's momentum falls to zero quickly, that is if a short time period is required to stop, then the impulse force will be high. If the rope slows him/her down over a larger time period, then the impulse force will be lower. There is a crucial compromise between low impulse force and low elongation. If l_{max} , the maximum elongation, is large, then it will obviously decrease the impulse force, which is good for the climber. However, a large elongation results in a longer fall and consequently in an increased risk of impact with a ledge or other underlying feature of the cliff. Testing standards include limits for both maximum force and for maximum allowable elongation to ensure a proper balance is maintained.

Belay systems have evolved over the history of climbing into a reliable, practical, method of arresting a climber's fall. In modern free climbing, climbers use belay systems as a safety back up, not to directly assist an ascent. A lead climber begins his/her ascent of a cliff tied to the climbing rope. The lead climber's partner, or "belayer", feeds the climbing rope through a friction amplifying belay device as the lead climber ascends. During the ascent, the lead climber either places pieces of protection into imperfections of the rock, or utilizes fixed gear placed by previous climbers. The climber attaches the rope to each point of protection via a carabiner, a metal snap-link. The rope slides through the carabiner and

defines a simple pulley system. This process continues until the climber reaches the top of the pitch, a section of the climb between belay anchors. If during the progress of the climb the lead climber falls, say for example six meters above the last piece of protection, he/she will fall six meters to the protection, and then six meters past the protection, for a total of twelve meters. The belayer clamps tight on the rope with the belay device, ready for the impact of the falling lead climber. When the slack of the rope is taken up, everything pulls tight, and the falling climber stops. The rope stretches some, and so the total distance the climber has fallen is actually greater than twelve meters. At the instant the rope pulls tight, the kinetic energy of the falling climber ceases to increase, and the belay system begins to absorb significant amounts of energy. In the case of a twelve-meter free-fall such as this, the belay system would have to absorb 9.0 kJ.

Many complex forces arise in a belay system while catching a falling climber. Both the force of the falling climber and the force of the belayer arresting the fall pull down on the top piece of protection. Because of frictional forces, the net force on the top piece of protection is 1.6 times the force on the falling climber, rather than double. The rope tends to a straight line between the climber and top protection, and also between the top protection and the belayer. Because of this tendency, various forces result on each piece of protection between the belayer and the top protection. If not placed correctly, gear may be forced out of place, resulting in a dangerous scenario termed the “zipper” effect. Each piece may tear out successively, placing the falling climber in peril.

The highest forces in the entire belay chain exist at the top piece of protection; therefore, that piece is liable to be the first item to fail. The strength of this protective gear is largely dependent on the strength of the rock and how the gear was placed in the rock. In the unusual case that the top piece fails, the belay rope will go slack again. Ideally, the lead climber would have employed good protection technique and secured another piece below that could hold him. The climber will fall an additional distance of twice the span between the two placements, plus additional rope stretch.

When all of the excitement is over, the climber comes to a rest, and can either resume climbing (if his pants are still dry), or the belayer can lower him/her back to the start of the pitch. The climber just experienced an awesome display of energy transformation. His/her kinetic energy increased to a level on the order of kilo joules, and then was dissipated. Where did it all go? Each component of the belay chain played a role in converting nearly all of the kinetic energy to heat. The climber’s knot, and any other knots affected by the fall, cinched tight and absorbed energy. Rope friction over various carabiners and across rock features dissipated more energy. The belayer may have been pulled up, and any increase in vertical position converts some kinetic energy back into potential energy. As the belayer arrests the climber, the rope sliding past the belay device produces a lot of heat. If the belayer allows a significant amount of rope to slide through the belay device, the event is termed a “dynamic” belay. A dynamic belay absorbs more energy than a largely static belay (a belay with little rope slippage).

Perhaps the largest player in energy absorption is the rope itself. Each rope has a characteristic ability to absorb a specific amount of energy, which is proportional to the area under its particular stress/strain curve up to the rope’s breaking point. If a climber possesses energy beyond a rope’s energy

absorption limit, the rope will fail. Because nylon is viscoelastic, the aforementioned curve will vary according to how fast a load is applied. In addition, this curve will vary as ropes get older, stiffer, and weaker- indicating that their energy absorbing capacity has diminished. When a rope is initially shock loaded, it stores energy as mechanical potential energy, like a spring. The climber/rope spring system then undergoes damped oscillations until all of the energy is converted back into heat. What energy was not dissipated by the rope must be absorbed by less desirable means, such as plastic deformation of equipment in the belay chain, or deflection of the falling climber's body. When the climber comes to a rest, the rope is stretched under the climber's weight, and hence some energy remains stored as mechanical potential energy. The sum of this mechanical potential energy, the belayer's increased potential energy, and any energy absorbed in plastic deformations, is the only energy not converted to heat. With so many variations possible in a climbing situation, it is impossible to pigeonhole a specific percentage of energy absorption to each component of the belay chain (Harmston).

Now, with a scientific understanding of a climbing belay system, we can define the ideal functioning of some pieces of climbing gear in the belay chain, and understand testing techniques that quantify performance values. A climbing rope ideally will absorb any amount of energy a falling climber is capable of producing. Through the whole ordeal of arresting a fall, a rope must remain in its elastic deformation regime to escape any permanent damage. A rope that stretches to absorb energy over a significant distance will reduce the impulse force. Modern ropes possess this revolutionary characteristic of a large energy absorption capacity. Not only is this reduced force less harmful to the falling climber, but also the protection is also more likely to hold its purchase in the rock. A rope should be supple enough to handle, knot, and clip easily. In addition, a rope should be durable, maintain its strength over time, and resist cuts and abrasion.

The purpose of rock climbing protection, or gear placed into the rock by a climber, is to provide a secure point of attachment to a rock face. It must be safe, and be strong enough to withstand the forces of a fall. It should be multi-directional, or capable of holding a fall in many directions. Often, the top piece of protection is the weak link in the belay chain. The top piece is subjected to a force 1.6 times the magnitude of the force the falling climber experiences. In addition, the strength of its placement is dependent on the hardness and friction characteristics of the rock surface. The strength of a placement is also largely dependent on the skill of the climber who secured it. Protection should not exert excessive expansion forces on the surrounding rock, especially if a particular piece is used in a rock flake or in very soft rock. Expansion forces are the normal forces pushing outward on the rock, and are high, for example, when a wedge-chock with a very small taper angle is used (The Mountaineers 205). If expansion forces are excessive, the rock may deform to the point that the placement will fail. Protection should be simple to place, and even usable in blind placement situations. Protection should be easily retrievable. Gear should be lightweight enough to carry while climbing. Individual pieces that are versatile enough to use in multiple ways also reduce a climber's load because they reduce the amount of gear needed to protect a climb.

Protection should be durable, resistant to the elements, and provide years of safe use. In addition, according to Chris Harmston, the quality assurance manager for Black Diamond Equipment Limited, appeal to climbers plays an important role in the design of gear. Visually, gear needs to have the right proportions and colors, as well as exceptional functional qualities, to be marketable.

The primary function of a belay device is to amplify the friction of a belayer's clenched hand, enabling him to hold a fall of substantial force. Most people are capable of easily holding 50lb of force on a climbing rope (The Mountaineers 135), so a belay device would ideally amplify this holding ability to the level that would hold a fall of average magnitude. A belay device should not have features, such as small radii edges, that could damage a rope. It should have strength sufficient to hold a fall, and consist of enough material to adequately dissipate heat (generated by absorbing some of the falling climber's energy) so that the device does not become untouchably hot under normal conditions. A belay device needs to allow the belayer to have smooth, precise control of the rope for lowering a climber or for rappelling. A belay device should be usable with a variety of rope diameters, and even accommodate twin or double ropes for either climbing or for rappelling. Finally, an ideal belay device would not produce twists or snarls in the rope as it advances through the device.

Carabiners are the ubiquitous linking device used throughout the belay chain. They are used as a pulley with a rope sliding through them, as a link in belay anchors, to attach belay devices to a belayer's harness, as a method of organizing gear, or even as key chains. As with the top piece of protection, the carabiners linked to that top piece must also be capable of withstanding 1.6 times the force of the falling climber. Their diameter must be large enough to prevent rope damage when loaded. Carabiners should be light in weight, and easily operated by hand. Gate design should ensure that the gate remains closed while loaded since an open gate drastically reduces the strength of a carabiner. Carabiners used for clipping the climbing rope into protection should have a large clearance between its opened gate and its respective striker. Wide gate clearance facilitates efficient rope-clips. A climber that has to fumble with difficult gear is at increased risk for a lead fall. Delayed rope-clips easily unsettle a climber, because his/her fall will be at a maximum should a slip occur at such a critical stage.

In the past, UIAA standards were used to determine if equipment was safe. They included such methods as drop tests for ropes, and charpy tests for carabiners (The Mountaineers 133). More recently, manufacturers utilize CEN standards to test their gear (Harmston). Many manufacturers now submit their products to independent lab testing (USHBA) and even send their products to Europe for objective results. CEN standards "exist for every item in the belay chain" (Harmston). Some strength standards are as follows: harnesses- 15kN, carabiners- 20kN (closed, major axis) 7kN (open, major axis) 7kN (minor axis), active cams- 5kN, and passive chocks- 2kN.

Ropes are a very complex and dynamic piece of equipment; simple static breaking-strength tests are not sufficient to ensure safety. To exercise their functional properties and to accurately quantify their performance, ropes are subjected to drop tests. CEN drop tests employ a fall factor of 1.7, a static belay, and an 80 kg steel weight. The fall factor is the ratio of the length of the fall to the length of the rope above

the belay. If more rope is out, the fall factor will be lower, more rope is available to absorb energy, and the fall force is proportionally lower. Often, a long fall at the top of a route will generate lower forces than a short fall at the beginning of a route due to the corresponding difference in fall factors. The maximum fall factor in lead climbing is two (The Mountaineers 91). The CEN drop test results in an extraordinarily hard fall. On the first fall, the force must not exceed 12kN (the maximum a human can withstand). The rope is allowed a five-minute relaxation time, since nylon requires ample time to recover from strain. Without relaxation, work hardening would reduce the energy absorption capacity and the breaking strength of a rope. The rope must then successfully hold four identical falls without breaking, for a total of five severe falls (Harmston).

Metal components are subjected to slow, tensile strain tests. Impact testing would not yield any useful results, since climbing falls do not produce an impact situation relative to metals. A material exhibits impact behavior only if the load is applied within a critical time value. This critical time value relates to the inverse of the speed of sound through the material. For metals, this is on the order of microseconds. The impact time of a falling climber is on the order of tenths of seconds, or even longer, so metals behave about the same holding a climbing fall as they do in a tensile strength test (Harmston).

A surprising fact in climbing gear design is that no item is engineered with a factor of safety greater than one. Some industrial critical applications require a factor of safety of up to three. Chris Harmston emphasized that a climber's technique in using climbing equipment, not the gear's factor of safety, keeps a climber safe. Experienced climbers do not rely on a lone protection placement if others are available. Placing protection on lead is truly an art, and the discussion of the seemingly endless illustrations of wise protection technique is certainly beyond the scope of this article. To summarize, even though extensive testing is performed to ensure safety, gear is only as safe as the user. Incorrect applications, worn gear, and climber inexperience are more significant detriments to a climber's safety than a minimal factor of safety in design. If engineers designed gear to perform against any foreseeable situation, it would be so bulky and heavy it would be unusable as climbing equipment.

According to Chris Harmston, the development of modern dynamic climbing ropes is the most significant advance in mountaineering technology in recent history. These new kernmantle (core surrounded by a sheath), nylon ropes have revolutionized the climbing world. They enable climbers to lead desperate routes boldly, without fear or concern that the rope might break. John Long, an accomplished climber and author, commented on these miracle ropes: "Though there have been isolated cases of ropes being cut over sharp edges or chopped by rock fall, *a modern climbing rope has never simply broken from the impact of a fall.*" (Long 64). In other words, a falling climber is not capable of generating enough energy in a fall, even in a fall the whole length of a rope, to exceed the energy absorption capabilities of a modern climbing rope. Long also humorously illustrates how severe the tests are that ropes are subjected to. He says, "...the UIAA test is more severe than any fall you could possibly take in the field (due to the high fall factor and perfectly static belay). Indeed, the UIAA simulated fall is so severe it's about like tying

off a dairy cow and marching her off the cliff's edge for a 300-footer." (Long 65). I am not aware of any scientific studies involving hurtling Holsteins, but Long pointedly illustrates the effectiveness of modern ropes.

So, what did climbers do before modern, dynamic ropes? A variety of options was available. In 1864, a climber could choose from ropes made of hemp, flax, cotton, manila, or sisal. In 1864, most climbers preferred hemp. Soon abaca manila, treated with oil, became the most popular climbing rope because its long fibers rendered it stronger than the alternatives (Wheelock, 5-6). Natural fibers, however refined they may be, still have curbed the progress of climbing. Early on, the golden rule of climbing was "The leader must not fall!" These ropes simply could not reliably hold a significant lead fall. Rope strength did increase marginally, and climbers adopted dynamic belays. A dynamic belay, when the belayer allows increased rope slippage, absorbs a higher amount of energy, decreasing the force on the rope. Lead falls became feasible, and the new adage was "The rope must run!" Though a dynamic belay made lead falls on these archaic fibers possible, it does have its drawbacks. If a fall were to catch an inattentive belayer by surprise, his natural reaction is to brake with full force, removing any semblance of a dynamic belay (The Mountaineers 133-134). A dynamic belay requires full and focused attention from the belayer. Decreased force from a dynamic belay comes at a price, however. Allowing the rope to run increases the length of the fall, increasing the probability of impact with a ledge or other obstruction, which may result in climber injury.

At the onset of World War Two, manila ropes were still in use, but a revolution was in the works. A few years before, in 1935, a team headed by Dr. Wallace Carothers at Du Pont, succeeded in their object of seven years of research: the development of nylon 6,6. In 1939, nylon became available for retail sale, though not as climbing ropes until 1942 (Kotz, Treichel 526; Wheelock 6-8). Soon after nylon became available, all production was diverted to military needs. It was not until 1952 that nylon became available again for civilian use. The first twisted-nylon climbing ropes were an epiphany to the climbing world. They changed everything! Even these early nylon ropes were twice as strong as manila (Wheelock 7), and more abrasion resistant. Manila has only one-quarter the elongation of nylon. For this reason, manila ropes have a much higher shock force than does nylon. Suddenly, with the advent of nylon ropes, climbers could take falls, without a dynamic belay, that would have certainly snapped earlier manila ropes. The rope must run theory passed into history (The Mountaineers 134). Nylon ropes became the standard during the climbing boom of Yosemite in the late 50's and early 60's.

The world of climbing changed with nylon, but even more advances were still to come. Twisted rope construction had its shortcomings. The outer surface was rough, easily abraded, and subject to the elements. Unfortunately much of the strength was found in the outer surface, hence abrasive wear to the surface due to extended use weakened these ropes. The fibers were still relatively short, a significant factor in rope strength. The introduction of modern, kernmantle ropes again changed climbing. Kernmantle ropes consist of a core of nylon fibers that run the entire length of the rope, jacketed by a braided nylon sheath. The fibers are heat treated to give the rope optimum energy-absorbing characteristics (Harmston). Such

long fibers allow for a tremendously strong rope, packaged in a small diameter. These new ropes are an additional 50% stronger than early twisted nylon ropes (Wheelock 8). The outer sheath protects the inner core, where most of the strength of the rope exists. The sheath also prevents rock crystals, which can readily sever nylon fibers, from contacting the core fibers. The smoother, outer sheath reduces rope drag through a belay system, enabling the lead climber to ascend more freely. Initially, the standard nylon rope length was 120 feet. During the Yosemite era, the standard length became 150 feet. Currently, ropes are commonly available in lengths of 165 ft (50 meters), or 200 feet (60 meters). Even with all of the superior features of kernmantle ropes, they still have limitations. Nylon loses strength with use, up to 20% after 100 days of use (Wheelock). Ropes subjected to hard falls and to the elements lose some of their elasticity, resulting in lower energy absorbing capacity and in higher shock forces. Climbers should keep a history log of their ropes usage to determine when to retire them.

A principal object of a belay system is to secure a falling climber to a cliff by some means. Over the course of this century, the methods of accomplishing this purpose have changed considerably. Before the 20th century, the belay method consisted of a strong lead climber who ascended a pitch without any belay, who then lobbed his rope down to his/her climbing partners. The lead climber assumed a solid stance, and braced against the force of his followers using the rope to assist their climb (Wheelock). This method provides only a modicum of security, and is obviously only useful in terrain the lead climber is very confident in. A hip belay is a slightly more advanced belay technique. Once in a suitable, low profile stance, the lead climber can pass the rope around his hips to take up slack as his climbing partner ascends. If the follower falls, the lead climber arrests his fall by extending his arms to lock his elbows and clamping down on the rope with his hands betwixt his knees. Today the hip belay is still taught and used, especially in areas where very long routes of a low-angle prevail. The hip belay has the advantage of being very efficient, and uses a minimum of gear. It is an essential technique for climbers of today to know, for if they find themselves with insufficient gear by some incident they must have the skills to move safely across technical ground.

The above two techniques have one thing in common, their method of attachment to the rock. They both rely on a climber's stance in some feature of the cliff face. What about cliffs void of suitable belay stances? Natural anchors provide the next level of protection. Strong trees, rock flakes and horns, and solid boulders may all be harnessed with some type of sling. Anchors are useful to secure a belayer, or as a means of protection to catch a falling lead climber.

Human and natural anchors were all that existed until the advent of climbing pitons, circa 1910 (Long 5). Pitons are knife-like metal pins of various shapes with an eye on one end. The climber drives them into rock cracks or fissures, with a piton hammer. Pitons provide a means of protection where none else is available. Early pitons were made of soft steel, which conformed to the shape of the rock. Modern pitons are made of chrome-moly steel, which is sufficiently hard to mold the crack to *its* form as it is driven in (The Mountaineers 238). According to Yvon Choinard, up until 1976, pitons were the "most well known

and widely used aid”(US Patent 3,948,485). Pitons opened up many routes that were otherwise not protectable, but they do have many inadequacies. Often they are placed as fixed gear, and relied upon by many subsequent climbers who climb the same route later. The strength of a piton placement is fundamentally dependent on the skill of the climber who placed it. Many subsequent climbers may use the convenient fixed piton, but its strength is suspect. It is hard to tell how long a piton has been in a location, and impossible to tell how many brutal lead falls it has been subjected to. Naturally, environmental concerns arise from the use of fixed pitons, which eventually corrode and stain a scarred rock face.

Climbers soon adopted masonry and quarry bolts as climbing anchors, providing a new level of protection. Bolts can be placed where no crack exists to install a piton. Various types of hardware are either hammered or twisted into holes drilled into a rock surface. Most are of the expansion dowel type, which expand radially during placement to secure themselves to the rock (US Patent 6,109,578). Modern bolts are quite strong, the 3/8” diameter variety can withstand a shear force of up to 5,000 lbs. Early bolts were much less resilient. Some 1/4” diameter bolts placed long ago still exist as fixed placements, and should be avoided due to dubious strength. Some climbers have termed them “coffin nails”, alluding to your fate if you rely upon them. Most modern bolts are equipped with a hanger, a device designed to allow attachment of a carabiner to the bolt without inducing prying forces on the bolt. Some climbers paint hangers to match the rock and to minimize aesthetic impact. Bolt anchors have facilitated a new type of climbing- sport climbing. Sport routes, or short rock climbs protected solely by bolts, have appeared across the globe. A new breed of climbers has emerged. Sport climbers focus more on the gymnastic and technical aspects of climbing increasingly difficult routes, without having to focus so much on the intricacies of a belay system. Modern bolts can sustain multiple falls without weakening appreciably, so sport climbers can push their limits, and climb routes where multiple falls are likely.

The widespread use of bolts and pitons as fixed anchors has given rise to public concern over the environmental impact of these anchors. Most climbers are very conservative in what they leave behind, but the unrestrained placement of fixed gear by a few climbers has left much of the public with an image of destructive, anti-green rock climbers (Bergman 58). Some feel that climbers are turning U.S. national parks into artificial climbing walls (Martin 36). In alpine areas, the norm is to leave only a minimal amount of gear; just what is required to safely descend a route. Knowledgeable individuals, such as David Moore (Superintendent for Joshua Tree National Monument), still recognize climbers as some of the most conscientious visitors of national parks and monuments (J.G. 14). Still, much must be done to preserve access privileges granted to climbers. The thoughtless actions of a few could lead to widespread loss of access. For example, the anti-anchor movement gained leverage in June of 1998 when the National Forest Service reinterpreted the 1964 Wilderness Act’s statement concerning “permanent installations”. The conclusion was that fixed anchors, whether bolts, pitons, or slings left wrapped around trees, were all prohibited because they were fixed installations (Bergman, 59). This dictum rendered many climbing areas, with years of history, unclimbable. Thus, climbers have the responsibility to be frugal with their fixed gear and to minimize their impact on the environment to prevent further restrictions. A study of environmental

issues regarding climbing is intrinsic to the study of equipment design because these issues forever changed the make up of climbing gear.

Many changes were underway even before the fixed anchor ban. Climbers are generally sensitive to the environment (Martin 36-38), and have been inventive in methods to minimize their impact. One climber and designer said, “The sport of rock climbing is evolving due to pressure from the public to improve the aesthetics of rock faces used for recreational rock climbing “(US Patent 6,109,578). The use of pitons has all but disappeared, except on a few particular climbs, such as difficult aid climbs, where nothing else will work. Some climbers paint bolt hangers to match the surrounding rock to render anchors undetectable. These approaches to minimize environmental impact are effective in many cases, but what about the majority of cases when a bolt is not needed, because of an available crack or fissure in the rock, but the use of pitons is undesirable because of the damage they evoke? Environmental issues require another type a climbing gear to protect crack climbs without damaging the rock.

Before intense pressure from the public began, resourceful English climbers (US Patent 3,948,485; US Patent 4,069,991), found another method of protection virtually harmless to rock faces. On their way to a climb, they would hunt for ordinary machine nuts along railroad tracks, sling them with cord, and wedge them in cracks for protection as they climbed. Thus, from these humble beginnings, began the technologically advanced science of “clean” climbing gear. Building upon this idea of machine nuts, world-renowned climbers Yvon Choinard and Thomas Frost devised a new piece of climbing gear, invented in 1971 and patented in 1976, termed the Hexentric, which is still in use today.

Constructed of extruded aluminum, the Hexentric has three modes of placement. The cross-sectional shape is of an irregular hexagon, whose three pairs of opposing sides are parallel. Each pair of sides is of a different width.

Two pairs of sides are used for placement in cracks; the other pair is utilized as a sling or cord attachment location. The third placement option is orthogonal to the other two, and is made by placing the sides

of the extrusion against the crack faces (US Patent 3,948,485). The early machine nut usage had limitations. Machine nuts could only fit one size crack, whereas the Hexentric could fit three sizes. The machine nut could only be placed in a bottleneck, or crack restriction, to be secure. The Hexentric, on the other hand, utilizes passive camming action in its two primary modes, and can therefore be placed in parallel cracks. The sling attachment is at an angle to the contact faces, rather than parallel, so as to exert a moment on the Hexentric when a downward force is applied. This moment forces the effective radius to increase, increasing the normal force against the rock surface, thereby increasing the frictional force by which the Hexentric is secured in the crack.

Improvements upon the Hexentric were soon to come. In 1978, Thomas Saunders and James Clark patented a variation of the Hexentric. Their design had a primarily triangular cross-section, and was designed to have a stronger camming action (US Patent 4,069,991). These and similar devices grew out of



Figure 1: Yvon Choinard's Hexentric. (US Patent 3,948,485)

favor in later years when more advanced protection devices became available. Nevertheless, in June of 2000, Metolius Mountain Products patented a new Hexentric-like device that revitalized this type of protection. Again, it has an irregular hexagonal cross section, but has curved sides (US Patent 6,070,842). This alteration has a two-fold effect. First, the curved sides provide a better purchase on irregular rock surfaces than did the flat sides of the Hexentric. The contact points of the Metolius device often are at a more effective position, near the vertices of the hexagon. Second, the new gear looks more technically advanced and is more visually appealing, important factors in the success of climbing gear (Harmston).

Many climbing equipment manufacturers have produced a type of device even simpler than the Hexentric, called the taper (also called a



Figure 3: Black Diamond passive wedging chock. (US Patent 5,794,914)

stopper or a passive wedging chock) (The Mountaineers 195). Tapers are six sided, usually solid, metal devices typically slung with a swaged loop of wire. The larger top portion tapers down to the narrower base. Tapers are slotted in the constriction of a crack, and are generally very secure when placed correctly. Tapers have two modes of placement. Placing the wider faces in contact with the rock is the primary and more secure mode. Placing the narrower faces in contact with the rock is the secondary mode. Designers have continually developed tapers since their introduction by introducing curved sides to allow for better placements in irregular cracks, and by introducing various offsets to accommodate flaring or other unusual crack shapes. New designs are still being patented to this day. In 1998, Black Diamond patented a new passive wedging chock (US Patent 5,794,914).

Some climbers discovered that they could stack tapers antiparallel to each other. This mode of placement allowed tapers to be used in near-parallel cracks because the top taper provided a slanting surface for the primary taper to wedge against.

A number of manufacturers built upon this idea, and developed spring-loaded wedging devices, such as the roller chock pictured to the right. These devices (Figure 4) consist of a taper and a smaller piece that slides against the taper, such as a roller, another taper, or a hemispheric piece of metal. The smaller piece is spring biased

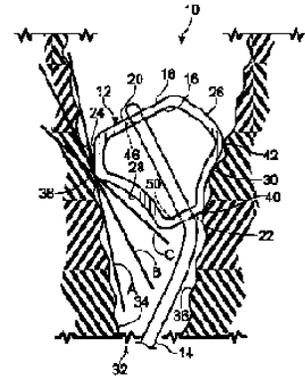


Figure 2: New hexagonal chock produced by Metolius. (US Patent 6.070.842)

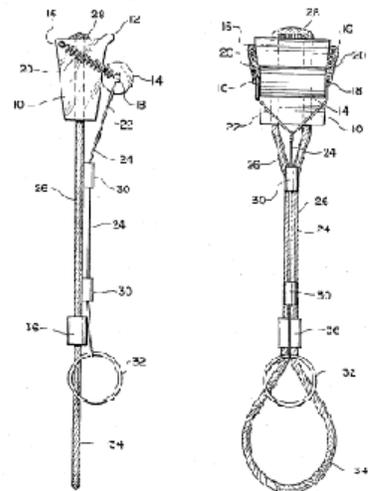


Figure 4: Karl Guthrie's roller chock. (US Patent 4,643,378)

toward the upper, thicker end of the taper, and may be pulled down with a release mechanism for placement or removal (US Patent 4,643,378). The same end result is achieved with this design as with the Hexentric. The normal forces against the rock's surfaces are amplified when this device holds a fall, thereby increasing its security. Spring-loaded wedging devices are different from the equipment we have previously discussed, in that there are moving parts. Moving parts add a new level of complexity and introduce new design challenges. These moving parts must be reliable and durable.

All of the above devices have their own specific limitations. For example, for tapers to be useful a climber must carry a large variety of sizes. Hexentrics are useless in flaring cracks, and none of the devices is suitable for use in pocketed rock features. Certainly with modern technology, we could engineer a device that addresses these shortcomings. What if there was a hybrid protection device that overcame these limitations, and combined the good qualities of the above devices? A device that optimized the camming properties of the Hexentric, had a wide range in just one mode of placement, that could instantly adjust to rock irregularities and flaring cracks, and could be placed in mere seconds with one hand would be a lead climber's dream come true. How would we construct such a device? Let us start at the fundamental design stage. A Hexentric can be placed in parallel cracks because of its camming action. However, its camming angle varies depending on the crack size it is used in, so the security of a Hexentric varies with how well it fits the crack. The normal force on the rock surfaces, and therefore the frictional holding force, relates to this camming angle. For the device to stay in static equilibrium, or stay secure in the crack, the camming angle, θ , must satisfy this relation:

$$\mu \geq \tan \theta$$

To ensure the device holds we must construct a camming device that maintains an optimum camming angle. What if we determined the optimum angle, and decided that it should be a constant over a range of crack sizes? Let us see what would satisfy these conditions.

$$\frac{dR}{Rd\theta} = \arctan \beta$$

This expresses that the camming angle must be constant over a variable radius, or crack width. After solving this and expressing it in terms of a polar function, we can write the radius as a function of θ .

$$R(\theta) = R_0 e^{\theta \arctan \beta}$$

This happens to be a logarithmic spiral, pictured in Figure 5b (Custer; Bonney, Coaplen, Doeff 677). In other words, an ideal device could maintain an optimum camming angle (β) throughout a variable radius range if it had an axis at the center of the crack and a shape that matches the above curve.

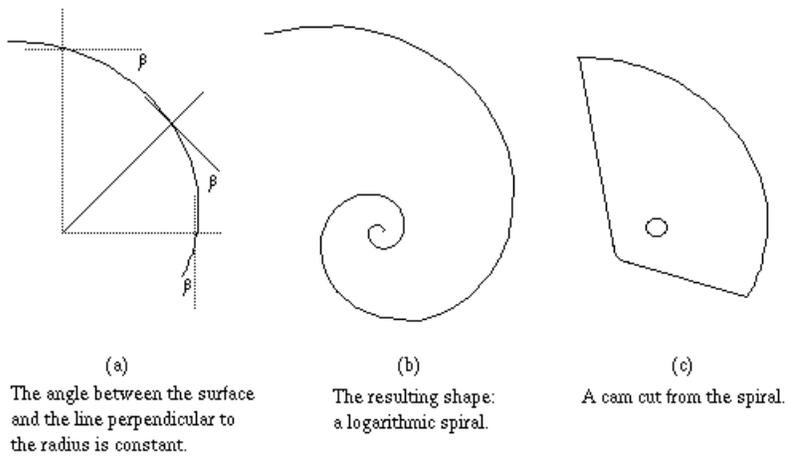


Figure 5: Development of the ideal cam shape. (Custer)

Now we need to construct a device, using these specifically shaped cam lobes, that can be placed in a crack and that provides a secure point of attachment. The basic idea is to mount three or four opposed cams on an axle. Thus, static equilibrium can be achieved, and the axis of rotation is positioned in the center of the crack (Figure 6). Spring biasing the cams outward enables the device to conform

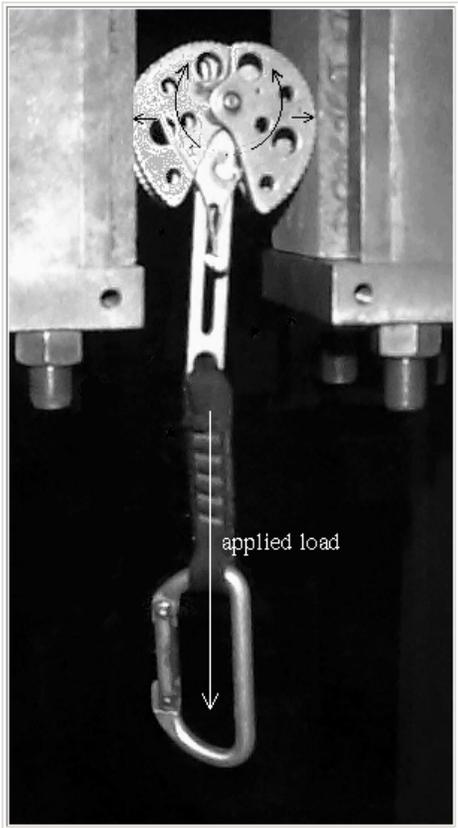


Figure 6: Placement of a Wild Country Friend in a simulated vertical crack with superimposed force diagrams. (Custer)

to the irregularities of a crack. A trigger release mechanism allows the climber to retract the cams with one hand for easy placement or removal.

Early in the 1970's, the Lowe's had the right idea when they designed the L.A.S. Split Cam Nut, but it had some serious limitations. In 1973, Ray Jardine invented the ubiquitous "Friend", which became commercially available in 1978 (Long-Climbing Anchors 9), and was patented in 1980 (US Patent 4,184,657). Jardine did in fact derive the logarithmic cam profile using polar coordinates (Bonney, Coaplen, Doeff 678-679). He mounted the cams and axle onto a rigid aluminum body, which also served as the trigger guide and attachment method. The Friend is an exceptionally successful design. The Friend is still sold in its near-original form today, and in fact, some of the original friends are still in use! The Friend is placed quickly and easily with one hand, and automatically adjusts to a wide range of crack sizes while maintaining an optimum camming angle throughout its range. Jardine patented the ideal camming angle implemented in his device. Jardine's Friend, the seminal design in climbing protection, dramatically expanded the limits of rock climbing.

According to Chris Harmston, this type of camming device is the second most significant advance in climbing gear in recent history (next to dynamic ropes).

The Friend did have its limitations however. In Figure 6, you see it placed in a vertical, parallel-sided crack with a downward force. This is where the Friend is truly in its own element. But what happens if the only crack available is horizontally oriented? The rigid stem may be flanked by the edge of a crack, and under force, this could result in dangerously high stress levels in the stem (The Mountaineers 204). A moderate fall could easily break the stem. In addition, this bulky design is not easily built to fit smaller cracks and still maintain adequate strength.

It was not long before other designers began to improve upon Jardine's design. Soon these "spring-loaded camming devices", or SLCD's, began to appear with flexible cable stems, solving the horizontal crack dilemma. With flexible stems, SLCD's could then be safely placed in almost any orientation, assuming the placement was secure.

In 1987, Black Diamond Equipment introduced the Camalot, an SLCD designed by Tony Christianson (Harmston). The Camalot utilizes a double axle design, which expands the usable range of the cam and eliminates the dreaded "umbrella" effect. In fact, the dual axles even enable the Camalot to be used as a passive chock if needed (The Mountaineers 203).

SLCD's still have a tendency to "walk" into a crack if jostled by rope movement. A subtle rope movement to one side will push one side of the cam deeper into the crack, which then locks into its new position. If the rope swings back the other way, the other side finds a deeper purchase. This process continues successively for each side as long as sufficient rope movement is maintained and the cam movement into the crack is unrestricted. Sometimes cams walk so far into a crack that they are not retrievable. Flexible stems helped to alleviate this phenomenon, but the use of adequately long runners and correct positioning of the device by the climber are the only sure methods to avoid cam walking.

In 1989, David Waggoner patented a new SLCD design intended to address both walking problems and issues with flexible cable stems wearing and fraying (Figure 7). Instead of attaching the cam actuating cables directly to the trigger mechanism, Waggoner used an intermediate, flexible braided metal sleeve. Unlike full length actuating cables, this sleeve has the same axis as the support cable. Thus, when rope drag moves the support cable around, the force transmitted to the release cables is minimal, reducing walking. Also, when the sleeve is pulled tight, the body of the SLCD becomes rigid. This feature has two advantages; the unit is easier to place, and the manufacturer can use a more flexible support cable. A more flexible cable further protects against walking. In addition to these rigidity properties, the sleeve protects the vital inner support cable, increasing the effective life and safety of the product (US Patent

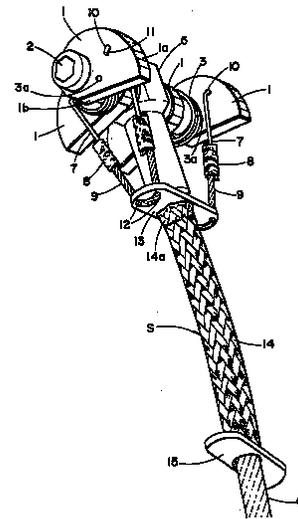


Figure 7: Improved SLCD, designed by David Waggoner. (US Patent 4,832,289)

4,832,289).

Other improvements are in the works for SLCD's, such as devising ways to build a strong cam that is diminutive enough to fit into a small crack. Tony Christianson, the inventor of the Camalot, has developed a single axle cam that has the properties of a dual axle by using eccentric bearings, providing for two axes of rotation for the cams. Because the cams are on a single axis, the cam can be built to fit smaller cracks (US Patent 6,042,069). Who knows what future developments will bring to the SLCD?

Most cracks and fissures encountered by climbers are in the under four to five inch category. SLCD's perform beautifully in all but the smallest cracks, and other gear can fit into small seams where SLCD's cannot go. Occasionally, however, climbers encounter much wider cracks. SLCD's become very awkward and unstable in cracks larger than five inches, and traditional chocks larger than five inches in width would certainly be unreasonably heavy. Another type of gear must be used. In 1984, Craig Luebben, finished what began as a senior honors thesis in engineering. The end result was the Bigbro, a spring loaded tube chock. It consists of two aluminum tubes, one that fits inside the other. It expands to adjust the crack width via an internal spring, and locks into place with a threaded collar. A sling is attached to one end. The force of a fall directed on this sling exerts a moment upon the device, resulting in a camming action that further secures it in a crack. Currently, virtually no other device exists that will protect cracks beyond 6.5 inches. The largest Bigbro expands to a colossal twelve inches (Long HTRC 31).

Most devices discussed thus far encompass gear used by the "traditional" rock climber who prefers to create their own protection system, using their own equipment and ingenuity. "Sport" climbing is another realm of climbing. Sport climbers ascend short, difficult routes protected solely by bolts. The only gear they need for protection is a rope, harness, and "quick draws"- short webbing runners with a carabiner on each end used to attach the rope to the bolt hangers. Sport climbers are prime targets of anti-fixed gear activists. To preserve sport climbing, new gear must be developed to reduce permanent impact on rock faces.

In 1996, Phillip George and Gregory Horwath patented a "removable bolt". Instead of leaving permanent bolts and anchors on a sport climb, the climber who establishes a route simply drills the standard diameter bolt holes and then places these spring loaded devices in the holes during the climb (US Patent 5,484,132). These devices are even easier to place or remove than SLCD's, since they are always a perfect fit. Subsequent climbers must have their own set of removable bolts, but the cliff is left with a much less disfigured appearance.

Karl Guthrie, the inventor of the roller chock pictured in Figure 4, patented an improvement upon George and Horwath's removable bolt anchor in August of 2000. Guthrie's design is simpler, and can be secured in holes as shallow as ½ inch in depth (US patent 6,109,578). These

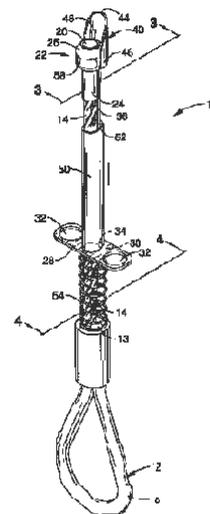


Figure 8: Modern removable bolt, designed by Karl Guthrie. (US Patent 6,109,578)

removable bolt anchors are ideal for sport climbers, providing a method of easy protection that is more environmentally friendly. Removable bolts may change the way concerned individuals feel about rock climbing, but their success depends upon the frugality of the climbers who place them. If thoughtless climbers proceed to drill holes for removable bolts without reservation, undoubtedly climbing will continue to be under attack.

In Europe, “climbers” who wish to venture into the vertical world, but have little climbing ability or expertise, may use a completely different belay method. This age-old style of climbing, termed Via Ferrata (meaning iron way), employs metal u-shaped bars embedded into the rock. The climber uses these holds to ascend, like a ladder, the route. However, most of these routes are highly exposed, and some type of belay method is required. A cable parallels the route, and is anchored intermittently to the rock. A climber anchors himself to the cable with a carabiner that slides upwards as he moves. When the climber encounters an anchor, he clips in above the anchor with another carabiner, detaches the lower carabiner, and then continues ascending. In the event of a fall, the climber would descend until his carabiner caught the cable anchor just below him. Just as in a lead fall with a traditional belay, the climber accrues a tremendous amount of kinetic energy that must be absorbed by the belay system. If a climber simply clips in with a static nylon runner between his/her harness and the carabiner, virtually no elongation will occur. Thus, the energy must be absorbed very quickly, and astronomically high impulse forces will result. A fall of this nature can have a fall factor of anywhere between zero (if the climber falls just after he clipped in above an anchor) and about five (if he falls just before clipping in and slides the full length before hitting the anchor). This scenario will result in a promptly broken sling, and a climber in peril (Petzl).

Via Ferrata climbers must use an energy-absorbing device to avoid the above situation. Pictured

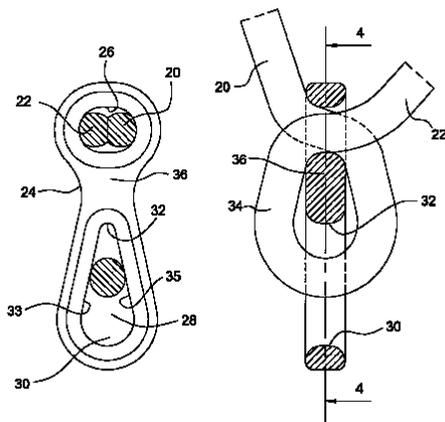


Figure 9: Front and side views of the ZYPER-Y by Petzl. (US Patent 5,947,229)

here is the ZYPER-Y, a device manufactured by Petzl, specifically designed for Via Ferrata use. A lanyard cord is woven through the device with an interference fit. Each end of the cord (20 and 22 on Figure 9) protrudes from the device, and each are used successively to clip in to the cable as the climber passes cable anchors. If the climber falls, the cord pulls through the device through much resistance, absorbing significant amounts of energy. The manufacturer claims that the device will limit the force of even a factor five fall to below 6kN (US Patent 5,947,229).

Many other articles of climbing gear exist that deserve equal consideration, such as carabiners, harnesses, climbing shoes, slings, ascenders other various gadgets, and then the myriad of gear specific to ice climbing. Volumes

could be written about the design of each, but here we have focused on ropes and protection, two of the most revolutionary categories of climbing equipment. Discussion of other types of equipment will be left to other articles.

There is vast potential for continuous improvements. It may be that the only remaining task for designers is to refine existing devices. Some feel that most of the possible improvements in gear types have already been made. Chris Harmston said that the prime task for engineers now is to create gear that is “faster, lighter, and stronger”, and that most of the invention phase of climbing gear development likely has passed. Still, much is to be done even if a maverick designer does not devise some spectacular and revolutionary new piece of equipment. New materials may be implemented that increase strength, decrease weight, and improve durability. Engineers may aim to improve the factor of safety while maintaining usability. The industry can continue in its endeavor to minimize the impact climbing has on the environment, and gear can be redesigned to be ever more ergonomic.

Technological advances in climbing equipment have benefited climbers in significant ways. Over the past century, climbing gear has evolved from the Stone Age to the space age, and the new standards of climbing accomplishments reflect this change. 100 years ago climbers were scrambling up mountainsides in thick lug-sole boots, relying upon equipment that provided only a modicum of protection. Michael Loughman summarized the plight of the early climber when he said, “Historically (climbers) have not placed great faith in the rope. The risk of falling had been controlled chiefly by adopting a particular stance on the slope, always keeping three points of contact with it, and proceeding in a slow and deliberate manner.” (Loughman 150). The climber himself was truly his only means of trustworthy protection. Advances in climbing standards were stunted because climbers were inhibited to make dynamic or daring moves. Only the bold dared to venture near the limits of their climbing ability. Modern equipment reversed this trend. Michael Loughman explained: “On steep rock with modern equipment and methods, falls of twenty and even forty feet do not usually cause serious injury.” (Loughman 150). Now, with the arsenal of tools available to the climber, it is not unusual for many adventurers to test their limits in the vertical world. Climbers routinely ascend routes once thought impossible. New ratings for difficulty levels had to be invented to accommodate these harder climbs.

Increased safety of gear relates directly to continually higher difficulty standards. Confidence in climbing gear is crucial to the success of a lead climber (Harmston). Almost no sane climber will push to his very limits without the assurance that he will be safe in the event of a fall. Technology is the climber’s ally. Improved testing techniques and advanced designs ensure that, if equipment is used correctly, a climber will be safe. According to John Long, “Climbing is the safest of the so-called thrill sports because it employs over a century’s worth of refined technique and solid technology to the normal end of having fun.” (Long 3). Thus, a lead climber is free to be bold and to test his/her limits. A skilled climber, using modern gear, can rapidly identify the correct piece for the application and secure it to the rock quickly. Every second saved during the strenuous process of placing gear on a difficult climb is crucial. Not only

does modern equipment allow old routes to be climbed more efficiently, but new routes can be climbed that were previously impossible to protect. Application of technology to mountaineering has truly expanded the enjoyment and heightened the fulfillment avid climbers experience. It is imperative, however, that climbers understand the importance of using the proper technique with climbing gear. The success of any protection method is dependent on the protection placement. If properly used, gear will keep a climber safe. If misused, gear is lethal. Lead climbers need to know the strength and limitations of each piece of equipment they use. Climbers should frequently inspect their gear to check for wear or damage, which may result in significantly weaker protection and perilous circumstances.

More individuals may now experience the thrill of climbing because equipment is much more affordable than in the past. The cost of carabiners today, not even accounting for inflation, is less than the cost of carabiners in 1970 (Harmston). When one considers the research and development required for a single new piece of equipment, in addition to the tremendous work required to put a device into production, climbing equipment becomes a veritable bargain. It takes a team of 5 to 6 people up to three years to take a device from the design stages through to production. Production and manufacturing issues can demand anywhere from five, up to ten times more engineering time than the actual designing of a device (Harmston). Equipment is truly a better value to the climber because of the technology applied to mountaineering.

Presented above was a plethora of new devices designed to protect climbing routes. Each new device may seem to be the end all in gear, replacing the need to use any other device. In reality, we need a variety of types of gear. One particular device may be poor in one instance, while another is perfectly suited. A typical traditional lead climber carries with him a selection of cams, passive chocks, and other devices. What he chooses to take depends on his style, on the route in question, and on the type of rock he is climbing. Even pitons, though damaging to the rock, are still occasionally used because nothing else will work. Each new device just adds to the repertoire of routes that climbers are capable of safely protecting.

Mountaineering has truly benefited from the application of modern engineering technology to its tools. More people from increasingly diverse backgrounds enter the climbing lifestyle because technology has made it more accessible to them. The risk factor is now acceptably low. Requisite paraphernalia is now affordable to most, and the sport offers increasingly exciting adventures. These newcomers bring with them new perspectives, new styles, enthusiasm and desire for adventure. The makeup of the world's climbers has transformed, and mountaineering is more enriched because of it. Technology has not removed the challenge from the sport or ruined its rugged nature, but has enhanced our enjoyment of the sport, has taken climbing to new levels, and has increased our chances of coming home so we can pleasure in yet another day of climbing.

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