FORCES INVOLVED IN LEADER FALLS

-by Michael Strong-

A leader fall can generate an enormous amount of energy which must be absorbed by the components of the climbing system: the climber, rope, protection points, and the belay system. Obviously, it's important that this energy does not exceed the limits of any link in the chain. It's in your best interests, therefore, to have a good understanding of how the energy of a fall is transmitted throughout the protection system.

THE PHYSICS OF FALLING

Determining the amount of energy that's produced during a fall is a study in basic physics. Yes, physics. Here's your chance to apply the concepts which you learned in high school to something practical and fun.

$$\text{Energy of motion} = 1/2 \text{ mass} \times \text{velocity}^2$$

According to the above formula, the amount of energy the climbing system absorbs in a fall is equal to 1/2 the climber's weight times the square of the climber's speed at the moment the rope begins to stop the fall. In practical terms, this means the falling climber accelerates, falling faster each second. The longer the fall, the greater the acceleration, and the greater the energy that must be absorbed!

The energy of a fall is dispersed *largely* (but not totally) by the climbing rope. As a result, a great deal of energy (human energy, that is) has been spent estimating the damage done to the rope during falls of different lengths. Enter the fall factor.

A. The Fall Factor

The ***fall factor*** is a rating of the seriousness of a fall. It provides an estimation of the damage to your rope when you fall on it. It's expressed as a ratio between the length of the fall and the length of rope available to absorb the fall.

$$\text{Fall Factor} = \frac{\text{length of the fall}}{\text{length of available rope}}$$

For example, if you climb 10' above the belay and fall before placing a piece of protection, you'll fall 20' on 10' of rope before the force of the fall is contained at the belay (assuming the belayer doesn't let the rope slip through the belay device and that you can fall freely past the belayer). This is a factor-2 fall, the highest possible. You experience the greatest impact force possible in this situation.

$$\text{Fall Factor} = \frac{\text{20' fall}}{\text{10' of rope}} = 2.0$$

Figure 1 illustrates a factor-2 fall.

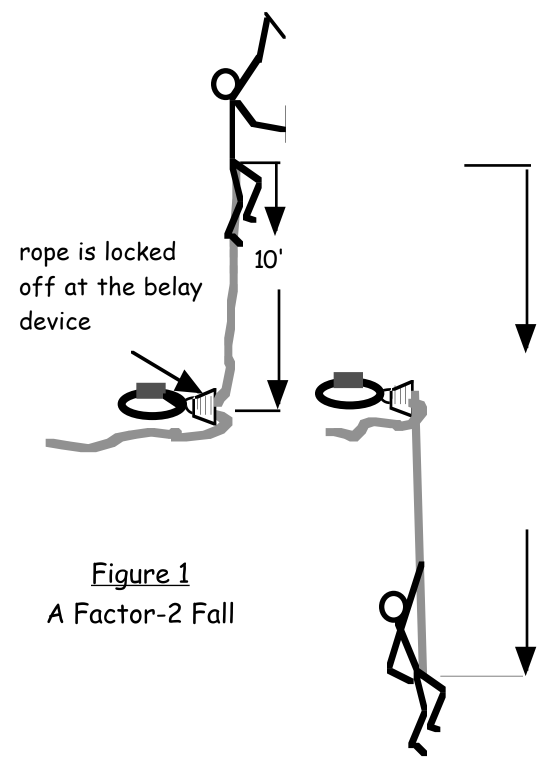


Figure 1
A Factor-2 Fall

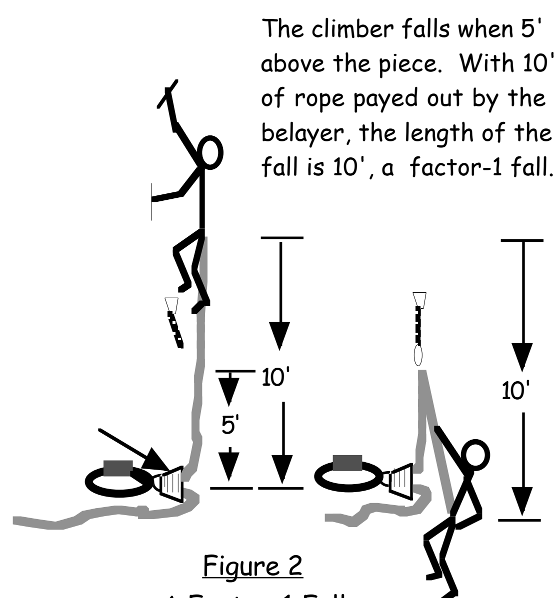


Figure 2
A Factor-1 Fall

This time, let's say that you place a piece of protection 5' above your belay, climb 5' higher, and then fall, as shown in Figure 2. The fall factor in this situation is 1, *providing that the belay is static* (i.e. the rope does not slip through the belay device).

B. Impact Force

The force felt by the climber when the fall is stopped is called the ***impact force***. Impact force is determined by the length of time over which the fall is stopped. The shorter the time, the higher the impact force, and vice versa. Imagine taking the factor-2 fall illustrated in Figure 1 on a steel cable. Since the cable doesn't stretch, the energy of the fall is transferred to you in an instant, likely with enough impact force to break your back! A fall on a climbing rope is stopped over a longer period of time, with the rope absorbing much of the energy of the fall, keeping impact force within acceptable limits.

Does a longer fall produce more energy? Yes, because the climber continues to accelerate until the fall is stopped.

Does a longer fall produce a greater impact force? Not necessarily! Interestingly enough an 8' fall on 4' of rope produces the same fall factor (hence impact force) as a 60' fall on 30' of rope. The energy of the longer fall is absorbed by the proportionally longer section of rope.

Does this mean that the longer fall is just as safe as the shorter one? No, for you'll fall faster during the longer fall. The consequences of impact with a ledge or outcropping are likely to be far more serious. Also, at the end of a longer fall, force is exerted on the protection system and your belayer over a longer period of time, increasing the possibility for failure of your protection system, and slippage of the rope through the belay device (not necessarily a bad occurrence as we'll see later).

C. The Effects of Friction

The factor-1 fall illustrated in Figure 2 above is relatively frictionless (i.e. the rope passes through only one carabiner). As you progress upwards and place more pieces, friction develops in the system as the rope passes through multiple carabiners.

The upshot of this friction? No longer does the entire length of rope between you and the belayer experience the same force during in a fall. ***The section of rope between you and your last piece takes a disproportionate share of the load during a fall***, and the fall factor is increased even more!

What can we learn from the concepts of fall factor, impact force and friction?

1. Avoid a factor-2 fall at all costs. Without friction in the system you'll experience a tremendous amount of force. So will your belayer when the fall comes onto a belay device in the seat harness, or the anchor, if the belay is from the anchor.

2. Reduce the fall factor by placing protection early and often at the beginning of a lead. If the climb does not protect right away, consider using the anchor as your first piece. Should you fall before getting a piece in, the fall will be a little shorter. In addition, the friction of the rope passing through the anchor protection reduces the force on your belayer.

3. Keep your protection system as free from friction as possible. Reduce rope drag by using runners to keep the rope from zig zagging between protection points. Make sure that the rope does not get wedged in a crack or pulled forcefully into the rock during a fall (e.g. against the lip of a roof or onto the edge of a corner), for if you fall when this happens, the length of rope below this point is unavailable to absorb the energy of your fall. You and the top piece of protection will experience a tremendous force, perhaps enough force to cause the piece to pull, or even enough force to severely abrade, or cut your rope!

LEADING - AN HISTORICAL PERSPECTIVE

In the early days of climbing (the late 1800's and early 1900's), the golden rule was "***the leader must not fall***". Back then, climbers were not as concerned about their protection failing as they were about the rope breaking. Ropes were not only weaker, but they weren't designed to absorb the impact of a fall (by stretching) like today's ropes are. After all, they were made from hemp. If the belayer held the rope too strongly, or if the rope otherwise experienced too much impact force, it snapped.

In the 1930's the Sierra Club introduced the *dynamic belay*. By allowing the rope to slip through the hands in a controlled fashion, the belayer could hold leader falls without the rope breaking or the top piece of protection pulling. Impact force was dissipated by the rope running freely around the belayer's body until forces were brought under control. The golden rule changed to ***"the rope must run"***.

There were tradeoffs involved with allowing the rope to run. The most significant was a longer leader fall and an increased potential for the leader to hit a ledge or rock outcropping before being stopped. Rope burns to the belayer's hands and back were also likely unless the belayer wore leather gloves and positioned a belay pad around the back. Despite its drawbacks, this system was an improvement to the previous one. Many of the classic routes in Yosemite were put up during the era of the dynamic belay. To prepare, climbers practiced dynamic belaying, simulating leader falls by dropping elevated weights.

During WW II, when natural fibers were in short supply, Dupont began making ropes from nylon. These laid-construction ropes were lighter, stronger and more resilient than the hemp ropes of the day. *Goldline* became the climbing rope of choice. For the first time the impact force of a fall was largely contained *by the natural resiliency of the rope.*

Despite this important improvement in rope design (natural stretch), laid ropes were far from ideal for leading. They were stiff and thus created excessive rope drag in the protection system. The absence of a protective sheath meant the loss of considerable strength once the rope strands became fuzzed from abrasion. They also handled poorly and spun a climber during free rappels and while ascending.

The first *kernmantle* ropes were introduced by Edelrid in 1951. These ropes featured a load bearing core (kern) protected by and outer protective sheath (mantle). This construction design solved most of the problems inherent to laid ropes. They were stronger and more supple, producing far less friction in the protection system. With these refinements, the golden rule of leading changed to the present "***the protection must not fail***".

Modern ropes stretch so well that it's not necessary, nor desirable, for beginners to learn dynamic belay theory and technique. Today's ropes are designed to keep the impact force created by even a factor-2 fall within tolerable limits. Without question, *the rope is the key ingredient in energy absorption during a leader fall!*

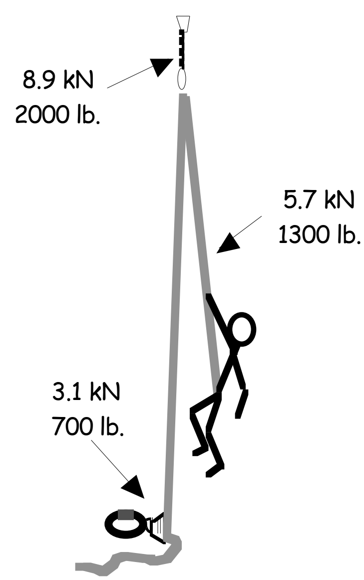
Does this mean that a dynamic belay is never provided? No, but it does mean that it's not common. Rope slippage will occur if the fall factor is high or the belay friction is low.

ENERGY DISTRIBUTION DURING FALLS

Whenever you fall, energy is transmitted to the elements of the protection system: You, your harness, the rope, the protection points and their attachments, the belay device, the belayer's harness, the belayer, and perhaps the anchor, depending on whether or not the belay is from the harness or directly from the anchor.

It's important to understand that the energy of a fall is not distributed equally between these components, that it's dissipated *along* the protection chain. Figure 3 illustrates the likely distribution of force during a fall (on a single piece of protection) with an impact force of 5.7 kN.

> kiloNewton: a metric unit of force. It measures the amount of force it would take to break a piece of equipment. 1 kN = 224.8 lbs. of force.



What does Figure 3 tell us? That 5.7 kN of force is felt by the climber during this fall. Secondly, that 8.9 kN is placed upon the protection point, and 3.1 kN is on the belayer at the belay device.

Why is 3.1 kN (appr.) placed upon the belay side of the rope? Because friction on a rope making a 180° bend over a carabiner edge creates an "average tension ratio" of approximately 52%[1]. In other words, the belayer feels about half of the force of a fall; about 3.1 kN in this situation. This is why a lighter person can hold a heavier person on a top rope. Keep in mind that when the rope passes through only 1 piece, the effects of friction are minimized, especially in a fall on a vertical or overhanging section of rock.

Why so much force on the top piece? Because the top piece experiences 2 forces:

1. The impact force of the climber's fall, and
2. The force that the belayer can apply with the belay device.

The end result is a lot of force on the top piece of protection, especially if the belayer provides a static belay. Your placement, not the strength of the piece and its attachments (sling and carabiner), is likely to be the weakest link in the chain. Your biggest fear should be *failure of your protection*!

If you're making the transition from sport routes where you've become accustomed to clipping bolts (that are usually very solid), to climbs that require gear placement, be very careful! Make sure that each of your placements is solid.

What if the belay device can hold only 2.2 kN of the 3.1 kN of force on the belay side of the rope? The belay goes dynamic! You will fall further than if the belay were static; how much further is hard to say. But if you are in no danger of hitting something on the way down, there's no harm done. Falling farther may be beneficial, because less force is placed on the top piece of protection. How much less force? It depends on the fall factor, as Figure 4 shows.[2]

If rope slippage at the belay increases your fall 20%, the force on the protection is reduced by the following amounts: 18% in a factor-.1 fall, 38% in a factor-.5 fall and almost 60% in a factor-2 fall. What this graph reveals is that the benefit of rope slippage is greatest at the higher fall factors, which is when rope slippage is most likely to happen anyway.

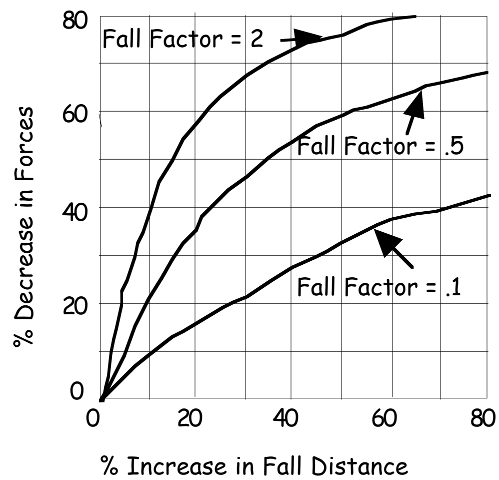


Figure 4
The Trade-Off in a Dynamic Belay

A serious consequence of rope stretch early on in the lead, especially right off of the ground, is the high potential of hitting the ground. To avoid this, use the following guidelines:

1. If your first clip is 13' off the ground or a belay ledge, the second one cannot be more than 4.5' above the first, and the third one no more than 7.2' above the second.

2. If your first clip is 16' off the ground or a ledge, the second one cannot be more than 6.2' above the first, and the third one no more than 9.8' above the second.

While you can (to a large degree) control the spacing of placements relative to each other when you place your own protection, it's not possible on bolted routes. But you can *always* make the decision to avoid a climb when the bolts are inadequately spaced or protection is not possible to place where you need it (to avoid grounding out).

Suppose there were one other piece of protection in the system shown in Figure 3, at a point between the belayer and the upper piece holding the fall (Figure 5).

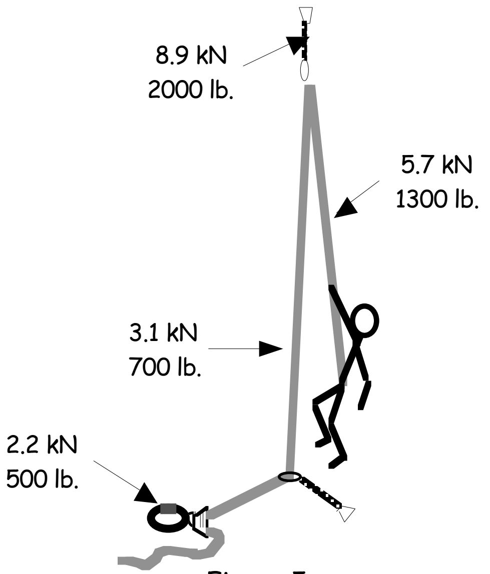


Figure 5
Distribution of Forces in A Fall
With An Additional Piece of Protection

Compare Figure 5 to Figure 3. Notice that in each case 3.1 kN (700 lb.) of force is on the belay side of the rope. Figure 5, however, illustrates a situation where the force exerted on the belayer is less (2.2 kN vs. 3.1 kN). Friction through the lower piece of protection in figure 5 results in less force being exerted on the belayer. This fall can be held statically.

A potential downside to any statically held fall is that the maximum force possible is transferred to the upper piece of protection from both sides of the rope. This additional force may be just enough to pull the top piece out of the rock.

ROPE & EQUIPMENT TESTING

A. The Drop Test

The Union Internationale des Associations d'Alpinisme (UIAA) conduct various tests, including a sequence of 'drop tests' on samples of each rope model provided by the manufacturer.

For single ropes, an 80 kg. (176 lb.) weight is attached to one end of a 2.8 m. (appr. 9') section of rope and raised 2.3 m. (appr.8'). It is then dropped 4.8 m. (appr.16') over a 10 mm.-radius edge (designed to approximate a carabiner), which is positioned 30 cm. (1') above the point of rope attachment. The drop test approximates a severe real-life climbing fall. Rope samples must survive 5 of these falls! The ***impact force*** must not exceed 1200 kg. (appr. 2700 lb.) or 12 KiloNewtons (kN).

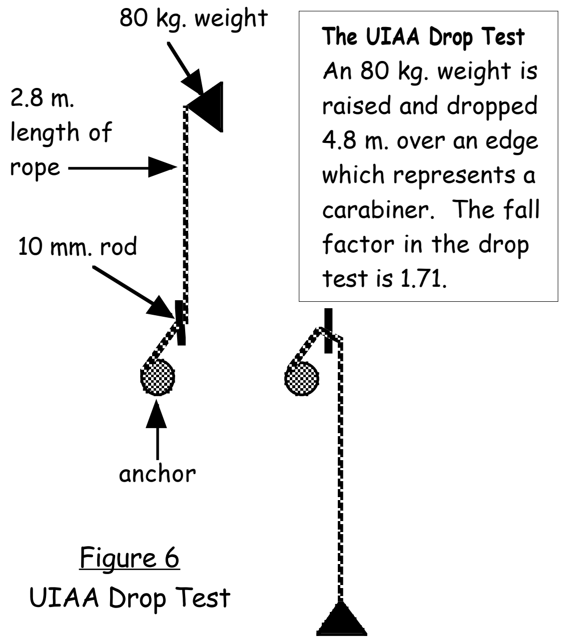


Figure 6
UIAA Drop Test

12 kN is a lot of force. The human body can absorb this amount of force for only a very short period of time! As a result, most manufacturers produce ropes which provide impact forces below this value. When examining rope hangtags, look for its impact force and remember that the listed value is for the force of impact ***on the first fall***.

Why is this important to consider? Because as a rope receives repeated falls it loses elasticity. The upshot is a higher impact force as falls are accumulated! For example, impact force increases 53% on the Edelweiss Stratos (10.5 mm.) from the 1st to the 4th fall. Impact force on the 11 mm. Black Diamond increases 28% from the 1st to the 4th fall!
This change is most pronounced in smaller diameter ropes.

An important thing to remember is that 80 kg. is used during the drop test, the weight of the "average climber". What is the impact force on the heavier, or lighter climber? All other factors being equal (except weight), a computer model shows that
during a factor .5 fall:

a) a 60 kg. (132 lb.) climber feels about 3.4 kN;
b) an 80 kg. (176 lb.) climber feels about 4 kN; and
c) a 100 kg. (220 lb.) climber feels 4.5 kN.

On the same length of rope, with a *fall factor of 1.5*;

a) the 60 kg. climber feels 5.4 kN;
b) the 80 kg. climber feels 6.2 kN;
c) the 100 kg. climber feels 7 kN!

One shortcoming of the drop test is that the block used for testing is solid, unlike the human body which is basically a bag of water. As a result, more force is placed on the rope by the impact of a solid block than the impact of a human body of the same weight. Recent tests by the Italian Alpine Club reveal that a climber only absorbs 66 lb. of force during a factor-1 fall of up to 13 feet![1] This value differs markedly from the values listed above from computer testing, and it seems awfully low. Without knowing the testing conditions, it's impossible to compare these figures.

B. Falls on Static Rope
Impact force increases dramatically when a static rope is substituted for a dynamic one. For example, if a fall on a dynamic rope with an impact force of 9 kN is replicated with a static rope, the impact force is doubled to 18 kN! Never lead climb on a static rope! While this is obvious, less apparent is the fact that slings and runners also behave like static rope.

Consider the following: A fall of less than 4' onto a static rope or sling can generate enough shock load to cause severe injury or death! It is one thing to hang from an anchor on a set of slings. Climbers do it fairly often, for example when converting to a lowering setup at the end of a sport lead. It is quite another to climb above the anchor attached to these slings and then take a fall. As the above example indicates, tremendous force can be applied to the climber.

Tremendous forces can also be applied to the rest of your gear. Fortunately, the UIAA sets minimum limits on all gear used in you safety system. These limits are outlined below.

Item	UIAA Specified Minimum Limits
Anchors	25 kN (appr. 5600 lb.)
Carabiners	20 kN (4500 lb.)
Slings	22 kN (4950 lb.)
Harnesses	15 kN (3375 lb.)

The above figures show the danger of taking a severe fall on a static line or a piece of sling webbing. While anchor, carabiner and sling may hold 18 kN of force, the harness may be in jeopardy of breaking!

Does the impact force often reach the upper limit of 12 kN? Not likely, because it is mitigated by other factors, most notably belay friction and movement of the belayer.

BELAY DEVICES & IMPACT FORCE

The type of belay device you use and how you use it effects the impact force. In practical terms, the amount of friction that your belayer applies at the belay device places an upper limit on the force that a fall can produce. Braking forces for the commonly used belay methods/devices are as follows:

Belay Method	Approximate Braking Force
Body belay	1 kN (250 lb.)
Figure of eight in rappel mode	1.5 kN (350 lb.)
Slot devices (ATC, Sticht plate, etc.)	2 kN (450 lb.)
Slot device with 2 carabiners	3 kN (700 lb.)
Müenter hitch	3 kN (675 lb.)
Grigri	9 kN (2025 lb.)

With any of these belay devices, falls are held statically if impact loads remain below the specified thresholds.

Can you control the level of friction with a consistent degree of precision? Not really. The best we can do is make prudent decisions during the extreme situations. On a sport route with solid 1/2" bolts, high friction at the belay device is acceptable. A belay device which provides low friction is called for when anchors and/or protection placements are poor. Incidentally, never use a body belay when belaying the leader if you are attempting to keep the impact forces low.

BELAYER MOVEMENT & IMPACT FORCE

Many climbers belay the leader from a belay device attached to the harness rather than directly from the anchor. The benefit of a belay from the harness is that some of the impact force is absorbed by belayer movement. One test showed that when the belayer is pulled forward, or upward, impact forces are reduced by 15% to 30%.[1]

If belayer movement is beneficial, the question then becomes, should the belayer maximize movement by belaying from ground level without the security of a belay anchor? Until very recently the answer would be no, absolutely not. But a common scene at sport climbing areas is an unanchored belayer providing a belay from the harness. The reasoning behind this practice is that should you fall, your belayer can move forward to reduce the length of the fall.

Strong words of caution are in order here! Remember that short falls can produce as much impact force as long ones. The theory that your belayer is an effective counterweight to the forces of your leader holds true only when your belayer is *much* heavier than you are. Expect your belayer to be pulled if you are close to each other in weight.

While the pull on the belayer may be relatively gentle if your belayer is heavier than you, the risk is still great, for the movement may be disruptive to the belay. The belayer may also be injured, or slam into the rock and lose the belay.

Another risk presents itself early on in the lead. When you are close to ground level, you don't want your belayer (hence the belay rope) to move very much, for you increase the chances of grounding out. In this situation, an experienced belayer either anchors in, or provides an unanchored belay from as close to the base of the climb as possible (or both), in order to shorten the amount of rope payed out.

Do not forget that frictional forces are minimal at the beginning of the lead when only 1 or 2 pieces are placed. More force comes onto the belayer when the leader falls in this situation, compared to when frictional forces are absorbed by the rope running through several pieces.

A final consideration relates to the type of belay the leader provides for the second. There are two options of where to belay from: directly from the anchor, or from a belay device in the harness. Which is better? It all depend on who you talk to. The standard practice for quite a while has been to belay from the harness in order to "protect" the anchor. Advocates of this school point out that the anchor should be the last place that forces are absorbed.

Those who prefer to belay directly from the anchor are right when they state that it is more comfortable. And as Long points out, the anchor should never be thought of as a backup. If it's not good enough to belay through, then it's not an anchor at all, but a severe liability.[3]

In the final analysis, the forces involved when belaying a second are minimal if the leader belays correctly. But they are certainly more than in a slingshot belay, because the rope usually passes directly from the belayer to the climber with a minimum of friction. Many neophytes are surprised at the difference in force, and can sometimes be caught unawares. Many seconds have been dropped and injured than one would expect.

SUMMARY

Considerable energy is generated in leader falls. Three factors combine to determine how this energy is distributed: *fall factor, belay friction and belayer movement*. These elements has been examined in detail and information on how to manage the forces has been presented.

Hopefully, you realize that many aspects of force distribution are in your control. Many decisions must be made while you work your way up the rock, and while we all learn from our mistakes, the 3rd pitch of a climb is no time to experiment with techniques that you do not understand. Take the time to fully understand the dynamics of lead climbing, and use your head in every situation.

1. Soles, C.," Single Rope Buyer's Guide", *Rock & Ice,* July- August, 1995.

2. *Mountaineering The Freedom of the Hills,* 5th Ed., The Mountaineers, 1992.

3. Long, J., *How to Rock Climb,* 2nd Ed., Chockstone Press, 1993.