What's the Advantage? Calculating Mechanical Advantage With the T-System

By Steve Achelis

In physics and engineering, the term *mechanical advantage* refers to the amount by which a machine multiplies the force put into it. In rope rescue, the "machine" consists of our ropes and pulleys. We use this "machine" to help us raise heavy loads.

Though most rescuers are not engineers, they do need to know how to calculate the mechanical advantage of rope rescue systems. Knowing this not only tells us how much force will be required to raise a load, it also helps us understand the forces that will be exerted upon the equipment in our system and, ultimately, if the forces will exceed the strength of the equipment.

The T-System, which is also referred to as the T-Method or the "adding the tensions" method, is a popular technique to calculate mechanical advantage. This article presents a step-by-step approach you can use to apply it. It contains a slight variation on the technique that is based on the shape of the letter T. This variation makes it easier to learn and use the T-System.

This explanation of the T-System may appear complicated, but it is not. Take a few minutes to work through these examples and you will be rewarded with increased confidence and safety.

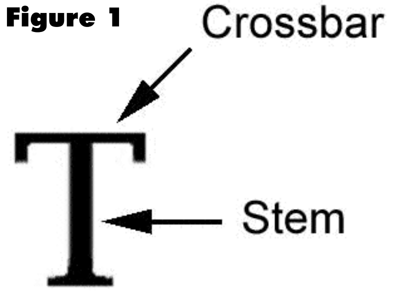
The T-System Exposed

The T-System is a great technique. It can calculate relatively complicated systems, including systems that could not be calculated using the "counting the lines" approach (which counts the number of ropes connected to components that move). However, the T-System cannot solve every system. It works wonderfully on typical rope rescue systems, but as the systems become more complex, the mechanical advantage becomes much more difficult to calculate, until ultimately, it can require software such as RescueRigger (www.rescuerigger.com).

The mechanical advantage of a system is expressed as a ratio—for example, a 2:1 or 3:1 system. The first number represents the force on the load, and the second number is the force with which the rescuers are pulling on the rope. For example, when we say a system has a 3:1 mechanical advantage, we're saying that for every three pounds of load, the pullers are holding one pound. It means that we would only need to pull 100 pounds to raise a 300-pound litter.

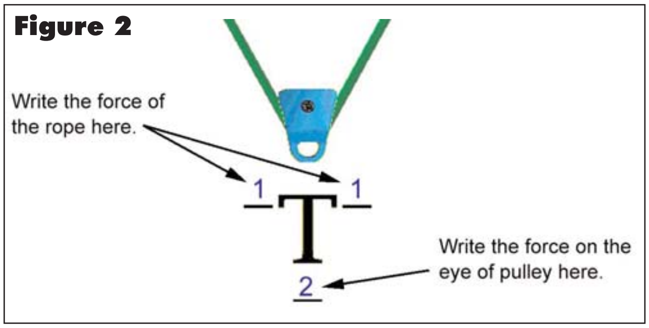
To make it easier to understand the T-System, let the letter T denote the forces entering and exiting each pulley. The horizontal line at the top of the T is the *crossbar* and the vertical line is the *stem* (see *Figure 1*).

Figure 1



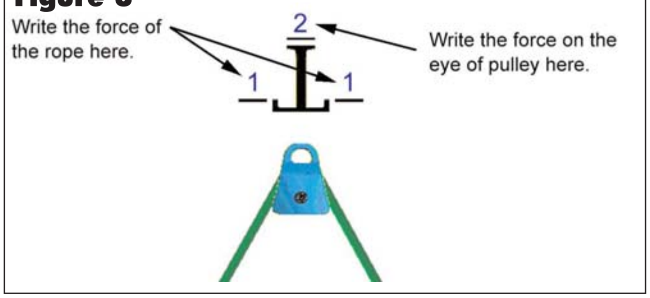
After drawing the letter T next to a pulley, I write the force of the rope entering and exiting the pulley near the ends of the crossbar. I then write the force on the "eye" of the pulley near the end of the stem (see *Figure 2*).

Figure 2



When the pulley is hanging vertically with the eye near the top, the T is inverted (see *Figure 3*).

Figure 3



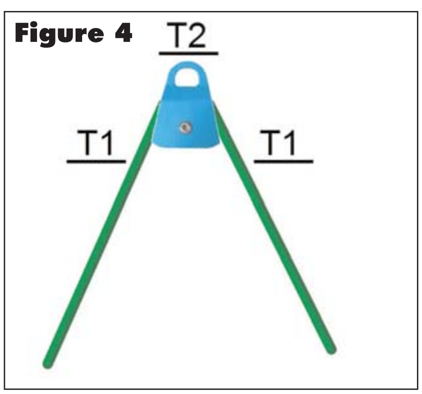
It is helpful to think of the T's crossbar as a balance-beam scale. The values on the left and right sides of the crossbar must be the same so the crossbar is balanced. Similarly, the value on the end of the T's stem must equal the sum of the two values on the crossbar. This is an important principle of the T-System—the T must balance from both left to right and top to bottom.

For example, in *Figure 3,* the values on the ends of the crossbar are in balance (i.e., both values are 1), and the value on the end of the stem equals the total value on the crossbar (i.e., 2).

The requirement to keep the forces on the T balanced comes from a basic principle of physics: In a static system where nothing is accelerating, the forces acting on a component are always matched by equal forces in the opposite direction. The T-System technique assumes that the pulleys are frictionless and that the rope makes a 180-degree turn around the pulley.

For simplicity's sake, you do not need to draw the T as shown in the previous illustrations. Instead, you can simply write the values next to the ropes and pulleys. It is helpful to write the letter T before the numbers (as shown in *Figure 4*) to show that these values are part of the T-System calculations.

Figure 4



It is important to remember that even though we did not draw a large T next to the pulley in *Figure 4,* the values still must balance. In *Figure 4,* both numbers where the rope enters/exits the pulley must be the same to balance the T's crossbar, and the number near the eye of the pulley must equal their sum to keep the T's stem in balance with the crossbar.

Pulleyless Machine

Figure 5

Figure 5 shows a hand holding a load. There are no pulleys in this system, so there is no mechanical advantage. For every pound of force we put into our "machine," a pound comes out. Therefore, this is a 1:1 system. In this example, the hand must hold all 100 pounds of the 100-pound load.

Adding a Pulley

Figure 6A adds a pulley to our system. We will now use the T-System to calculate the mechanical advantage of this system in four steps.

1. Draw blank lines—The first step is to draw blank lines where the rope enters and exits the pulley, and near the eye of the pulley as shown in *Figure 6A*. These three blank lines identify the ends of the T's crossbar and stem. We will use the blank lines to record the T values. If there were more pulleys, we would draw the three blank lines next to each of the pulleys.

2. Write T1 near pullers—The second step is to write T1 near the rope where the rescuers (i.e., the hand in these illustrations) will be pulling. This is shown in *Figure 6B* (on page 18).

3. Fill in the blanks—Now fill in the blanks with T values. There is always a temptation to start at the load, but it is important that you begin where the rescuers will pull the rope. Starting at the hand, move along the rope until you come to the first blank. This is the point where the rope enters our only pulley. Write T1 in this blank because that's the force coming from the hand to the pulley. This is shown in *Figure 6C* (on page 18).

Figure 6A

To keep the T's crossbar balanced, write T1 on the other side of the pulley. Then write T2 near the eye to keep the T's stem balanced. This is shown in *Figure 6D* (on page 18).

If there were more pulleys, we would continue following the rope while writ-

Figure 6B

Figure 6C

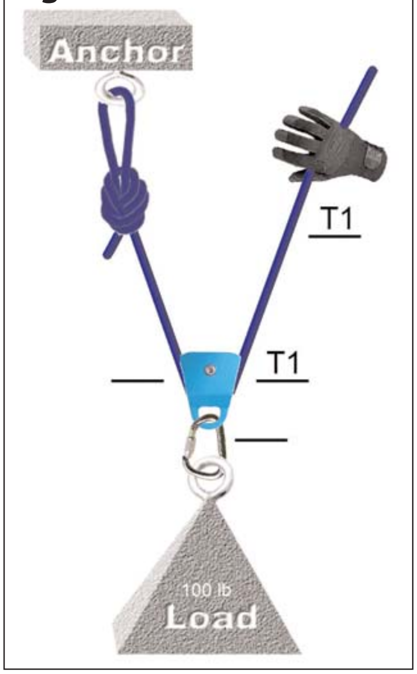
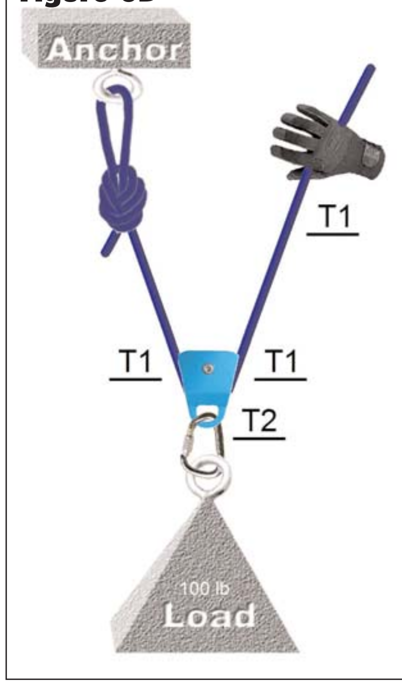


Figure 6D



ing down the T values at each pulley. This will be demonstrated shortly.

As you can see in *Figure 6D,* the force on the eye of our pulley is now 2. That means that the force on the carabiner connected to the pulley is also 2, as is the force on the load. The forces on the carabiner and load are shown in *Figure 6E* (on page 22).

4. Determine mechanical advantage—This step determines the mechanical advantage. Since we now know that the force on the load is 2 and the force on the hand is 1, we know that this is a 2:1 system. For every pound of force the rescuers put into our machine, we get two pounds of force out. So in this example, the

Figure 6E

hand is holding 50 pounds of our 100-pound load.

A Two-Pulley System

The system in *Figure 7A* contains two pulleys. Calculating the mechanical advantage of this system will follow the same four steps we just used, but Step 3 will be a little more complicated.

The first two steps have already been performed in *Figure 7A*. We drew three blank lines at the correct locations next to each of the pulleys to identify the T's crossbars and stems (Step 1). We then wrote T1 near the rope where the rescuers will be pulling (Step 2).

Step 3, filling in the blanks with T values, becomes more complicated due to the Prusik and the second pulley, but the basic process remains the same. Starting at the hand, move along the rope until you come to the first blank. This is the point where the rope enters the blue pulley. Write T1 in this blank, because that's the force coming from the hand. Then write T1 on the other side of the blue pulley, so the T's crossbar is balanced, and write T2 near the eye of the pulley, so the T's stem is balanced. This is shown in *Figure 7B*.

Now continue following the green rope from the blue pulley to the red one. When we reach the first blank line at the red pulley, write T1. Then write T1 on the other side of the red pulley, so the T's crossbar is balanced, and write T2 near the eye of the red pulley so the T's stem is balanced. This is shown in *Figure 7C*.

Do not assume that the value entering a pulley will always be T1 or that

Figure 7A

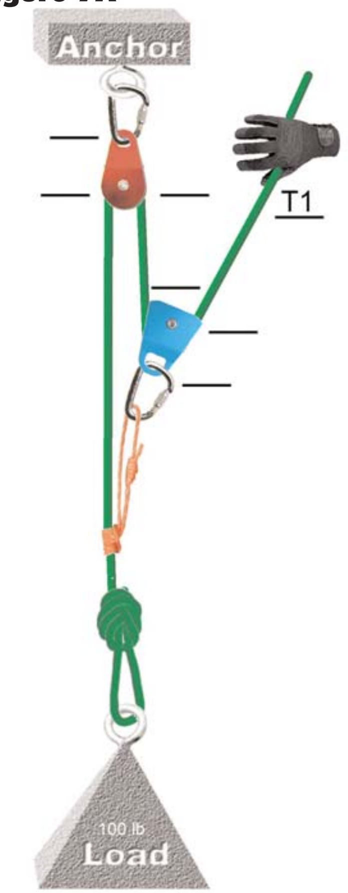


Figure 7C

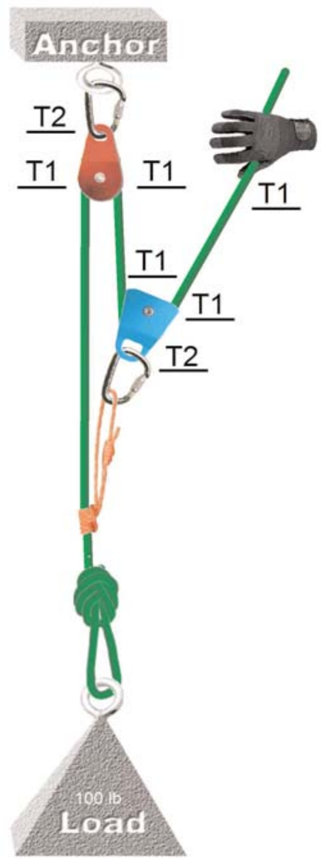


Figure 7B

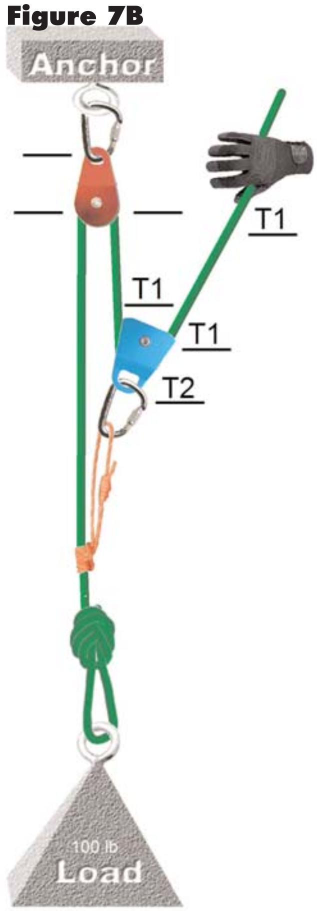
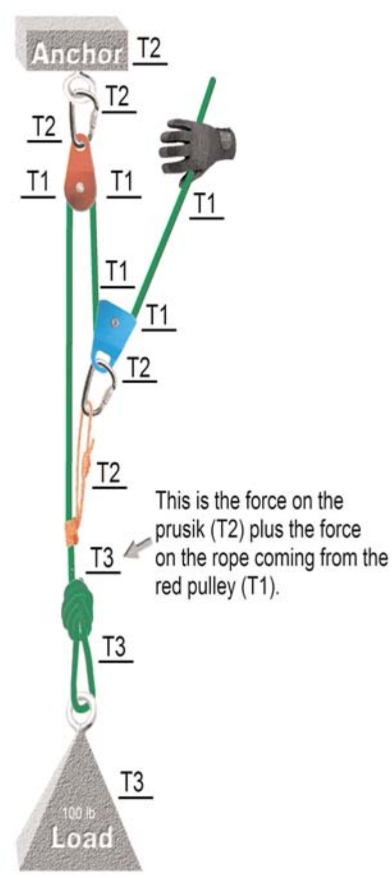


Figure 7D



the value at the eye of the pulley will always be T2. This has been the case in these examples, but it will not always be the case.

Since the force on the eye of the red pulley is 2, the force on the anchor is also 2. That should be fairly obvious. Similarly, since the force on the eye of the blue pulley is 2, the forces on the carabiner and Prusik below the blue pulley are also 2.

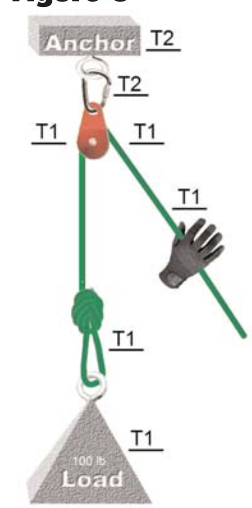
Here is where it gets a little more complicated: Since the force on the Prusik is 2 and the force on the rope coming from the left side of the red pulley is 1, the force on the rope just below the Prusik is 3 (i.e., 1+2). All of the T values have been labeled in *Figure 7D*. Make sure you understand how all of these values were calculated before reading further.

Step 4 determines the mechanical advantage. Since we now know that the force on the load is 3 and the force on the hand is 1, we know that this is a 3:1 system. For every pound of force rescuers put into this machine, they get three pounds out. In this example, the hand is holding 33.3 pounds of our 100-pound load.

A Pulley With a Twist

Figure 8 contains a system with one pulley. All of the T values have been calculated using the same four steps. Since we now know that the force on the load is 1 and the force on the hand is 1, we know that this is a 1:1 system. Even though this system has a pulley, there isn't any mechanical advantage! The hand is holding the full 100 pounds of our 100-pound load. This is a good example of the T-System preventing you from making a dangerous assumption.

Figure 8

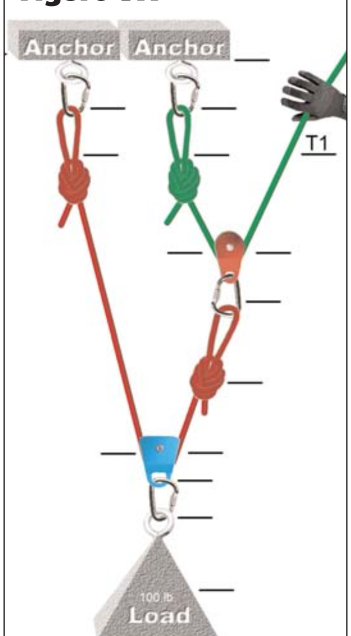


A Pulley Puzzle

Figure 9A contains a system with two pulleys. The first two steps have been completed for you. Try solving the mechanical advantage before peeking at the answer in *Figure 9B* (on page 24). Do not read any further if you want to solve the system shown in *Figure 9A*.

Solving this system is a little more difficult than the previous systems, because when the red rope enters the blue pulley, it already has a T value of 2. After balancing the T values at the blue pulley, you will find that the eye of the blue pulley (i.e., the T's stem) has a T value of 4. Thus, this is a 4:1 system. For every pound you put into this machine, you can lift four pounds of load. The hand only has to pull

Figure 9A



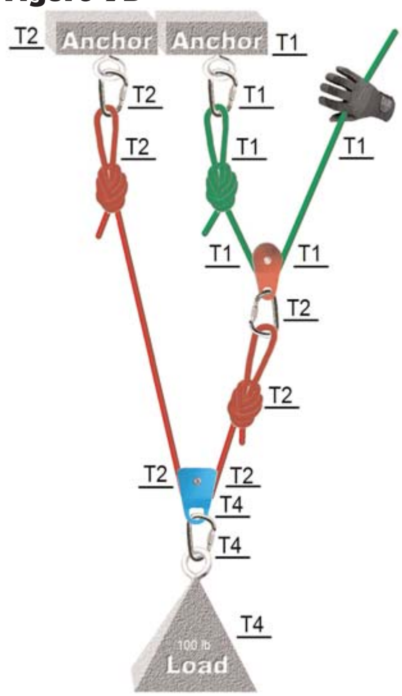
The T-System is a handy tool to calculate the mechanical advantage of a rope rescue system.

25 pounds to raise this 100-pound load.

It is also interesting to note that the anchor on the left has twice the load of the anchor on the right. This could be an important safety consideration.

Additional puzzles will be featured in future issues of *ART* Magazine.

Figure 9B



Conclusion

The T-System is a handy tool to calculate the mechanical advantage of a rope rescue system. It relies on your treating each pulley as a balanced T. The values on the ends of the T's crossbar must be balanced, and the value at the end of the T's stem must be balanced with the two values on the crossbar. You start with 1 where the rescuers will be pulling on the rope, and continue past each pulley while filling in the blanks. When you are done, you express the ratio by stating the value at the load compared to the value at the pullers (e.g., 2:1). ■

Steve Achelis is the vice commander of the Salt Lake County (UT) Sheriff's Search and Rescue Team. He is also the author of the RescueRigger software program that was used to create the illustrations in this article. For more information, visit www.rescuerigger.com or e-mail info@rescuerigger.com.

FIELD REPORT

Missing Subject on Lookout Mountain

By Hal Lillywhite

I was at work when the pager went off. The call was for a search that started at a civilized hour (9 a.m.) and in nice weather—what a deal! Nearby Hood River County was requesting help on a search that had been running for about three days. I arranged to leave work, then went home to pack for the mission. A 100-mile drive took five of us to the search base.

The Site

Lookout Mountain is an ancient shield volcano about 10 miles east of Oregon's Mt. Hood. A relatively easy trail takes hikers to the 6,525-foot summit, where, on a clear day, they are rewarded with views of eight major Cascade peaks. That summit was the apparent destination of our 38-year-old female subject.

The Search

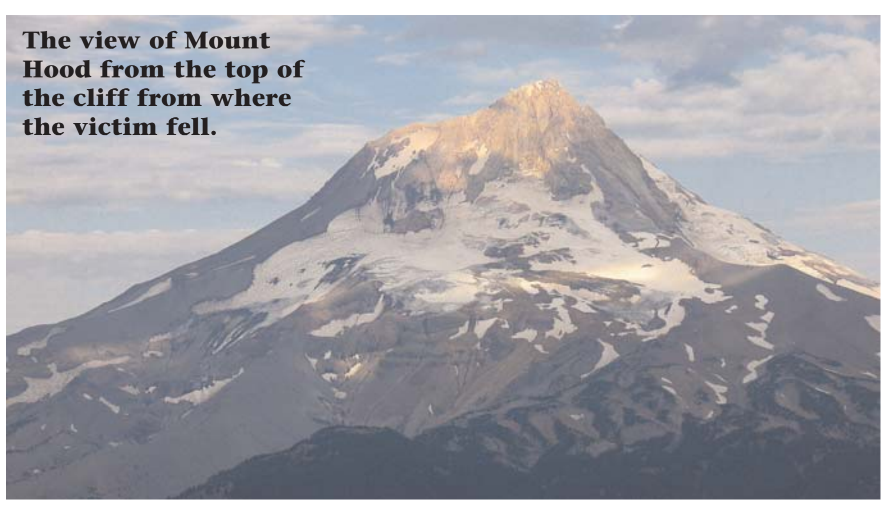
We staged at the trailhead and were assigned to search a moderately steep area between the trail and the road to Badger Lake. Other teams had already searched the areas on both sides of the trail and around the summit, with no results. Now it was time to search areas of lower POA (probability of area, the likelihood that the subject is in a given search area) that previously had been checked only from the air.

The terrain was fairly open and easy to search, at least compared to the areas west of the Cascade Range, where my agency, Portland Mountain Rescue, usually works. There were a few trees and some brush mixed with rocky, open areas. We started a grid search, with spacing of about 10 yards in the vegetated areas and 50–100 yards in the open areas. With that spacing, our POD (probability of detection, the probability that a search resource would find the subject if he/she were in the area) was 85%–90%.

Our first sweep went up from the road, then back toward base, ending when we encountered flagging placed by Explorer Scouts who had searched the area previously. Then we started back south, sweeping just below the trail. Initially we were in a vegetated area that slowed our progress and forced us to shorten the line to get good coverage. After about an hour, we entered a more-open area where we could spread out and cover a wider swath. Now the obstacles were rocks, talus and ridges. Views at times were spectacular: We had a good view of Mt. Hood and could look down on the valley and road to Badger Lake.

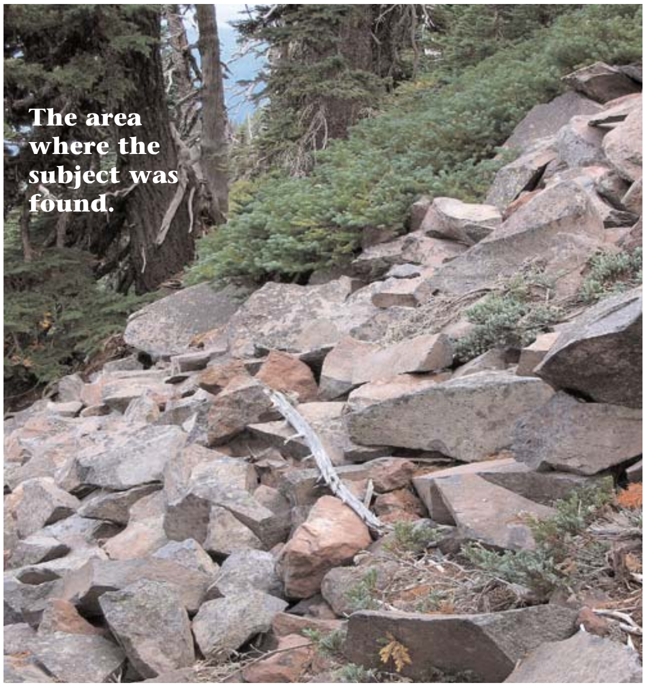
The Find

We were probably two-thirds done with our second sweep when Linda (not her real name), our least-experienced team member, reported that she saw a backpack in the talus. A more-experienced searcher asked her to check it out. About 30 seconds later Linda screamed, "We need help, we need help!" The pack was on the back of the subject. Every rescuer has a first time actually finding a subject. This was Linda's first find, and she thought she had found a body. However, she calmed down and determined that the



The view of Mount Hood from the top of the cliff from where the victim fell.

Photos by Hal Lillywhite



The area where the subject was found.

subject was alive, though unconscious. Our subject was in a fetal position on a declivity in the talus. The location, under a rock face about 20 feet high, pointed to a fall, with a high probability of spinal and head injuries.

The Rescue

Linda and Doug, the EMTs on our team, started examining the patient while I informed base of the find. A land evacuation would be bumpy and time-consuming, so I requested a helicopter. Then I sent the other two members of our team to scout evacuation routes in case we couldn't get air support. Our EMTs determined that this patient should get full spinal precautions and leg splints. She was also suffering from hypothermia.

Several other teams were nearby, and we soon had all the help we could use. Somebody brought a backboard, a basket litter and a bottle of oxygen from base. We splinted and backboarded the patient and gave her oxygen. We knew the crew on any helicopter would want to use their own litter, so we kept ours in reserve.

Our concern about not getting air support was unfounded. Though the Air Force 939th Air Rescue and Recovery Wing, out of Portland, is a reserve unit, it had a crew available that evening. As dusk approached, a helicopter arrived overhead and lowered a crew member and equipment. We quickly packaged the patient in their mesh litter and caterpillared her a few yards to a clearer area. By then it was fully dark, and we got to see what a good pilot could do with modern equipment. The aircraft hovered near both the cliff and some trees while winching up the crew member and our patient. Our patient was in the hospital before we got back to base.

Aftermath

Our subject had T12 and L1 fractures, one knee and one ankle nearly destroyed, and two broken ribs. Seeing where she fell, I was amazed she didn't fracture her skull. I don't know her ultimate outcome, but I was gratified when the trauma center found that she had feeling in her legs in spite of the fractured vertebrae. I was also glad we found her when we did: The weather, which had been mild while she was lost, turned cold right after she was rescued. I doubt she would have survived another night in the open. ■

Hal Lillywhite is a rescue-level member of Portland (OR) Mountain Rescue.