Climbing Falls and Impact Forces

SKILLZBOARD

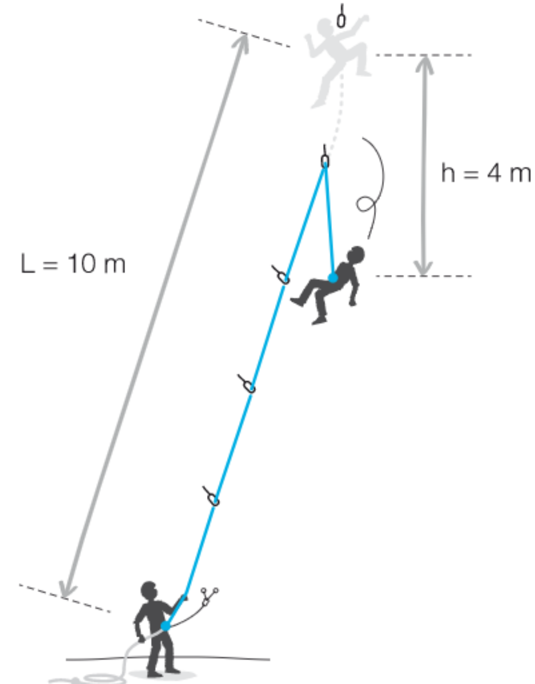
Background

It is widely recognized that an important parameter that determines the maximum force experienced by a falling climber is the *fall factor*.

But what is less well known is the relationship between the maximum force and the fall factor.

Is this relationship linear or something else? Is there a simple rule of thumb that helps us estimate forces?

And what are the other factors that affect these forces and how important are they? What role does the weight of the climber play, for instance?



$$F = \frac{4}{10} = 0,4$$

Image: Petzl.com

Rule of Thumb

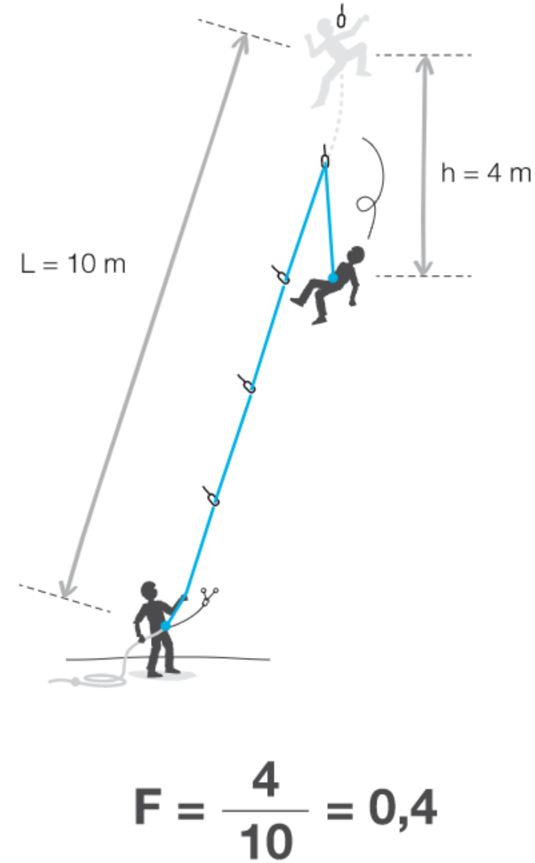
In the idealized case of a clean fall with minimal rope drag and when the belayer is not noticeably lifted up in the air, the *maximum force experienced by the climber* during the fall can be quickly estimated by a simple rule of thumb:

$$F_{max} = \sqrt{2WC(FF)}$$

where W = weight of climber,

C = stiffness of rope, and

FF, Fall Factor = $\frac{fall\ distance}{length\ of\ rope\ out}$



For average values of climber weights and stiffness of dynamic rope, this is roughly:

$$F_{max} \approx 4\sqrt{(FF)}$$

Image courtesy: Petzl.com

Simpler Rule of Thumb

For a clean fall on lead or top-rope, *the maximum force experienced by the climber* (weighing 80 kg or 176 lbs) is approximately given by (in kN):

$$F_{max} \approx 4\sqrt{(FF)}$$

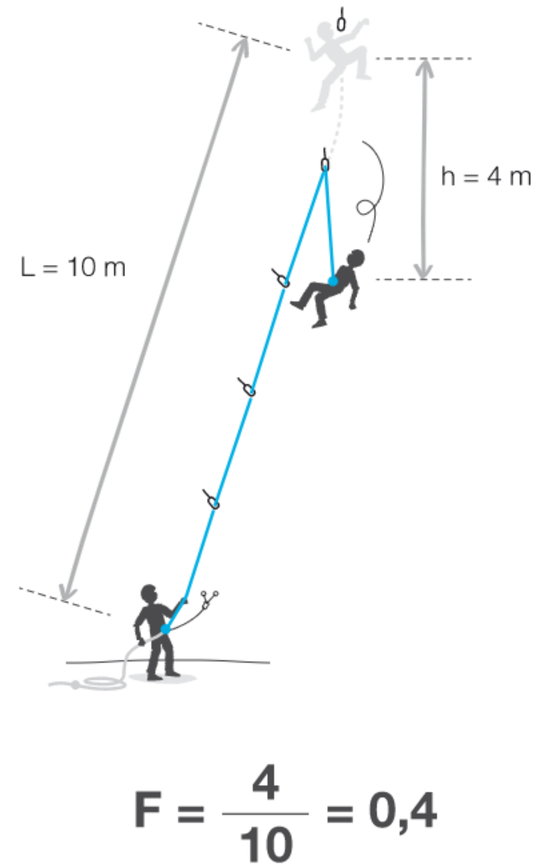
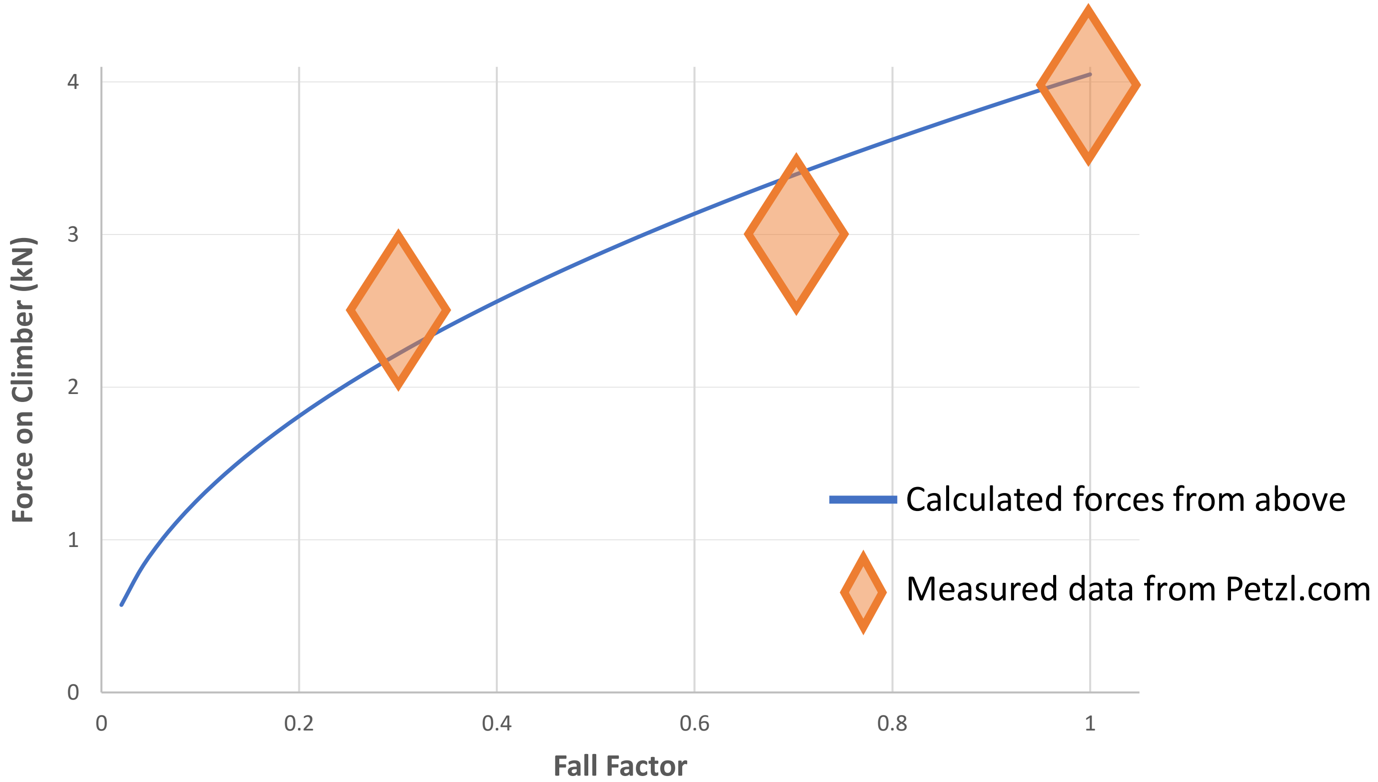


Image courtesy: Petzl.com

Testing the Theory

$$F_{max} = 4.0\sqrt{(FF)}$$

80 kg (176 lb) climber on a Petzl Volta 9.2 mm dynamic rope



This simple model agrees pretty well with measured data, especially if you keep in mind that Petzl has rounded off the force values to the nearest 0.5 kN.

Some Examples

$$F_{max} = \sqrt{2WC(FF)}$$

Example 1

80 kg (176 lb) climber on a Petzl Volta 9.2 mm dynamic rope

Weight of climber, $W = 80\ kg \times 9.8\ m/s^2 = 0.78\ kN$

From the spec sheet for this rope, $C = 80\ kg \times 9.8\ m/s^2\ /\ 7.5\% = 10.5\ kN$

$$\sqrt{2WC} = 4.0\ kN$$

Some Examples

$$F_{max} = \sqrt{2WC(FF)}$$

Example 2

60 kg (132 lb) climber on a Petzl Volta 9.2 mm dynamic rope

Weight of climber, W = 60 kg x 9.8 m/s^2 = 0.59 kN

Stiffness of the rope doesn't change, so C = 10.5 kN

$$\sqrt{2WC} = 3.5\ kN$$

Some Examples

$$F_{max} = \sqrt{2WC(FF)}$$

Example 3

100 kg (220 lb) climber on a Petzl Volta 9.2 mm dynamic rope

Weight of climber, W = 100 kg x 9.8 m/s^2 = 0.98 kN

Stiffness of the rope doesn't change, so C = 10.5 kN

$$\sqrt{2WC} = 4.5\ kN$$

Forces during a Big Lead Fall

Big lead falls where the climber ends up at roughly the same height as the belayer involve the largest fall factors typically encountered in a climbing scenario and tend to be in the range of 0.7 to 1. At the maximum value of *FF* = 1, the maximum force on the climber is:

$$F_{max} = \sqrt{2WC(FF)} \approx 4 \text{ kN}$$

In extremely rare cases, for instance, above the first pitch of a multi-pitch climb, or if the belay station of a single pitch route is at an elevated ledge, it is possible to fall significantly below the belayer and create a fall factor as large as *FF* = 2. In this extreme case, the force on the climber is:

$$F_{max} = \sqrt{2WC(FF)} \approx 5.7 \text{ kN}$$

Forces during a Big Lead Fall

At *FF* = 1, the maximum force on the climber is:

$$F_{max} = \sqrt{2WC(FF)} \approx 4 \text{ kN}$$

At *FF* = 2, the maximum force on the climber is:

$$F_{max} = \sqrt{2WC(FF)} \approx 5.7 \text{ kN}$$

<u>A quick note on the experience of *tensile forces* on the human body:</u>

3 to 5 kN = uncomfortable for most adults

5 to 8 kN = painful to very painful for most adults

Over 8 kN = strong potential for permanent spine damage

Forces during a Top Rope Fall

During a top rope fall with an attentive belayer, the fall distance is equal to the length that the rope stretches (i.e: no slack in the rope).

Therefore:

$$mgh = \frac{C}{2l_0}(\Delta l_{max})^2 = \frac{C}{2l_0}h^2$$

This can be rearranged to give:

$$FF = \frac{h}{l_0} = \frac{2W}{C}$$

These fall factors are small. Plugging some numbers gives: *FF* = 0.1 to 0.2

Forces during a Top Rope Fall

During a top rope fall with an attentive belayer, the fall factors are pretty small and given by: $FF = 2W/C$

More interestingly though, we can plug this back into the equation for the maximum force on the climber, to find that:

$$F_{max} = \sqrt{2WC(FF)} = \sqrt{2WC(2W/C)} = 2W$$

The maximum force on the climber is twice the climber's weight or about 1 – 2 kN. In practice, this rarely exceeds 1.5 kN.

The theoretical maximum force on the anchor is up to twice that force, or 2 – 4 kN. In reality, this number is usually smaller than 3 kN, even with a somewhat inattentive belayer allowing a few feet of slack in the rope.

Forces on Other Parts of the System

In the limiting case of zero friction and weightless rope, the rope exerts the same upward force on the climber and the belayer. In practice, however, the belayer often experiences significantly lower forces than the climber, mostly due to friction at the anchor or top piece.

Typical values: max force on belayer = (0.4 to 0.6) × max force on climber

The greatest forces in this system are typically experienced by the top anchor, topmost bolt or highest piece of gear that the climber falls on. This is essentially because the top piece supports the weight of the climber and the belayer.

Typical values: max force on top piece = (1.5 to 2) × max force on climber

A Few Additional Considerations

The formula provided here is intended to only be a quick and easy way to get an approximate answer and is based on average values of climber weight, rope stiffness and our ability to quickly and reasonably estimate a fall factor for any given scenario.

But how badly off are we likely to be in each of these numbers, and how much does that affect our estimate of the maximum force?

The good news is that since the force depends only on the square root of these terms, being off by say 50% in one of them only affects the force by about 23% … this is still usually plenty good for helping us assess the severity of a fall or whether a piece of gear or anchor is likely to hold.

A Few Additional Considerations

The three variables that appear in the final equation are:

- The weight of the climber
- The stiffness of the Rope
- The fall factor

As seen in the three examples considered before, changing the climber weight significantly (from 60 kg to 100 kg or 130 lbs to 210 lbs) only changes the pre-factor from 3.5 to 4.5

Most dynamic climbing ropes have similar stiffnesses, specified for instance, in terms of static elongation (for an 80 kg climber). Typical values range from 6% to 9%. Once again, this entire range changes the pre-factor from 3.5 to 4.5. Old ropes, close to the end of their lifetime tend to become stiffer, at which point, pre-factors of up to 5 are possible.

Estimating the Fall Factor

It's not always easy to estimate the fall factor accurately. There are two common approximations made in estimating the fall factor:

- It's not easy to visually estimate the total rope length, especially if it zig-zags at multiple spots. Simple straight-line estimates will therefore often underestimate the total rope length and overestimate fall factor.
- Zig-zagging of the rope can cause significant frictional forces on the rope at each carabiner that it makes contact with. This reduces the effective length of the rope to a value smaller than the true length of rope, making the real fall factor greater than the theoretical value.

Except in situations of extreme rope drag created by a few sharp turns in the rope, the above two factors often partially offset each other.

Derivation: Max Force on Climber

Approximate the rope as a linear, elastic medium obeying Hooke's Law:

$$F = C\frac{\Delta l}{l_0}$$

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Force on climber's end of rope (F)

Stiffness of rope (C)

Increase in length of rope from stretching (Δl)

Unstretched length of rope between climber and belayer (l_0)

Derivation: Max Force on Climber

- Consider the duration beginning with when the climber is about to fall and ending at the instant when the climber is instantaneously at rest at the end of the fall, when the rope is at maximum stretch.

- The non-conservative work done on the climber goes into changing the climber's total energy: gravitational potential energy + kinetic energy.

- We neglect the weight of the rope in relation to the humans and assume the belayer is not lifted up into the air. Since the kinetic energy at the start and end is zero, this implies the loss in gravitational potential energy of the falling climber must exactly match the (negative) work done by the rope on the climber.

Derivation: Max Force on Climber

Approximate the rope as a linear, elastic medium obeying Hooke's Law:

$$F(l) = C\frac{\Delta l}{l_0} = C\left(\frac{l - l_0}{l_0}\right)$$

From the work-energy theorem:

$$mgh = \int_{l_0}^{l_{max}} F(l)dl = \frac{C}{2l_0}(\Delta l_{max})^2$$

$$\Rightarrow \frac{C^2}{l_0^2}(\Delta l_{max})^2 = 2mgh\left(\frac{C}{l_0}\right)$$

$$\Rightarrow F_{max}{}^2 = 2(mg)C\left(\frac{h}{l_0}\right)$$

$$\Rightarrow F_{max} = \sqrt{2WC(FF)}$$

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W = climber's weight

FF = h/l_0

$$\Rightarrow F_{max} = \sqrt{2WC(FF)}$$

Sources of Error

How big are the errors in this simple formula, and what causes them?

As it turns out, friction between the rope and carabiners does not affect the final equation but it does affect our ability to determine the fall factor accurately (as described earlier). It also plays a significant role in determining the forces on the belayer and other parts of the system between the climber and belayer (for instance, a top bolt or anchor).

A second assumption is ignoring the elasticity and damping from the climber's harness and body. Stiffness constants for springs connected in series (what's happening here) combine like resistors in parallel. The harness and body tend to be much stiffer than the rope, except in the case of very short falls. The result is that these factors can be neglected within this approximation and that works well for all but the very shortest of falls.

Sources of Error

A third and important assumption in our calculation is that the rope is a linear elastic medium obeying Hooke's Law with one stiffness constant, *C*, for the entire range of falling scenarios.

Force vs elongation curves measured on different ropes show a fairly linear behavior for moderate falls but the value of *C* can vary somewhat as fall factors get significant.

For instance, the Petzl Volta 9.2 is rated at 7.5% static elongation (very small fall factors) and 33% dynamic elongation (fall factor 1). Calculating *C* from these numbers gives *C* = 10.5 kN for small falls and *C* = 14 kN for very severe falls.

This changes the pre-factor in the force calculation from 4.0 for gentle falls to 4.7 for very severe falls for an 80 kg (176 lb) climber.

Summary

- Max force on climber: $F_{max} = \sqrt{2WC(FF)}$
- For a very light climber on a skinny, stretchy rope, $\sqrt{2WC} \sim 3\ kN$
- For a fairly heavy climber on an older, stiffer rope, $\sqrt{2WC} \sim 5\ kN$
- Fall factors (FF values) typically lie in the range of 0.25 to 0.75 in most lead fall scenarios, so $\sqrt{(FF)} \sim 0.5\ to\ 0.9$
- Multiply these numbers to determine the max impact force on climber
- Topmost piece rope is clipped to experiences 1.5x to 2x the climber's force
- For low rope drag, force on belayer ~ 0.4x to 0.6x the climber's force
- For higher rope drag or if using an assisted braking device like the Edelrid Ohm, force on belayer ~ 0.2x to 0.4x the force on the climber