# Climbing Fall Calculator

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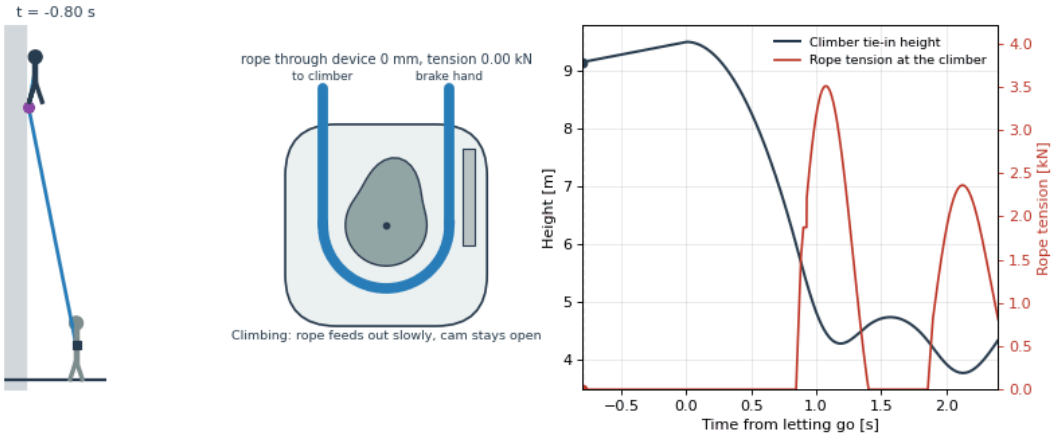
# Climbing Fall Calculator: Catching a Lead Fall with an Assisted-Braking Belay Device

A lead climber falls past their last quickdraw. How hard does the rope pull, how far do they drop, does the belayer get yanked off the ground, and do they stop before the deck? This page answers that end to end: it works out the rope's stiffness from the impact force printed on its label, the fall factor and the classic closed-form peak force, then runs a time-step simulation in Python of the climber, the rope, the friction over the top quickdraw, the belay device letting rope run until its cam bites, and the belayer being lifted. The simulation is checked against the closed form, and the results are checked for ground clearance and the load on the top quickdraw.

> 💡 This is a fun example of what a calculation page can do, not a safety tool. It is an idealised one-dimensional model with a linear rope. Real falls involve rope drag over many quickdraws, swings, the belayer moving toward the wall and how you belay. Learn to belay from a qualified instructor and follow your device maker's instructions.

## Summary

*Lead fall caught by a belay device*



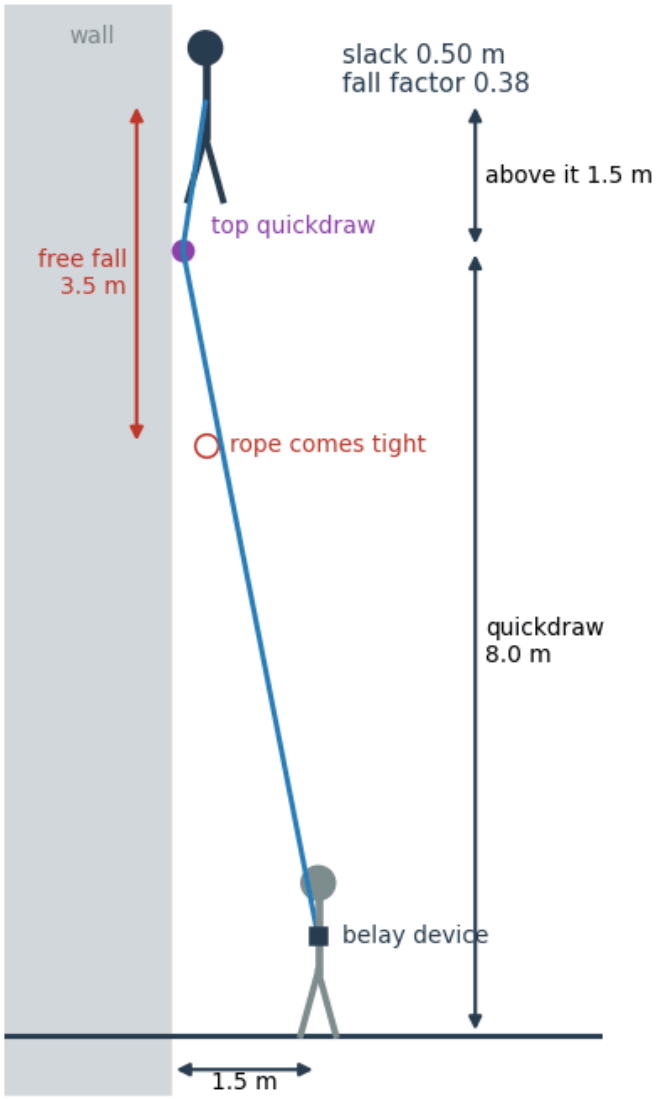

| Check | Status |
|---|---|
| Climber's feet stay clear of the ground | true |
| Peak load on the top quickdraw is within its rating | true |
| Peak force on the climber is below the rope's rated impact force | true |
| Simulated hard catch agrees with the closed form within 1% | true |
| Time step resolves the rope's bounce | true |

| | |
|---|---|
| Rope diameter is within the device's compatible range | true |
| Rope diameter is in the device's optimal range | true |

| Quantity | Value |
|---|---|
| Fall factor | 0.38 |
| Peak force on the climber | 3.51 kN |
| Peak force at the belay device | 1.87 kN |
| Peak load on the top quickdraw | 5.34 kN |
| Total height lost | 5.72 m |
| Rope run through the device | 50 mm |
| Belayer lifted | 1.74 m |
| Lowest clearance at the feet | 2.78 m |

# The problem

*Design sketch*




The climber is above their top quickdraw and lets go. They free fall twice their height above the quickdraw plus whatever slack is in the system before the rope comes tight. From then on the rope stretches and brakes them, the rope running over the quickdraw loses some of its tension to friction, the belay device lets a little rope run before it locks, and the belayer, if they are not anchored, is pulled up toward the first quickdraw, which softens the catch but adds to the drop.

The questions a climber cares about: will I hit the ground or a ledge, how hard will the catch feel, and how much load goes into the top quickdraw? Change any input below and the sketch, the simulation and every check update.

# Inputs

**The fall.** Heights are of the climber's tie-in point (harness), measured from the ground:

| | | | |
|---|---|---|---|
| Climber mass, $m_{climber}$ | $= 80\ \text{kg}$ | Top quickdraw height, $h_{bolt}$ | $= 8\ \text{m}$ |
| Height above the quickdraw, $h_{above}$ | $= 1.5\ \text{m}$ | Slack in the system, $L_{slack}$ | $= 0.5\ \text{m}$ |
| Tie-in height above feet, $h_{tie}$ | $= 1\ \text{m}$ | | |

**The belayer.** A soft catch lets the belayer be pulled up off the ground; an anchored belayer gives a hard catch:

| | | | |
|---|---|---|---|
| Belayer mass, $m_{belayer}$ | $= 75\ \text{kg}$ | Belay mode, $belay_{mode}$ | `'Belayer lifts (soft catch)'` |
| Distance out from the wall, $d_{belayer}$ | $= 1.5\ \text{m}$ | Device height above feet, $h_{device}$ | $= 1\ \text{m}$ |

**The belay device.** An assisted-braking device lets a little rope run while its cam rotates, then pinches it. A tube device holds whatever the belayer's brake hand can grip, multiplied by the friction in the device:

| | | | |
|---|---|---|---|
| Device, $device_{type}$ | `'Assisted-braking cam'` | Rope run before the cam locks, $s_{lock}$ | $= 50\ \text{mm}$ |
| Resistance while the cam closes, $F_{cam}$ | $= 1\ \text{kN}$ | Tube device holding force, $F_{brake}$ | $= 1.5\ \text{kN}$ |

**The rope and the quickdraw.** The rated impact force is printed on every dynamic rope's label (EN 892 / UIAA 101). The friction coefficient is an effective value for the rope running over the carabiner, including some rope drag:

| | | | |
|---|---|---|---|
| Rated impact force, $F_{rated}$ | $= 8.8\ \text{kN}$ | Rope damping ratio, $\zeta_{rope}$ | $= 0.1$ |
| Rope to carabiner friction, $\mu_{biner}$ | $= 0.2$ | Wrap angle at the quickdraw, degrees, $\theta_{wrap^\circ}$ | $= 180$ |

**Rope diameter and the device's rope range.** Defaults are the Petzl GRIGRI's published range (see the spec section below):

| | | | |
|---|---|---|---|
| Rope diameter, $d_{rope}$ | $= 9.5\ \text{mm}$ | Device minimum rope, $d_{dev,\,min}$ | $= 8.5\ \text{mm}$ |
| Device maximum rope, $d_{dev,\,max}$ | $= 11\ \text{mm}$ | Optimal range, lower, $d_{opt,\,min}$ | $= 8.9\ \text{mm}$ |
| Optimal range, upper, $d_{opt,\,max}$ | $= 10.5\ \text{mm}$ | | |

**Limits and standard test.** The quickdraw rating is the weakest major-axis strength in it (EN 12275 carabiners are at least 20 kN). The EN 892 single-rope drop test uses an 80 kg mass at a fall factor of 1.77:

| | | | |
|---|---|---|---|
| Quickdraw rating, $F_{anchor,\,rating}$ | $= 20\ \text{kN}$ | Required clearance at the feet, $z_{clear,\,req}$ | $= 0.5\ \text{m}$ |
| Test mass, $m_{test}$ | $= 80\ \text{kg}$ | Test fall factor, $f_{test}$ | $= 1.77$ |
| Gravity, $g_n$ | $= 9.81\ \text{m/s}^2$ | | |

**Simulation and chart settings.** The time step should be a small fraction of the rope's bounce period:

| | | | |
|---|---|---|---|
| Simulated time, $t_{sim}$ | $= 3\ \text{s}$ | Time step, $dt_{sim}$ | $= 0.2\ \text{ms}$ |
| Animation frames, $animation_{frames}$ | $= 30$ | | |

## Rope stiffness from the label

Every dynamic rope is drop tested to EN 892 (and UIAA 101): an 80 kg mass falls on a short length of rope at a fall factor of 1.77, and the peak force on the mass is the rated impact force on the label. Treating the rope as a linear spring of stiffness $EA/L$, an energy balance gives the classic peak force for a fall factor $f$:

**$F = W + \sqrt{(W^2 + 2\,W \cdot EA \cdot f)}$**

Run backwards with the test mass and fall factor, the rated impact force gives the rope's effective modulus, $EA$, the force that would stretch it to double its length:

| | |
|---|---|
| $W_{test} = m_{test} \cdot g_n$ | $0.785\ \text{kN}$ |

| | |
|---|---|
| $EA_{rope} = \frac{F_{rated} \cdot (F_{rated} - 2 \cdot W_{test})}{2 \cdot W_{test} \cdot f_{test}}$ | 22.90 kN |

Lower rated impact force means a stretchier rope and a softer catch.

## Fall factor and the closed-form catch

The fall factor is the free fall divided by the rope paid out. It, not the length of the fall, sets how hard the catch is: a long fall high on a route with lots of rope out can be softer than a short one close to the belay.

| | |
|---|---|
| $L_{belay,\ side} = \sqrt{(h_{bolt} - h_{device})^2 + {d_{belayer}}^2}$ | 7.16 m |
| $L_{rope,\ out} = L_{belay,\ side} + h_{above} + L_{slack}$ | 9.16 m |
| $h_{free} = 2 \cdot h_{above} + L_{slack}$ | 3.5 m |
| $fall_{factor} = \frac{h_{free}}{L_{rope,\ out}}$ | 0.382 |
| $v_{catch} = \sqrt{2 \cdot g_n \cdot h_{free}}$ | 8.29 m/s |

For a hard catch, with the belayer fixed, no friction at the quickdraw and no rope running through the device, the peak force on the climber follows from the same energy balance:

| | |
|---|---|
| $W_{climber} = m_{climber} \cdot g_n$ | 0.785 kN |
| $F_{cf} = W_{climber} + \sqrt{{W_{climber}}^2 + 2 \cdot W_{climber} \cdot EA_{rope} \cdot fall_{factor}}$ | 4.57 kN |

Friction over the quickdraw follows the capstan equation: the belayer's side carries only a fraction of the climber's side tension:

| | |
|---|---|
| $friction_{ratio} = \exp(-\mu_{biner} \cdot \theta_{wrap^\circ} \cdot \pi \ / \ 180)$ | 0.533 |

## How the simulation works

The climber and the belayer are point masses moving vertically. The rope from the climber, over the quickdraw and down to the device is one spring whose unstretched length is the rope paid out plus any rope that has run through the device. At each time step:

- **Rope tension.** Stretch is the rope's path length minus its unstretched length. Tension is the elastic force $EA\,\delta/L$ plus viscous damping set by the damping ratio, with the damping never larger than the elastic force, so a rope that has just come tight cannot jerk the climber before it stretches. A slack rope carries nothing.
- **Quickdraw.** The belayer's side carries the climber's side tension times the capstan friction ratio. The quickdraw carries both.
- **Belay device.** If the belayer's side tension exceeds what the device holds, rope runs through until it does not. A cam device resists with the cam closing force until the set length of rope has run, then locks for good. A tube device holds only the set holding force throughout, so it keeps feeding rope in a big fall.
- **Belayer.** In a soft catch the belayer leaves the ground when the vertical pull beats their weight, and comes back down onto it.

The equations of motion are stepped forward with the semi-implicit Euler method, which is stable and accurate at a step much smaller than the rope's bounce period:

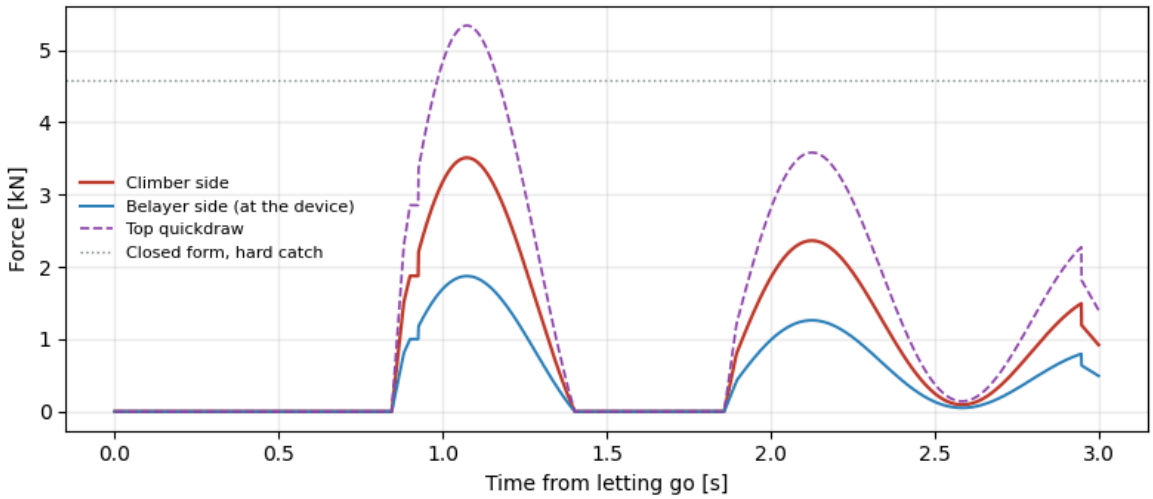
| | |
|---|---|
| $T_{rope} = 2 \cdot \pi \cdot \sqrt{\frac{m_{climber} \cdot L_{rope,\,out}}{EA_{rope}}}$ | $1.124\ \mathrm{s}$ |
| $step_{resolved} = dt_{sim} \leq T_{rope} \,/\, 200$ | OK |

**What this is and is not.** This is a one-dimensional lumped model with a linear rope. Real dynamic ropes stiffen as they stretch and lose much of their energy in the first catch, rope drag over several quickdraws and edges cuts the force reaching the belayer, belayers are pulled toward the wall as well as up, and the climber swings into the wall. Cam devices differ in how much rope runs before they lock. A full multibody model with a flexible rope and the actual device geometry captures far more (see Credit, below). Treat the numbers here as a feel for how the inputs trade off, not a prediction.

The simulation is the Python node Fall_Simulation: a stepping loop of about forty lines, a second hard-catch run used as the benchmark, a four-way device comparison, and the charts.

## Rope force through the catch

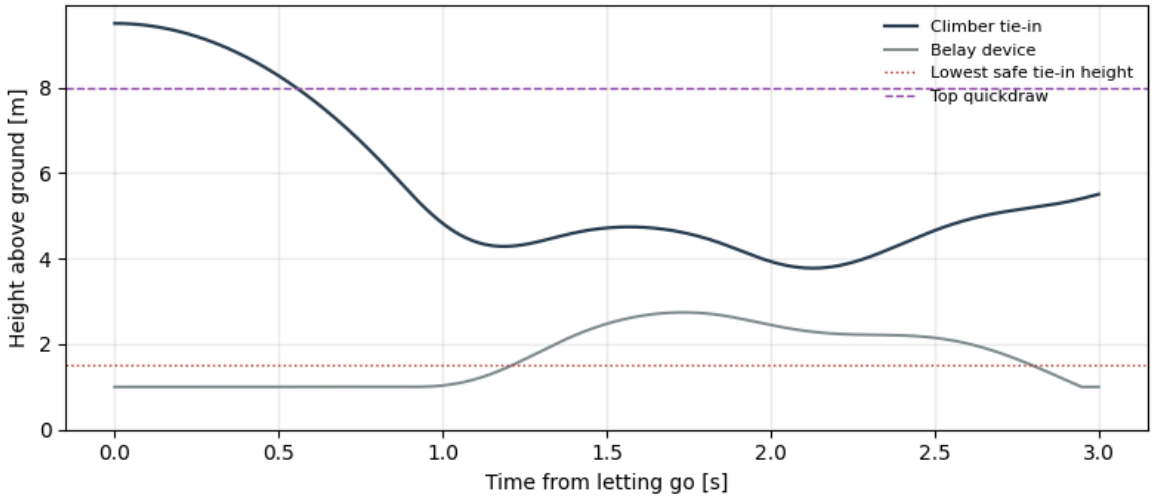
*Rope force history*




Rope tension at the climber, at the belay device and the vertical load on the top quickdraw. The flat step as the rope first loads is the device letting rope run while its cam closes; once it locks the tension climbs to its peak. The second hump is the belayer dropping back to the ground and the rope loading again. The dotted line is the closed-form hard catch.

## Climber and belayer heights

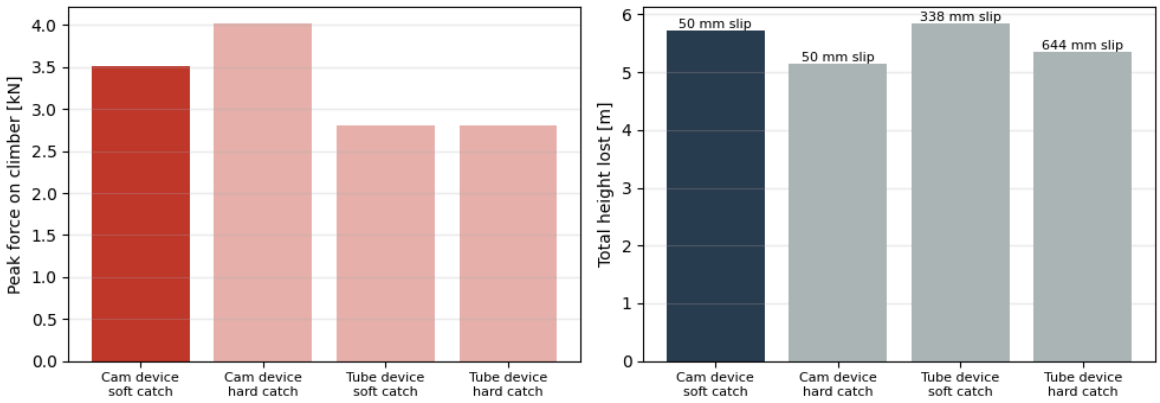
*Climber and belayer height*




The climber's tie-in drops through the free fall, decelerates as the rope stretches, and bounces. The belay device rises as the belayer is lifted. The dotted red line is the lowest the tie-in can go while keeping the required clearance under the climber's feet.

## Device and belay comparison

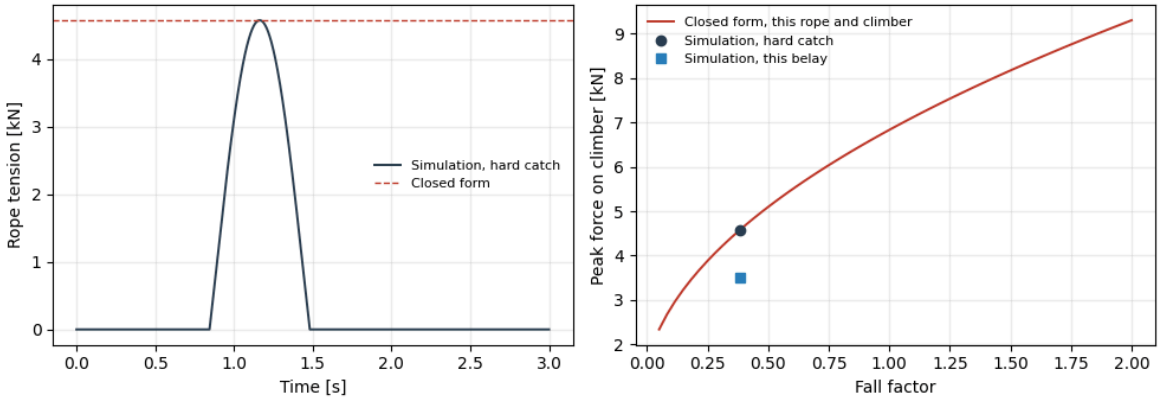
*Device and belay comparison*




The same fall run four ways, with the current case in strong colour. A soft catch lowers the peak force but adds the belayer's lift to the drop. A tube device that cannot hold the load lets rope run, which softens the catch further but adds more height loss, and it depends on the belayer's grip.

## Checking the simulation

*Benchmark against the closed form*




The benchmark is a second run of the same fall with friction, damping, slip and belayer movement switched off. That is exactly the case the closed form describes, so the simulated peak should match it to within the time-step error. The right-hand chart shows the closed form across fall factors, with the hard-catch simulation on it and the real belay below it.

| | |
|---|---|
| $F_{bench} = F_{bench,\,kN} \cdot 1\ \mathrm{kN}$ | $4.57\ \mathrm{kN}$ |
| $bench_{error} = \left\lvert \frac{F_{bench}}{F_{cf}} - 1 \right\rvert$ | $1.185 \times 10^{-7}$ |
| $bench_{agrees} = bench_{error} \leq 0.01$ | OK |

## Checks

The simulation reports the peak forces, the lowest point of the tie-in and how far the rope and belayer moved:

| | |
|---|---|
| $F_{peak} = F_{peak,\,kN} \cdot 1\ \mathrm{kN}$ | $3.51\ \mathrm{kN}$ |
| $F_{belayer} = F_{belayer,\,kN} \cdot 1\ \mathrm{kN}$ | $1.872\ \mathrm{kN}$ |
| $F_{anchor} = F_{anchor,\,kN} \cdot 1\ \mathrm{kN}$ | $5.34\ \mathrm{kN}$ |
| $drop_{total} = drop_{m} \cdot 1\ \mathrm{m}$ | $5.72\ \mathrm{m}$ |
| $slip_{device} = slip_{mm} \cdot 1\ \mathrm{mm}$ | $50\ \mathrm{mm}$ |
| $lift_{belayer} = lift_{m} \cdot 1\ \mathrm{m}$ | $1.743\ \mathrm{m}$ |
| $t_{lock} = lock_{ms} \cdot 1\ \mathrm{ms}$ | $80.4\ \mathrm{ms}$ |
| $peak_{g} = a_{peak,\,g}$ | $4.47$ |

The climber's feet are the tie-in height minus the tie-in to feet distance; they must stay above the ground by the required clearance. The quickdraw load is checked against its rating, and the peak force on the climber against the rope's rated impact force, which is the harshest catch the rope is designed for:

| | |
|---|---|
| $z_{low} = z_{low,\,m} \cdot 1\ \mathrm{m}$ | $3.78\ \mathrm{m}$ |
| $clearance = z_{low} - h_{tie}$ | $2.78\ \mathrm{m}$ |
| $deck_{free} = clearance \geq z_{clear,\,req}$ | OK |
| $anchor_{util} = \frac{F_{anchor}}{F_{anchor,\,rating}}$ | $0.267$ |
| $anchor_{ok} = F_{anchor} \leq F_{anchor,\,rating}$ | OK |
| $softer_{than,\,test} = F_{peak} \leq F_{rated}$ | OK |

## Results

A $80\ \mathrm{kg}$ climber falling from $1.50\ \mathrm{m}$ above a quickdraw at $8.0\ \mathrm{m}$, with $0.50\ \mathrm{m}$ of slack, free falls $3.50\ \mathrm{m}$ and reaches $8.3\ \mathrm{m/s}$ when the rope comes tight. With $9.16\ \mathrm{m}$ of rope out, that is a fall factor of $0.38$.

The rope peaks at $3.51\ \mathrm{kN}$ on the climber, about $4.5$ times their weight, against $4.57\ \mathrm{kN}$ for a hard catch. The device let $50\ \mathrm{mm}$ of rope run before locking, $80\ \mathrm{ms}$ after the rope came tight, and the belayer was lifted $1.74\ \mathrm{m}$. In total the climber dropped $5.72\ \mathrm{m}$, leaving $2.78\ \mathrm{m}$ under their feet. The top quickdraw saw $5.34\ \mathrm{kN}$, a utilisation of $0.27$ of its rating.

If the clearance check fails, the fall is too close to the ground: clip the next quickdraw before moving up, take in slack, or have the belayer stand closer and anchor down. Try setting the quickdraw height to 3 m to see how the first few clips are where ground falls happen.

## Example device: Petzl GRIGRI specs

The assisted-braking device that inspired this page is the Petzl GRIGRI. From Petzl's product page and technical notice:

| Spec | GRIGRI |
|---|---|
| Type | Belay device with cam-assisted blocking, for belaying a lead or top-rope climber, lowering and rappelling |
| Standards | CE EN 15151-1 type 6 (belaying and rappelling without a panic blocking element), UKCA, UIAA |
| Compatible ropes | EN 892 dynamic single ropes, 8.5 to 11 mm; EN 1891 low-stretch ropes, but not for lead climbing |
| Optimal rope diameter | 8.9 to 10.5 mm. Thinner ropes are harder to grip; thicker or worn ropes are harder to feed |
| Weight | 175 g |
| Principal materials | Aluminium, stainless steel, nylon |
| Users | One person |

How it blocks, in Petzl's words: when the climber falls, the hand holding the brake side of the rope causes the cam to engage; the device pivots on the carabiner, the cam pivots, and the rope is pinched between the two brake plates. That is the sequence the hero animation sketches. Petzl also notes that blocking can be weaker on new, treated, icy, wet or muddy ropes, and that a small jump or step forward when catching a fall reduces the impact force on the climber, which is the soft catch modelled here.

Petzl does not publish how much rope runs before the cam locks or how long it takes, so the cam inputs on this page are illustrative, not GRIGRI data. The rope range checks:

| | |
|---|---|
| $rope_{compatible} = d_{rope} \geq d_{dev,\,min} \wedge d_{rope} \leq d_{dev,\,max}$ | OK |
| $rope_{optimal} = d_{rope} \geq d_{opt,\,min} \wedge d_{rope} \leq d_{opt,\,max}$ | OK |

GRIGRI is a trademark of Petzl. This page is not affiliated with or endorsed by Petzl.

## Credit

This page was inspired by Tiziano Minotto's multibody simulation of an assisted-braking belay device arresting the fall of an 80 kg climber, built in RecurDyn at FunctionBay S.r.l. Their model represents the rope as a flexible finite element beam sliding through a fully modelled device, and captures the cam closing, the contact forces and the latency before the device locks in far more detail than the lumped model here. Worth a look if you like this kind of thing.