A Simulation of Climbing and Rescue Belays

Tom Moyer

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This presentation and the associated model can be downloaded at http://www.xmission.com/~tmoyer/testing  (© Tom Moyer)
All images in this presentation were generated with RescueRigger (rescuerrigger.com)
How do TTRL belays compare to climbing belays?
Mauthner - Gripping Ability on Rope in Motion study

46 N min  
209 N average  
425 N max

No load above which 100% of the population can grip
What gripping ability is required to hold the load statically?

**F / f = force multiplication factor (FMF)**

For a brake bar rack with 5 bars, FMF ≈ 20 with 6 bars, FMF ≈ 25

For an ATC, FMF ≈ 7.5
Climbing Scenarios – Static Loads

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Hand Force $T_0$</th>
<th>Rope Tension $T_1$</th>
<th>ATC FMF</th>
<th>Tension $T_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rappelling</strong></td>
<td>$T_0 = 785 \text{ N}$</td>
<td>$T_1 = 785 \text{ N} / 7.5 = 105 \text{ N}$</td>
<td>ATC FMF = 7.5</td>
<td>$T_2 = 785 \text{ N} / 7.5 = 69 \text{ N}$</td>
</tr>
<tr>
<td><strong>Belaying</strong></td>
<td>$T_0 = 518 \text{ N}$</td>
<td>$T_1 = 518 \text{ N} / 7.5 = 69 \text{ N}$</td>
<td>66% efficiency over biner</td>
<td>$T_2 = 518 \text{ N} / 7.5 = 69 \text{ N}$</td>
</tr>
</tbody>
</table>

**Rope Tension Calculations**

- Rappelling: $T_1 = 80 \text{ kg} \times 9.81 \text{ m/s}^2 = 785 \text{ N}$; $T_0 = 785 \text{ N} / 7.5 = 105 \text{ N}$
- Belaying: $T_2 = 80 \text{ kg} \times 9.81 \text{ m/s}^2 = 785 \text{ N}$; $T_1 = 785 \text{ N} \times 0.66 = 518 \text{ N}$; $T_0 = 518 \text{ N} / 7.5 = 69 \text{ N}$
50% efficiency over edge

Hand holds 49N

Brake bar (5 bars) fmf = 20

Vertical TTRL Belay

\[ T_2 = 200 \text{ kg} \times 9.81 \text{ m/s}^2 = 1,962 \text{ N} \]
\[ T_1 = 1,962 \text{ N} \times 0.50 = 981 \text{ N} \]
\[ T_0 = 981 \text{ N} / 20 = 49 \text{ N} \]
Low Angle TTRL Scenario

600 kg load

Rope tension $T_1$

Brake bar (6 bars) $f_{mf} = 25$

Hand holds 135N

**Low Angle TTRL Belay**

$T_1 = 600 \text{ kg} \times 9.81 \times \sin(35^\circ)$

$= 3.38 \text{ kN or } 760 \text{ lb}$

$T_0 = 3.38 \text{ kN} / 25 = 135 \text{ N}$
Dynamic Models

Model dynamic events and compare to test data

Why model?
  • Repeatable
  • Cheaper than testing
  • Can study one variable at a time
  • Can study parameters that are difficult to test

Comparison Data
  • No Hand
    • Weber - PMI drop tests
    • Moyer - cordelette tests
    • Manufacturer’s ratings
  • With Hand
    • Petzl fall simulator
    • CMT test data & simulation (live belayers)
    • Rigging for Rescue TTRL tests (mechanical hand)
Gravitational potential energy
= strain energy in the rope

Rope Modulus \( M = \frac{T}{\text{strain}} \) or \( TL/\delta \)
Potential Energy = \( mg(h+\delta) \)
Strain Energy = \( \frac{1}{2}T \delta \)

\[ T_{\text{max}} = mg + mg \sqrt{1 + \frac{2M}{mg} F} \]

where fall factor \( F = \frac{h}{L} \)
Detailed Model
Iterative Dynamic Motion Equations

Includes:
• Nonlinear rope elasticity
• Knots
• Rope damping
• Carabiner friction
• Belay device friction
• Slipping in belayer’s hand
• Lifting of belayer

Iterative solution approach:
• From current rope tension, calculate $a = T/m + g$
• Calculate $\Delta v = a \, dt$ and $\Delta x = v \, dt$
• From new positions, calculate new rope strains $\varepsilon = \Delta L/L$
• From new strains, calculate rope tensions
• Calculate slip distances at friction devices to limit tension ratios to allowed values
• Calculate new rope strains and new rope tensions
## Model Parameters

### Fall Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climber mass (kg)</td>
<td>$m_c$</td>
</tr>
<tr>
<td>Belayer mass (kg)</td>
<td>$m_b$</td>
</tr>
<tr>
<td>Time step (s)</td>
<td>$dt$</td>
</tr>
<tr>
<td>Rope span angle (deg)</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>Runner angle (deg)</td>
<td>$\beta$</td>
</tr>
<tr>
<td>Belayer tie-in slack (m)</td>
<td>$b_{\text{slack}}$</td>
</tr>
<tr>
<td>Belayer-biner distance (m)</td>
<td>$L_1$</td>
</tr>
<tr>
<td>Climber height above biner (m)</td>
<td>$d$</td>
</tr>
<tr>
<td>Rope length (m)</td>
<td>$L$</td>
</tr>
<tr>
<td>Biner efficiency</td>
<td>$\eta$</td>
</tr>
<tr>
<td>Rope 2nd order modulus (N/strain$^2$)</td>
<td>$B$</td>
</tr>
<tr>
<td>Rope 1st order modulus (N/strain)</td>
<td>$A$</td>
</tr>
<tr>
<td>Damping coefficient (N/strain/s)</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>$k_a/k_b$</td>
<td>$k_{\text{ratio}}$</td>
</tr>
<tr>
<td>Number of knots</td>
<td>$#_{\text{knots}}$</td>
</tr>
<tr>
<td>Knot 2nd order stiffness (N/m$^2$)</td>
<td>$E$</td>
</tr>
<tr>
<td>Knot 1st order stiffness (N/m)</td>
<td>$D$</td>
</tr>
<tr>
<td>Knot minimum force (N)</td>
<td>$C$</td>
</tr>
<tr>
<td>Reaction time (s)</td>
<td>$T_r$</td>
</tr>
<tr>
<td>Force multiplier</td>
<td>FMF</td>
</tr>
<tr>
<td>Grip (N)</td>
<td>$\text{grip}$</td>
</tr>
<tr>
<td>Fall height (m)</td>
<td>$h$</td>
</tr>
<tr>
<td>Fall factor</td>
<td>$F$</td>
</tr>
</tbody>
</table>

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### Fall equations

**Fall height**  
$h = d + L_2$

**Fall factor**  
$F = h / L$

### Parameters at static load

$\delta_s = L + \delta_s$

$F_s = h_s / L_s$
Three Components are Critical to Understand

- The Rope
- The Friction Device
- The Hand
Rope Properties

2\textsuperscript{nd} order curve fits – Weber PMI Data

\begin{itemize}
  \item Model results with nonlinear properties match Attaway’s analytical predictions
  \item Nonlinear rope still obeys fall factor rule. Impact force is a function of fall factor.
  \item Impact force for a zero ff drop on nonlinear rope is 3 $\times$ weight instead of 2 $\times$ weight.
\end{itemize}
Knot Properties

2nd order curve fits – Weber PMI Data

- Knots modeled as rope sources rather than compliance terms
- Knots are much more significant on short ropes
Rope Properties - Damping

What is damping?

• Elastic force is proportional to deflection (strain)

• Damping, or viscous force is proportional to velocity (strain rate)

• Elastic energy is returned on rebound.

• Damping energy is lost to heating in the rope.

• Damping causes oscillations to die out.

Fig. 3 - Recorded force during a classical Dodero test (no rupture). Note the sudden reduction of the force during the return phase.
Pavier Damping Model

- Spring in series with a spring/dashpot combination
- Simple spring/dashpot combo produces unrealistic results.
  - Initial impact forces too high.
  - Damping values too low (too underdamped)
- Real ropes are close to critically damped.
- Damping values $k_a/k_b$ and $\lambda$ determined by trial and error to produce reasonable model behavior.
- Overall spring rate $k$ from slow-pull testing
- Damping values could be determined experimentally with good force/deflection measurements in drop tests or fast pull-tests.
Comparison to Weber PMI Data

Example Load Profile

• Drop-test values give maximum force, elongation, and energy.

• Data points are very close to the rope-only curve.

• Without damping, rope and rope + knots curves do not store sufficient strain energy.

• Therefore they over-predict both force and elongation.
Comparison to Weber PMI Data

Impact Forces
PMI 12.5mm Static Rope, M = 80 kg, L_s* = 6.1m (20 ft)

- Second-Order Rope
- Linear Rope k = 178 kN (40,000 lb)
- Second Order Rope with Knots (Attaway)
- This Model (Second Order Rope with Knots & Damping)
- Weber Drop-Test Data
- Linear Rope k = 67 kN (15,000 lb)

*L_s Length is at static resting point. Drop Distance is height above free (unstretched) length of rope.
Comparison to Moyer Cordelette Testing

UIAA Test

80 kg weight
Fall Factor 1.71
2.8 meter rope

Cordelette is at the direction change anchor

Black Diamond 10.5mm rope
- rated impact force of 8.4 kN (1888 lb)
Comparison to Moyer Cordelette Testing
Comparison to Moyer Cordelette Testing

UIAA Drop - 10/15/00 Boulder, CO
5mm Gemini Drop #1

- Runner load
- Runner load (data)
- Rope load
- Rope load (calc from data)
- Belay site load
- Belay site load (data)

UIAA drop, Boulder
80 m_
80 m_w
0.0005 dt
36 \( \alpha \)
14 \( \beta \)
0.4 L_t
1.96 d
2.67 L
0.78 \( \eta \)
62252 B
2657 A
2800 \( \lambda \)
6 \#_ratio
4 \#_knots
260,435 E
4.23 h
1.584 F
The Effect of Damping

The diagram shows the force in Newtons (N) over time (s) for a 5mm Gemini Drop #1. The graph compares runner load, rope load, belay site load, and their respective data and calculations. The graph highlights the first peak slightly shifted and a bigger effect on the second peak. A note indicates 'Same Drop – Damping Removed.'
Comparison to Moyer Cordelette Testing

UIAA Drop – 10/15/00 Boulder Colorado
5mm Gemini Drop #1

Load (N) vs. position

Model
Data
Drops with a Hand in the System

• Hand slipping makes rope properties relatively unimportant

Italian CMT has done extensive study of the behavior of the belay hand in climbing falls

• Force measurements in falls compared to slow-motion video of the belayer

• Three phases of belay-hand behavior identified
  • Inertial Phase
  • Muscular Phase
  • Slipping Phase
“INERTIAL” PHASE

The hand moves fast

THE UPPER BODY STANDS STILL

THE HAND MOVES FAST
“MUSCULAR” PHASE

The hand moves slowly

THE HAND MOVES SLOWLY

THE UPPER BODY MOVES
“HAND SLIPPING” PHASE

Possible rope slipping in the operator’s hand

NOTE THE SLIPPAGE IN THE HAND
FIX POINT BELAY

- runner load (model)
- sliding length in the brake
- falling mass speed
- falling mass displacement
- hand speed

**No more sliding in the brake**

**Inertial phase**

**Muscular phase**
Comparison to CMT Belay Simulation and Data

CMT Fall Parameters given:
- Mass $m = 80$ kg
- Fall height $h = 8$ m
- $L_1 = 7.15$ m
- Belay Device FMF = 7.5
- Hand mass = 2.5 kg
CMT Conclusions on Belaying

• Hand acts as an inertial load for the first few hundred milliseconds.

• Slip distance is proportional to fall height, not fall factor. *Confirmed.*

• Peak force occurs at maximum hand acceleration, not at lowest climber position.

• Only a small amount of belayer lifting is helpful (~20 cm). More lifting increases fall distance and does not decrease peak force. *Confirmed.*
Comparison to Petzl Fall Simulator

Petzl Simulator values:
- Hand Grip = 400N
- Rope Burn Warning = 1800J
- Reverso FMF = 5.0
- Munter Hitch FMF = 7.5
- Grigri FMF = \(\infty\) (no slipping)

- 11mm rope modulus \(\approx 44.1\) kN
- Carabiner efficiency = \(66.6\%\)
- Knot elongation included

- No rope damping
- No lifting of belayer

Peak Force
- on rope \(3000\) N
- on anchor \(5000\) N
- on belayer \(2000\) N
- on belayer's hand \(400\) N
Slide distance \(4.95\) m

Petzl Comparison
- Runner load
- Rope Load
- Belay site load (N)
- Climber position (m)
- Slide Distance (m)
Belay Device Details - FMF Values

Friction device properties are very important to the model predictions.

Attaway Friction Analysis

\[ \frac{T_2}{T_1} = e^{\mu\beta} \]
Total = 800°
4.4\pi

\[ T_1 = \frac{T_2}{31} \]
Belay Device FMF Values
Black Diamond Testing
Belay Device FMF Values
Black Diamond Test Data

Friction Device Force Multiplier Values (10.8mm rope)
Friction Device Force Multiplier Values
Variation with Rope Diameter - (HF side of variable devices)

- ATC
- Atoga
- Sheriff
- Bug
- Airbrake
- Airstyle
- Munter
- Pyramid
- Jaws
- VC
- Raptor
- Cubik
- Fixe
Friction Device Force Multiplier Values (10.8mm rope)
Variation with Hand Force - (HF side of variable devices)
Comparison to Rigging for Rescue Drop-Test Data

- Brake Bar
  FMF determined by trial and error.

- FMF = 14.3
  gives a slide distance equal to the measured value

- This underpredicts the measured peak force

- Measured values:
  5,626 N Peak Force, 184 cm slide distance, 231 cm FAS Extension

- Model values:
  3003 N Peak Force, 184 cm slide distance, 219 cm FAS extension
Comparison to Rigging for Rescue Drop-Test Data

- Slide distance is a function of the average mechanical hand force.

- Peak rope tension is a function of the peak mechanical hand force.

- Any spikes in the mechanical hand force will cause higher measured peak force values.

"Two Rope Mech Hand" set at 210 N
80kg mass 0 cm drop of 11 mm Sterling Superstatic straightline pull through hand

Rigging for Rescue Data – ITRS 2005
Comparison to Rigging for Rescue Drop-Test Data

Brake Bar FMF varies with Hand Force

Brake Bar FMF - 5 bars - Function of Hand Force

- RFR Drop Tests - peak force
- RFR Drop Tests - slide distance
Brake Bar FMF Testing at Black Diamond
Brake Bar FMF Testing at Black Diamond

Brake Bar FMF - 5 bars - Function of Hand Force

- RFR Drop Tests - peak force
- RFR Drop Tests - slide distance
- SMC slow pull tests - 11mm
- Slow Pull Tests
Brake Bar FMF Testing at Black Diamond

Brake Bar FMF - function of # of bars at 223N (50 lb) Hand Force
Back to the Original Question

How do TTRL belays compare to climbing belays?
Gripping Ability Required for Climbing and Rescue Scenarios

How much slip is too much?

• BCCTR belay standard, 1m maximum total extension.

• Petzl rope burn warning, 1800J

• Some belay device slip is good - reduces peak force.

• Too much sliding increases chance of collisions.

• A reasonable limit might be slide distance less than fall height.
Rope Stretch

- Rope stretch is very important at longer rope lengths
- A preloaded rope is much better
Differences Between Rescue Belays and Climbing Belays

• The hand is preloaded in a TTRL belay
• A TTRL belayer can optimize brake bar setup

• Reaction time may be longer for a TTRL belay.
• TTRL belay may already be sliding.
• TTRL belayers typically wear gloves.
• TTRL belayers are not expecting to catch falls.
Conclusions

• TTRL grip requirements are similar to climbing.
• Teams who prohibit manual devices should also prohibit them for lead climbing and rappelling.
• Brake bars are not very high friction devices.
• Unlikely that TTRL belay would ever meet 1m extension limit in the BCCTR test.

• The ideal rescue belay would be autolocking, force limiting and preloaded.
Thank You

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