A Simulation of Climbing and Rescue Belays

Tom Moyer

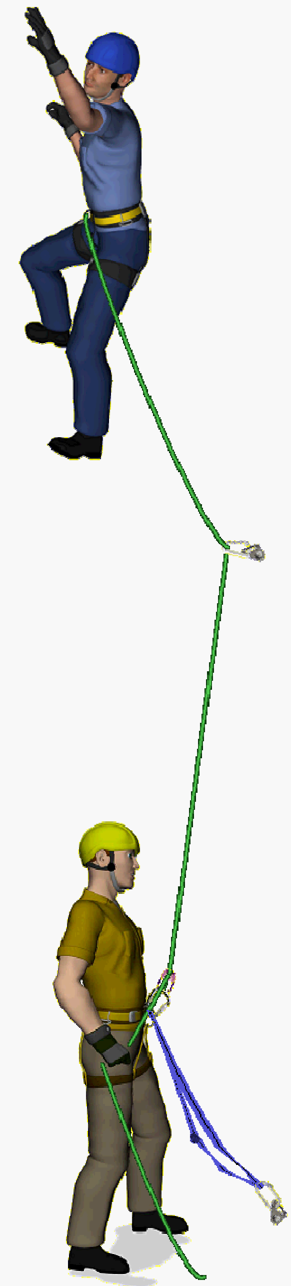
SALT LAKE COUNTY
S H E R I F F ' S   O F F I C E

SEARCH *RESCUE*

2006 International Technical Rescue Symposium

This presentation and the associated model can be downloaded at
http://www.xmission.com/~tmoyer/testing

All images in this presentation were generated with RescueRigger (rescuerigger.com)

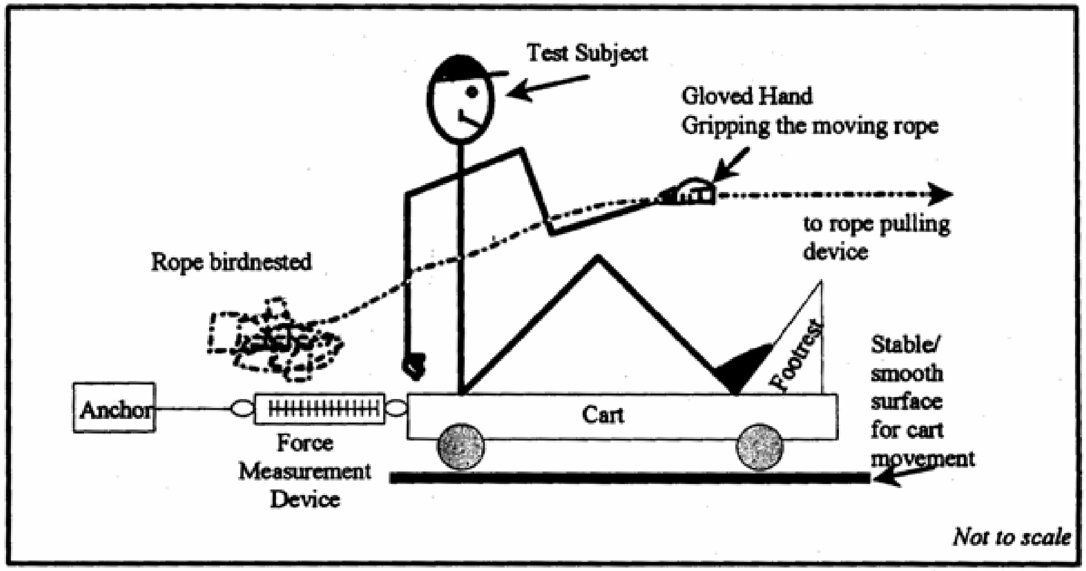


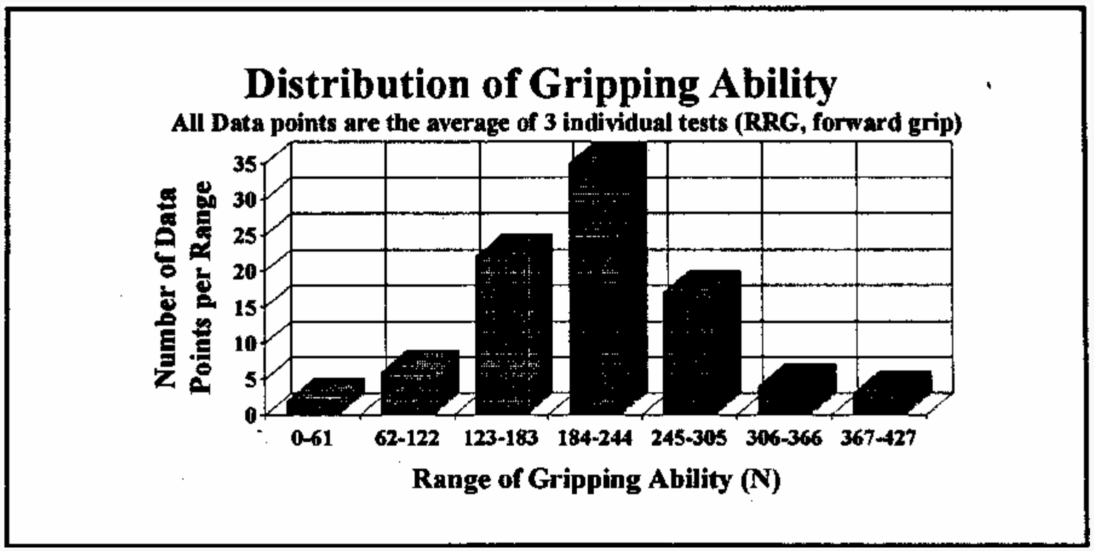
How do TTRL belays compare to climbing belays?

Mauthner - Gripping Ability on Rope in Motion study

46 N min
209 N average
425 N max

<u>No</u> load above which 100% of the population can grip



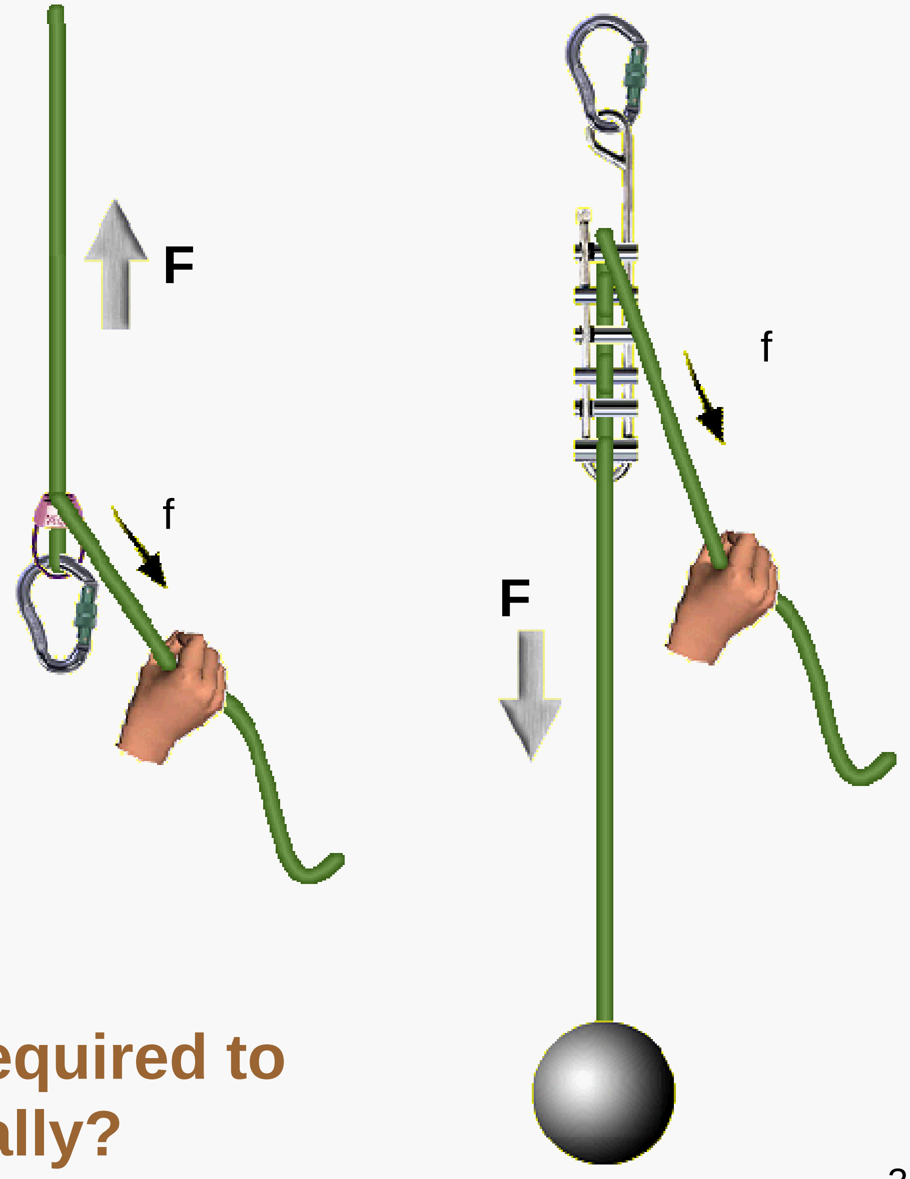


Force Multiplication Factors of Friction Devices

F / f = force multiplication factor (FMF)

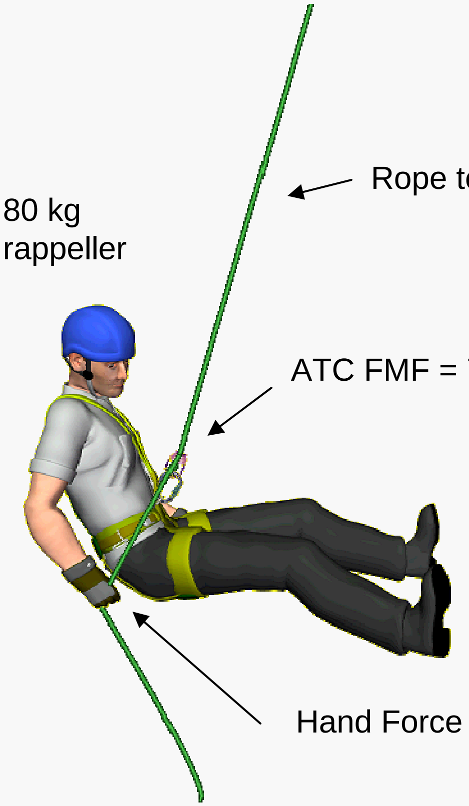
For a brake bar rack with 5 bars, FMF ≈ 20 with 6 bars, FMF ≈ 25

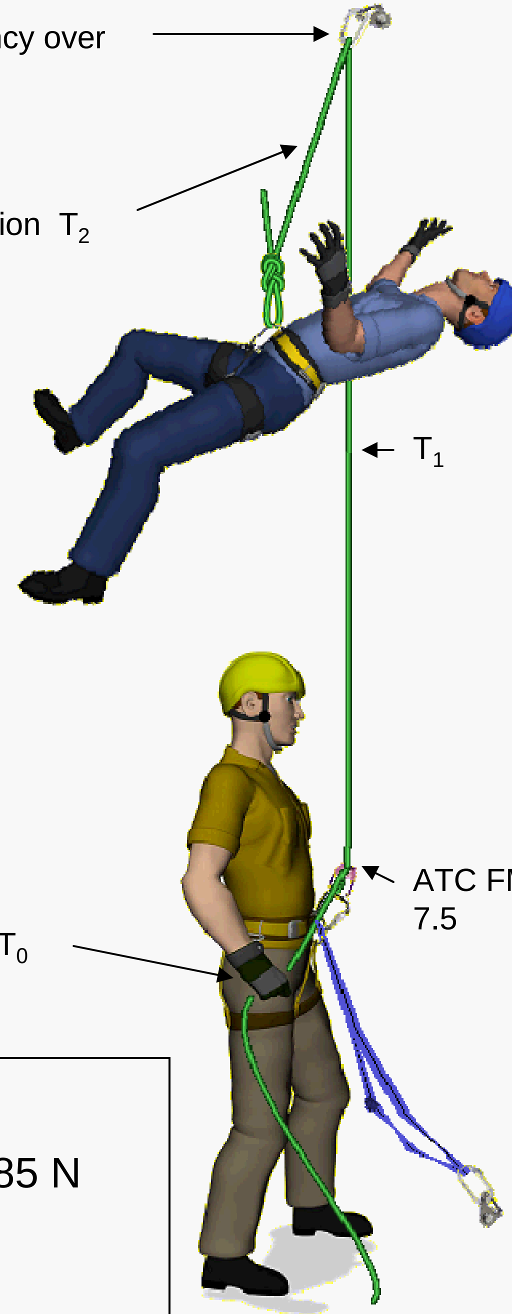
For an ATC, FMF ≈ 7.5



What gripping ability is required to hold the load statically?

Climbing Scenarios – Static Loads





<u>Rappelling</u>

T_1 = 80 kg * 9.81 m/s^2 = 785 N

T_0 = 785 N / 7.5 = **105 N**

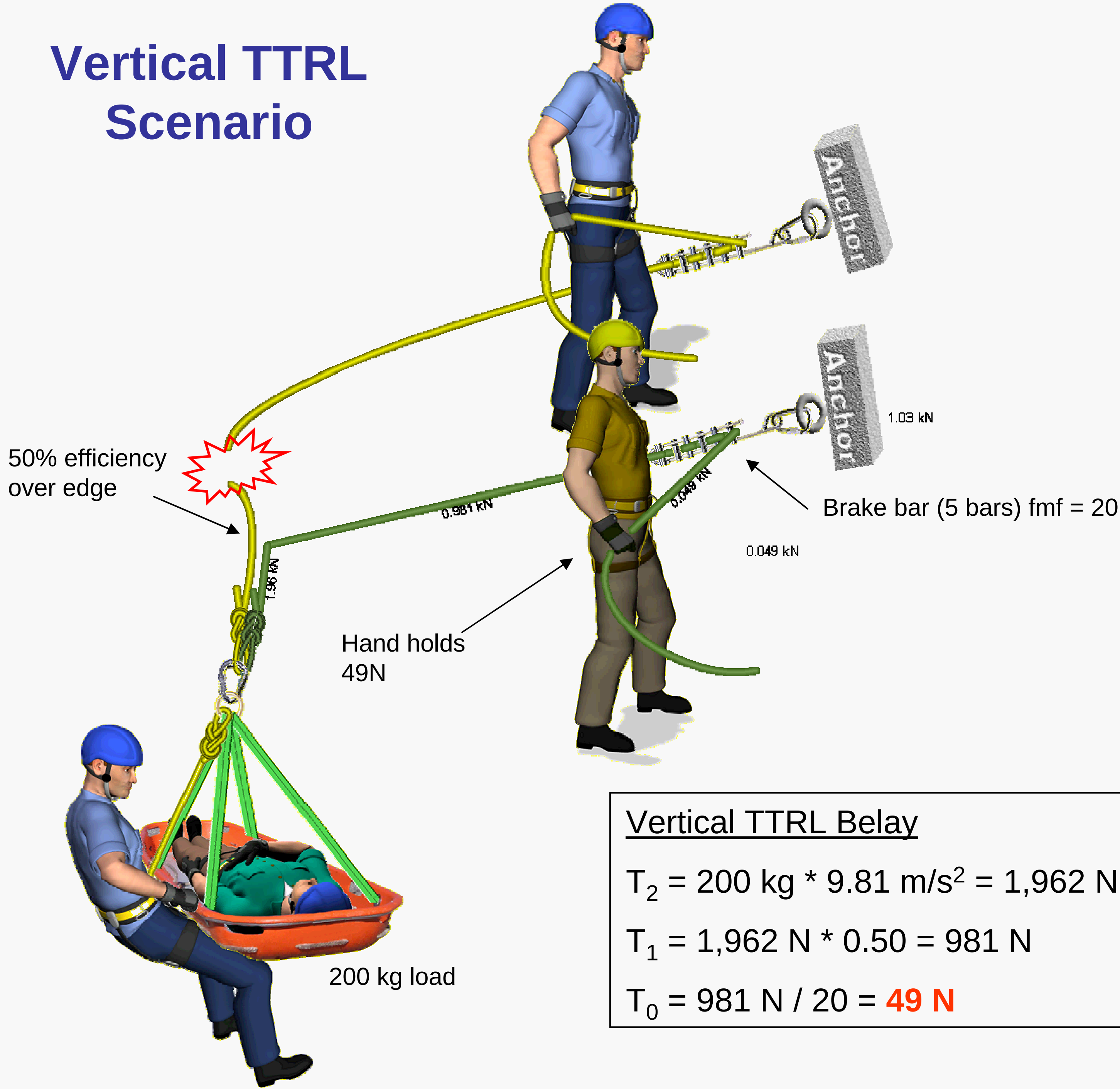
<u>Belaying</u>

T_2 = 80 kg * 9.81 m/s^2 = 785 N

T_1 = 785 N * 0.66 = 518 N

T_0 = 518 N / 7.5 = **69 N**

Vertical TTRL Scenario

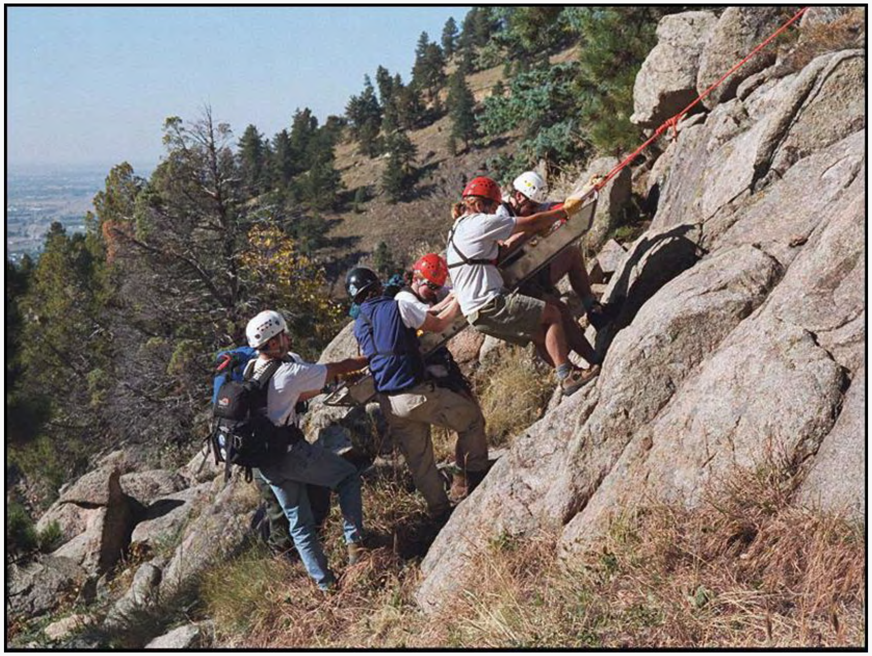


<u>Vertical TTRL Belay</u>

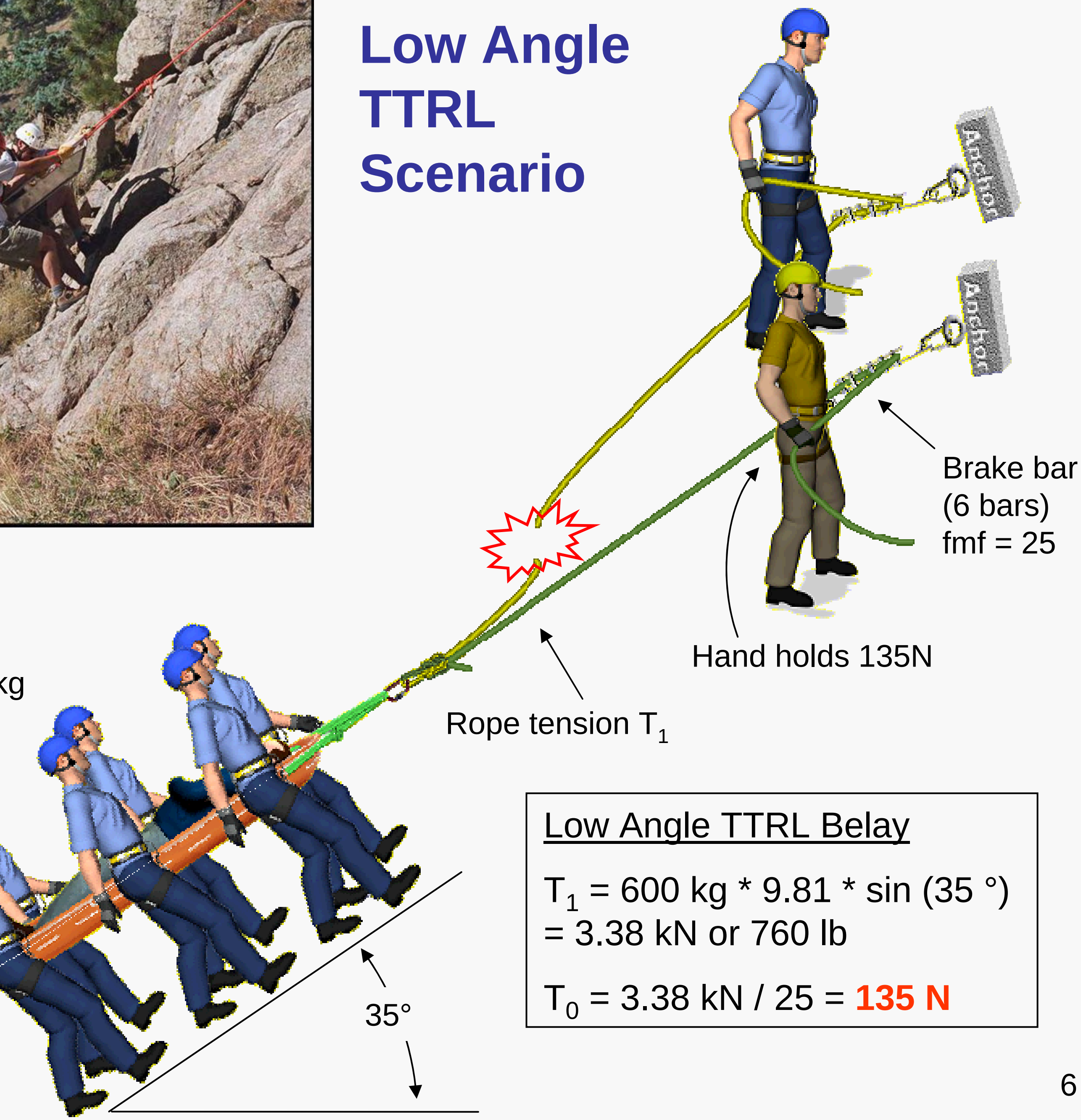
T_2 = 200 kg * 9.81 m/s^2 = 1,962 N

T_1 = 1,962 N * 0.50 = 981 N

T_0 = 981 N / 20 = **49 N**



Low Angle TTRL Scenario



Low Angle TTRL Belay

T_1 = 600 kg * 9.81 * sin (35 °)
= 3.38 kN or 760 lb

T_0 = 3.38 kN / 25 = **135 N**

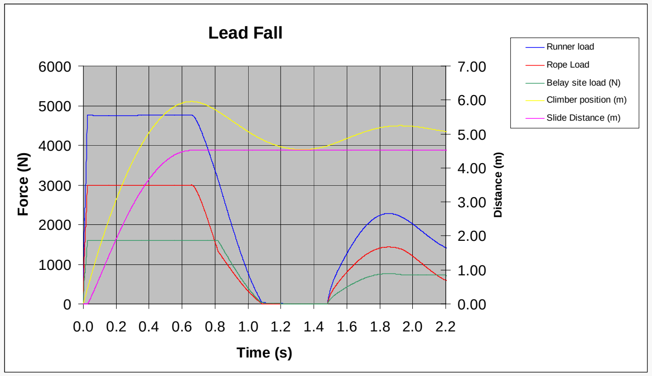
Dynamic Models

Model dynamic events and compare to test data

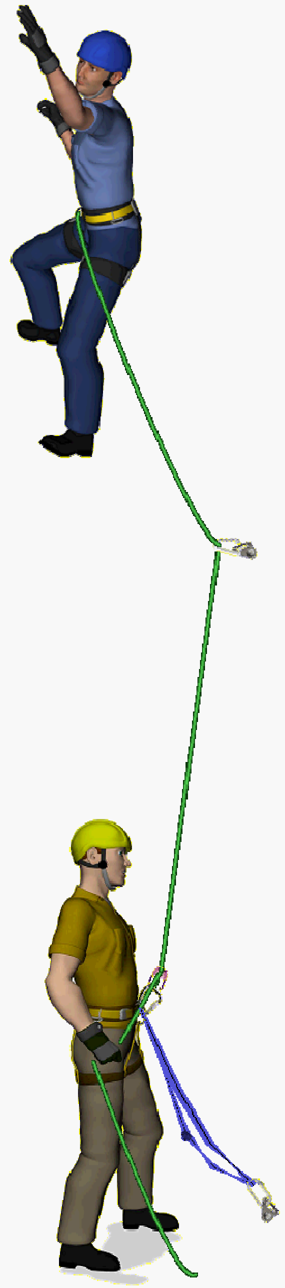
Why model?

- 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)



Simple Linear Model

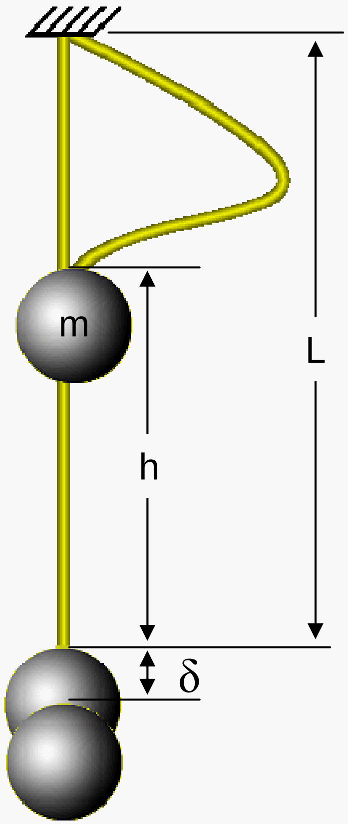
Conservation of Energy

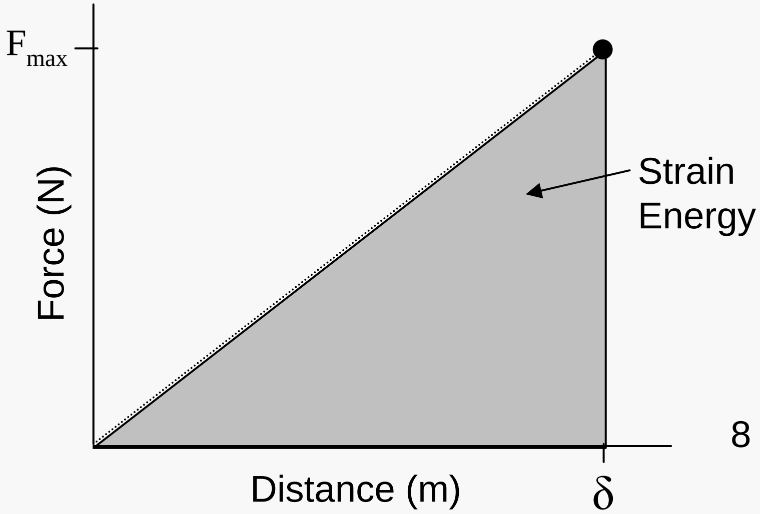
Gravitational potential energy
= strain energy in the rope

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

$$T_{\max} = mg + mg\sqrt{1 + \frac{2M}{mg}F}$$

where fall factor $F = h/L$





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

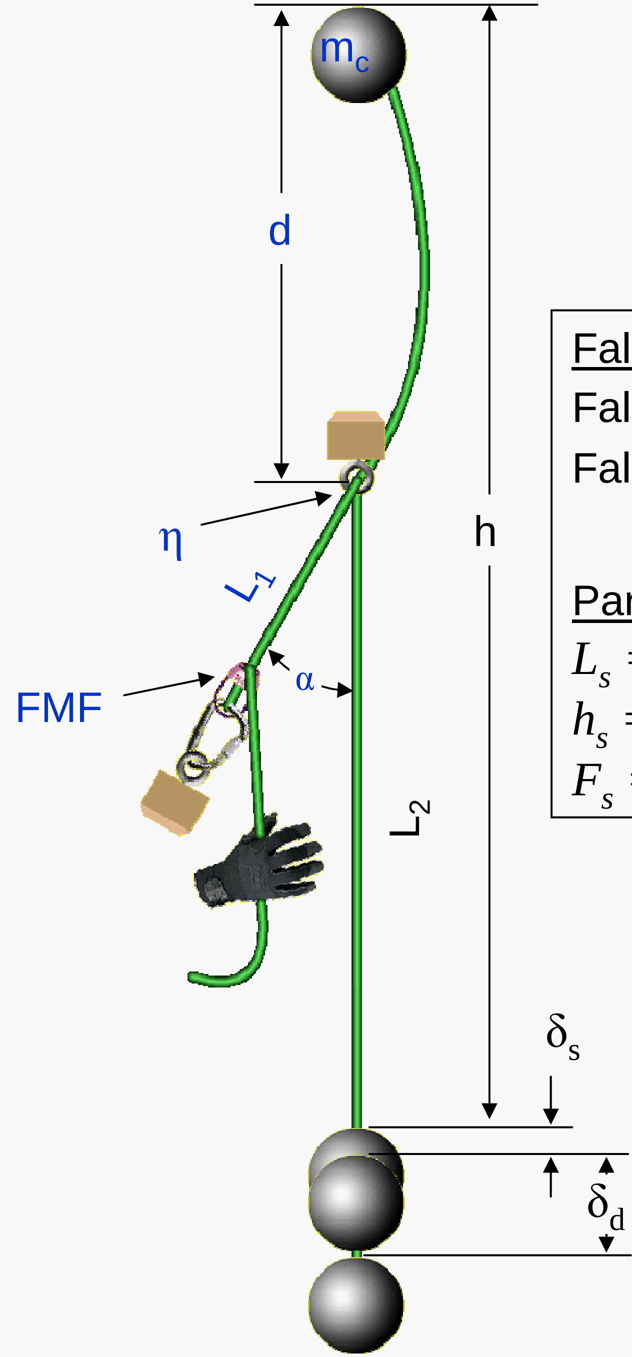
Iterative solution approach:

- 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

Climber mass (kg)	m_c
Belayer mass (kg)	m_b
Time step (s)	dt
Rope span angle (deg)	α
Runner angle (deg)	β
Belayer tie-in slack (m)	b_slack
Belayer-biner distance (m)	L_1
Climber height above biner (m)	d
Rope length (m)	L
Biner efficiency	η
Rope 2nd order modulus (N/strain^2)	B
Rope 1st order modulus (N/strain)	A
Damping coefficient (N/strain/s)	λ
k_a/k_b	k_ratio
Number of knots	#_knots
Knot 2nd order stiffness (N/m^2)	E
Knot 1st order stiffness (N/m)	D
Knot minimum force (N)	C
Reaction time (s)	T_r
Force multiplier	FMF
Grip (N)	grip
Fall height (m)	h
Fall factor	F



Fall equations

Fall height $h = d + L_2$

Fall factor $F = h / L$

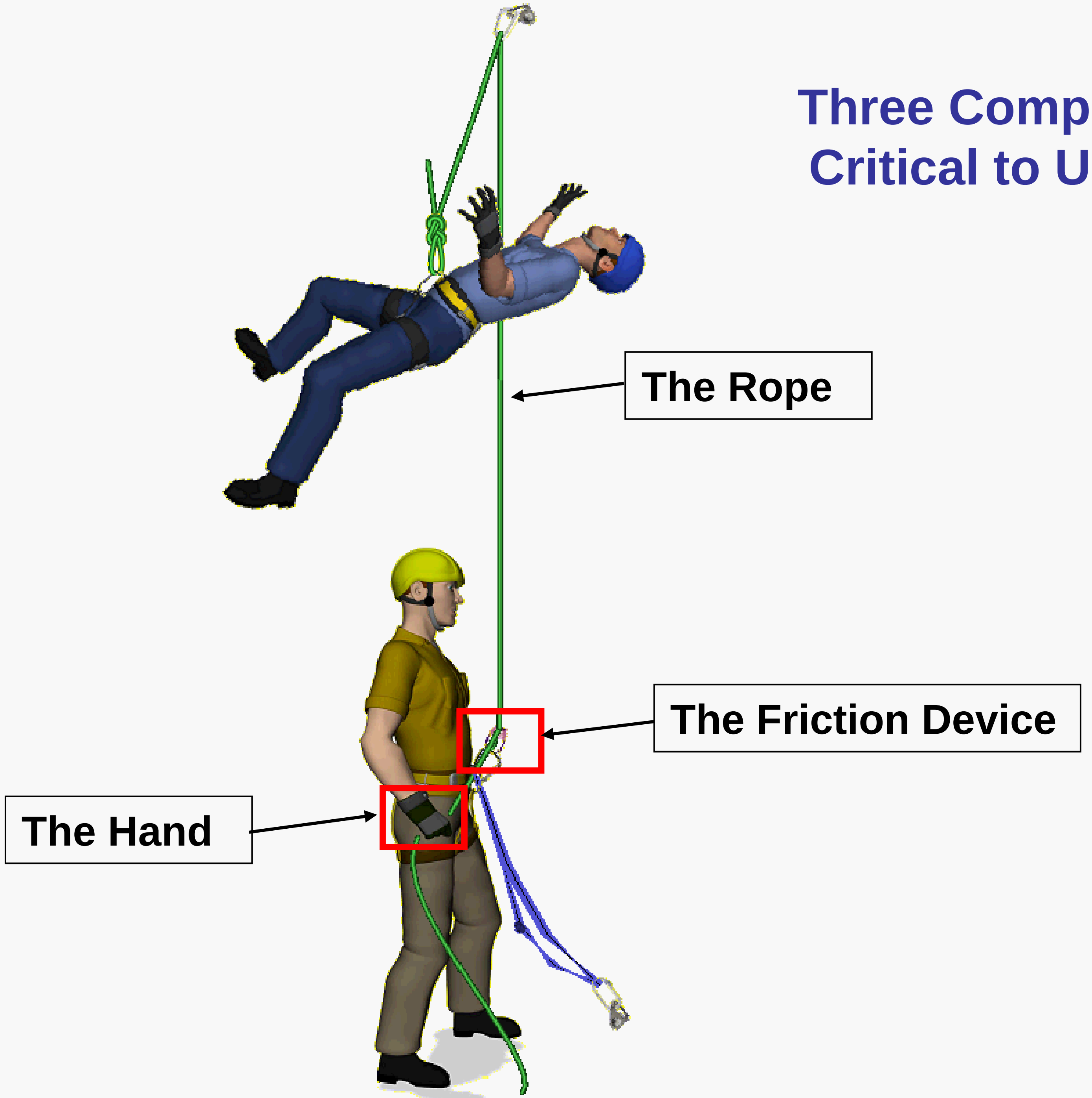
Parameters at static load

$L_s = L + \delta_s$

$h_s = h + \delta_s$

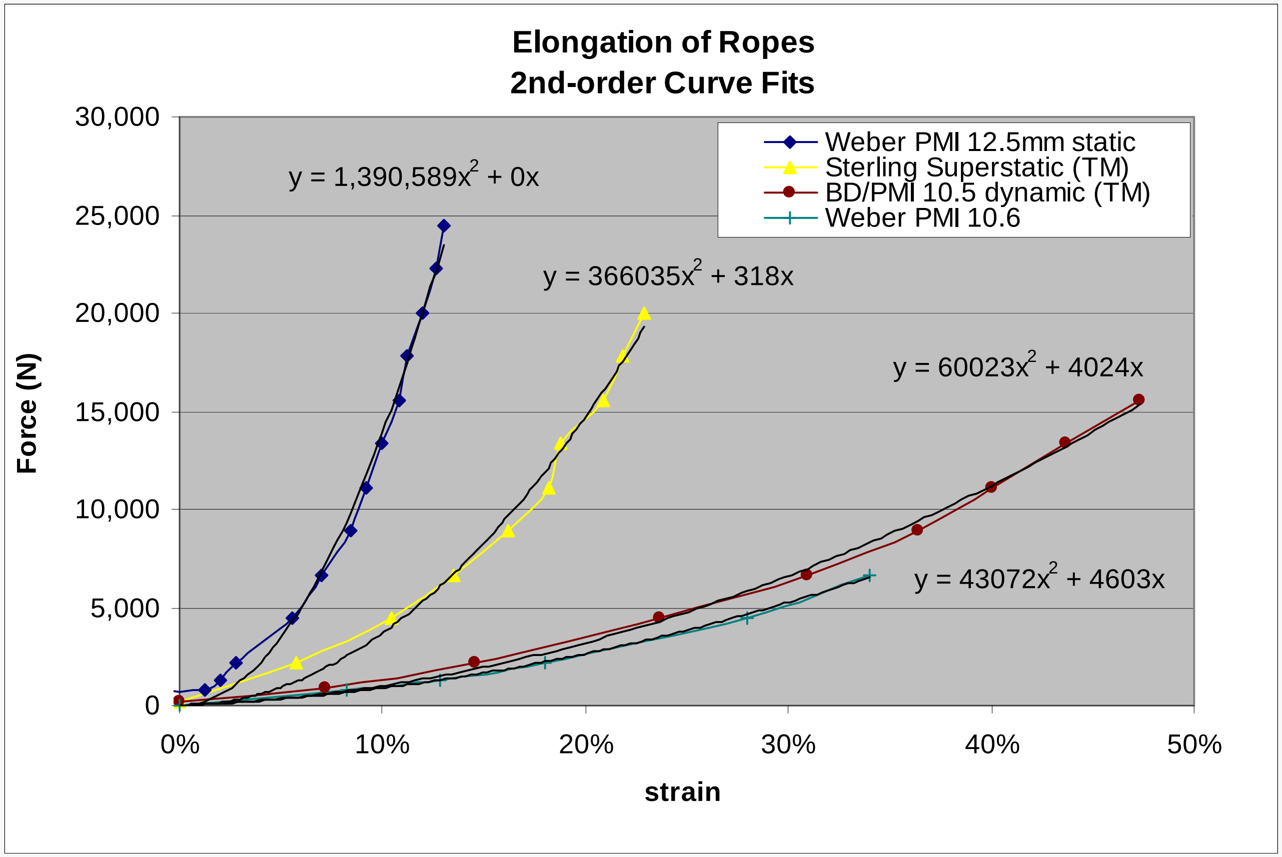
$F_s = h_s / L_s$

Three Components are Critical to Understand



Rope Properties

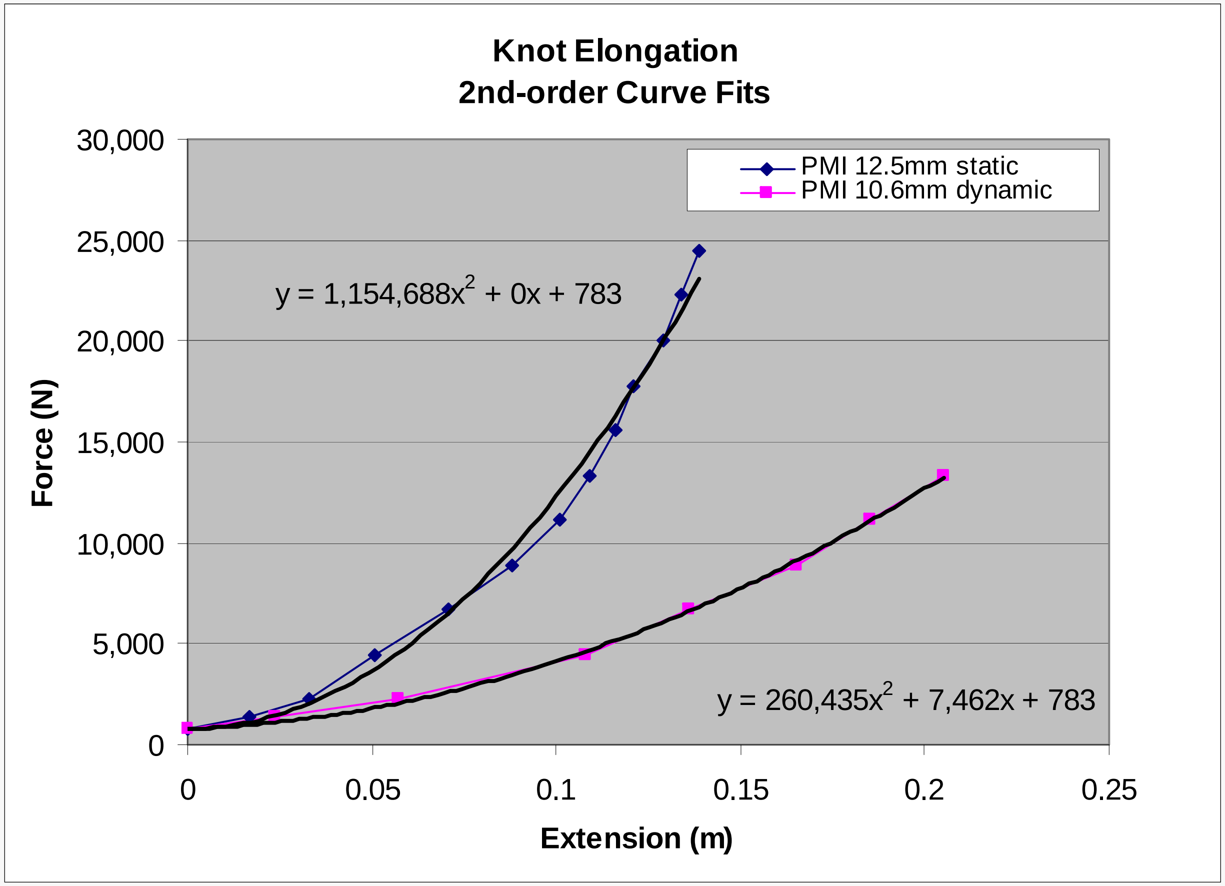
2nd order curve fits – Weber PMI Data



- Model results with nonlinear properties match Attaway's analytical predictions
- Nonlinear rope still obeys fall factor rule. Impact force is a function of fall factor.
- Impact force for a zero ff drop on nonlinear rope is 3 x weight instead of 2 x weight.

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

C. Zanantoni - CMT

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.

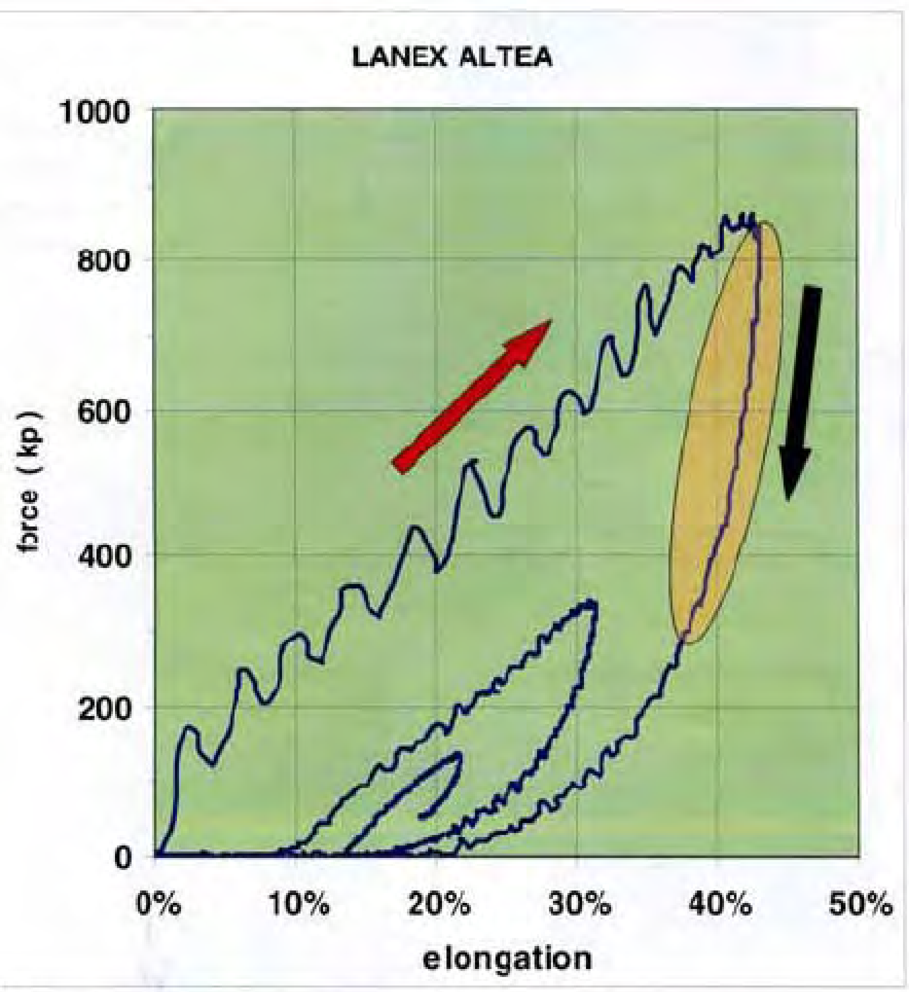
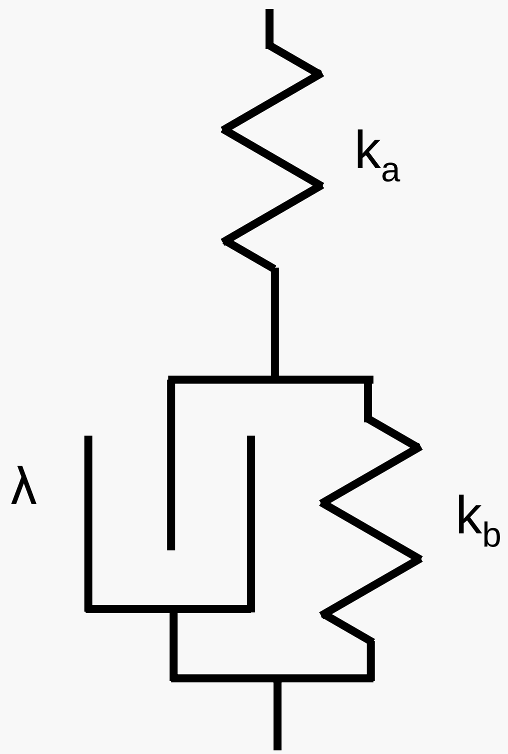


Fig. 3 - Recorded force during a classical Dodero test (no rupture). Note the sudden reduction of the force during the return phase

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 λ determined by trial and error to produce reasonable model behavior.

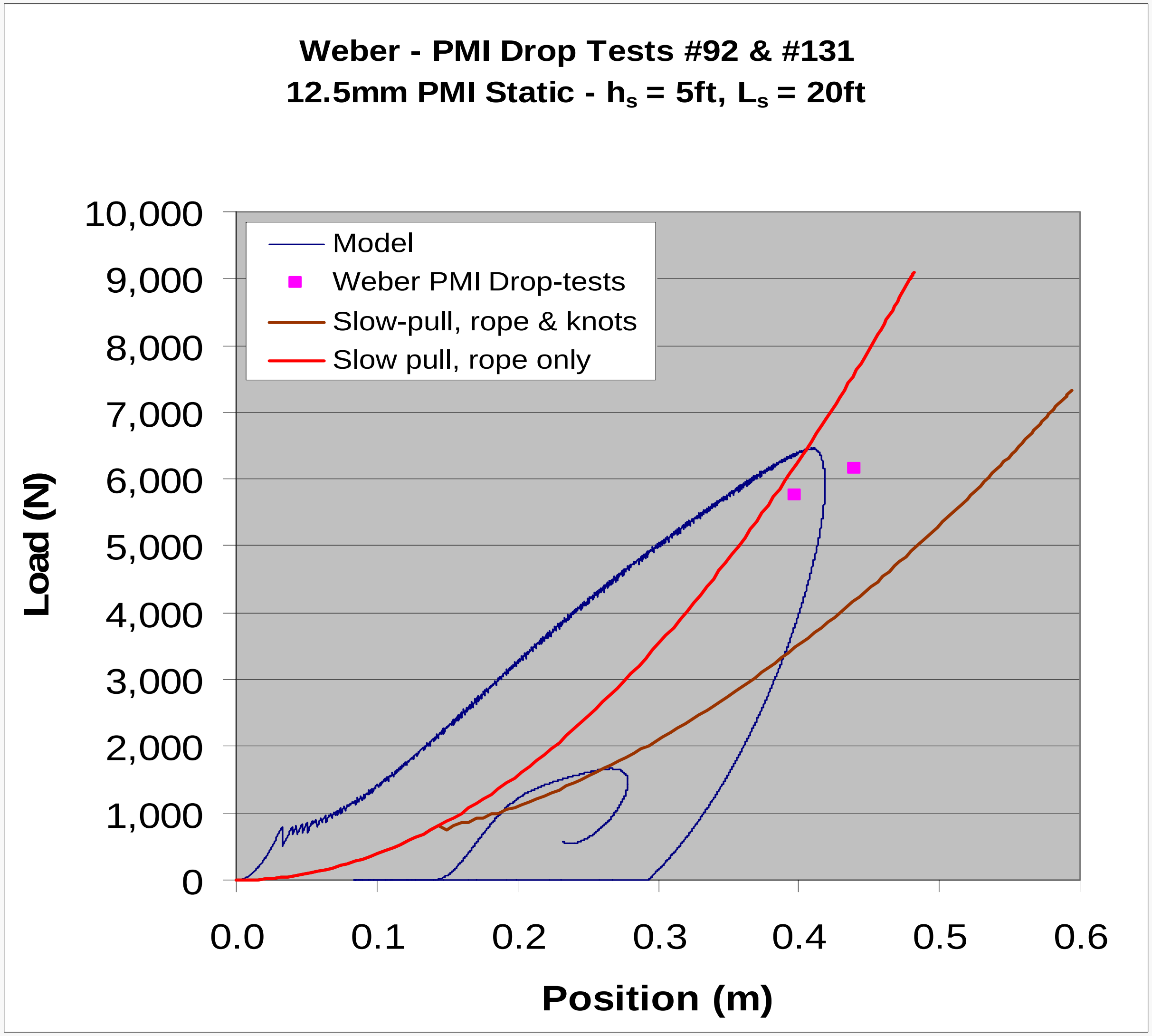
• Overall spring rate k from slow-pull testing

• Damping values could be determined experimentally with good force/deflection measurements in drop tests or fast pull-tests.

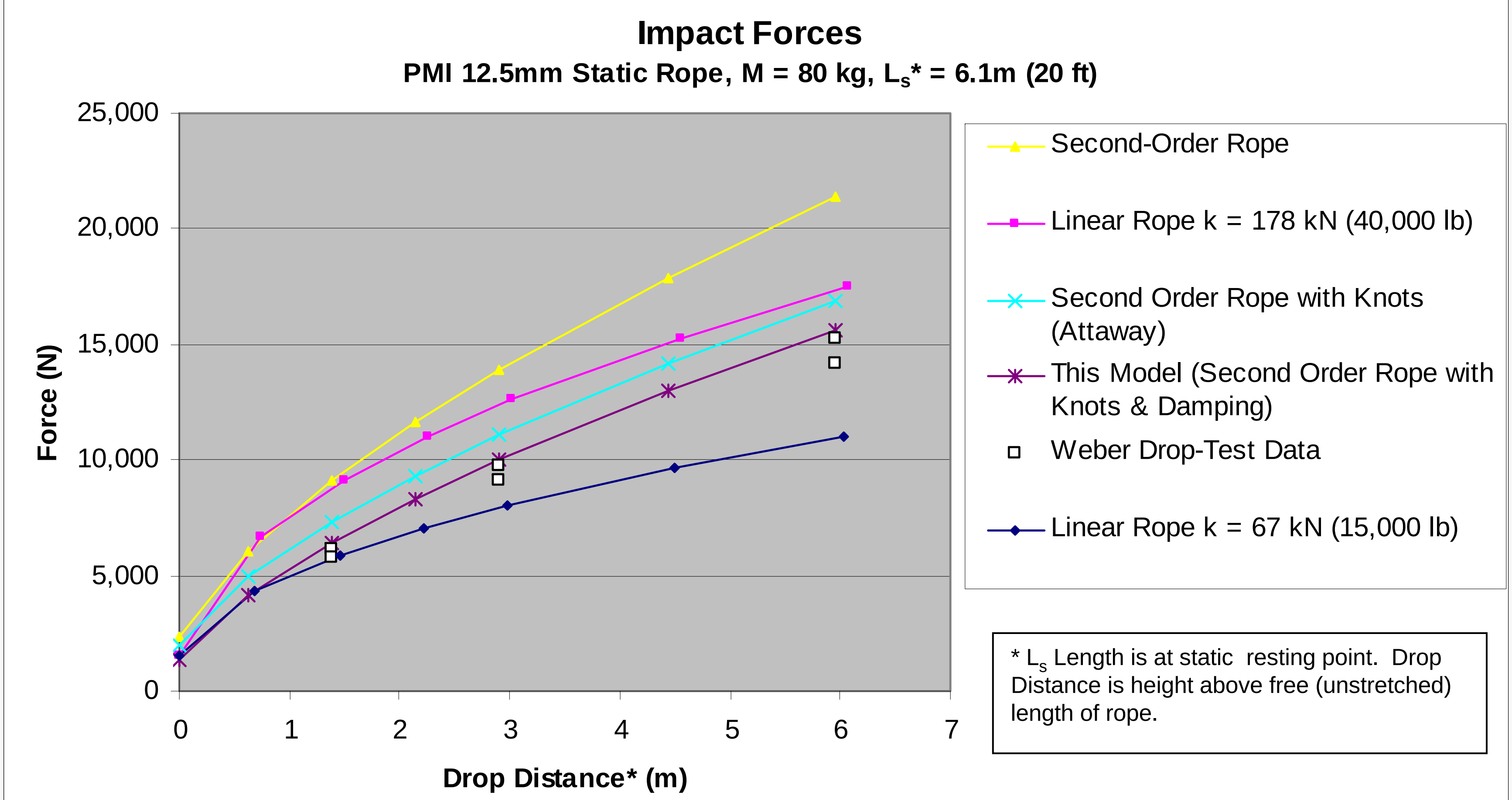
Comparison to Weber PMI Data

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



* 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

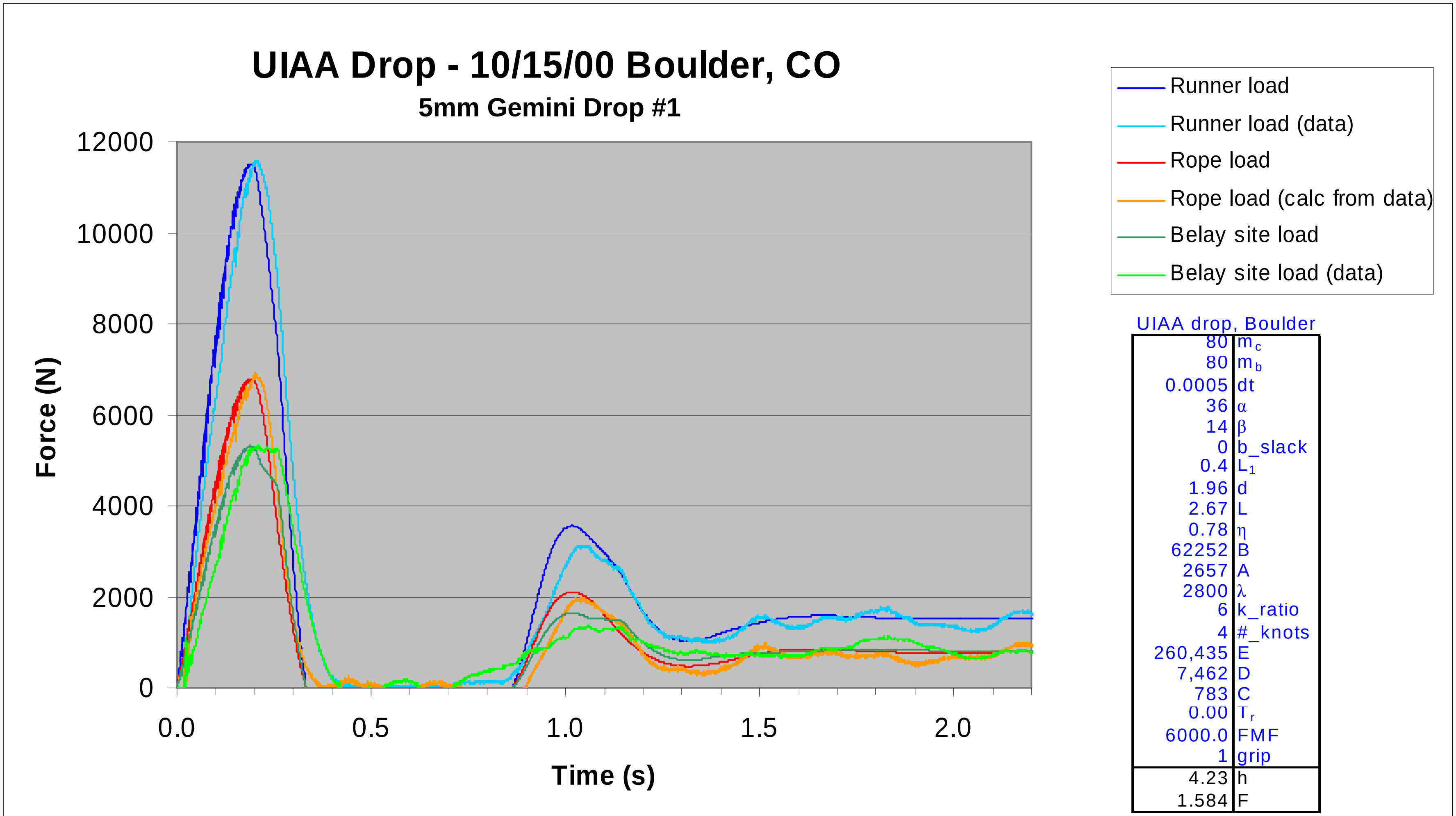
80 kg weight
Fall Factor 1.71
2.8 meter rope

Cordelette is at the direction change anchor

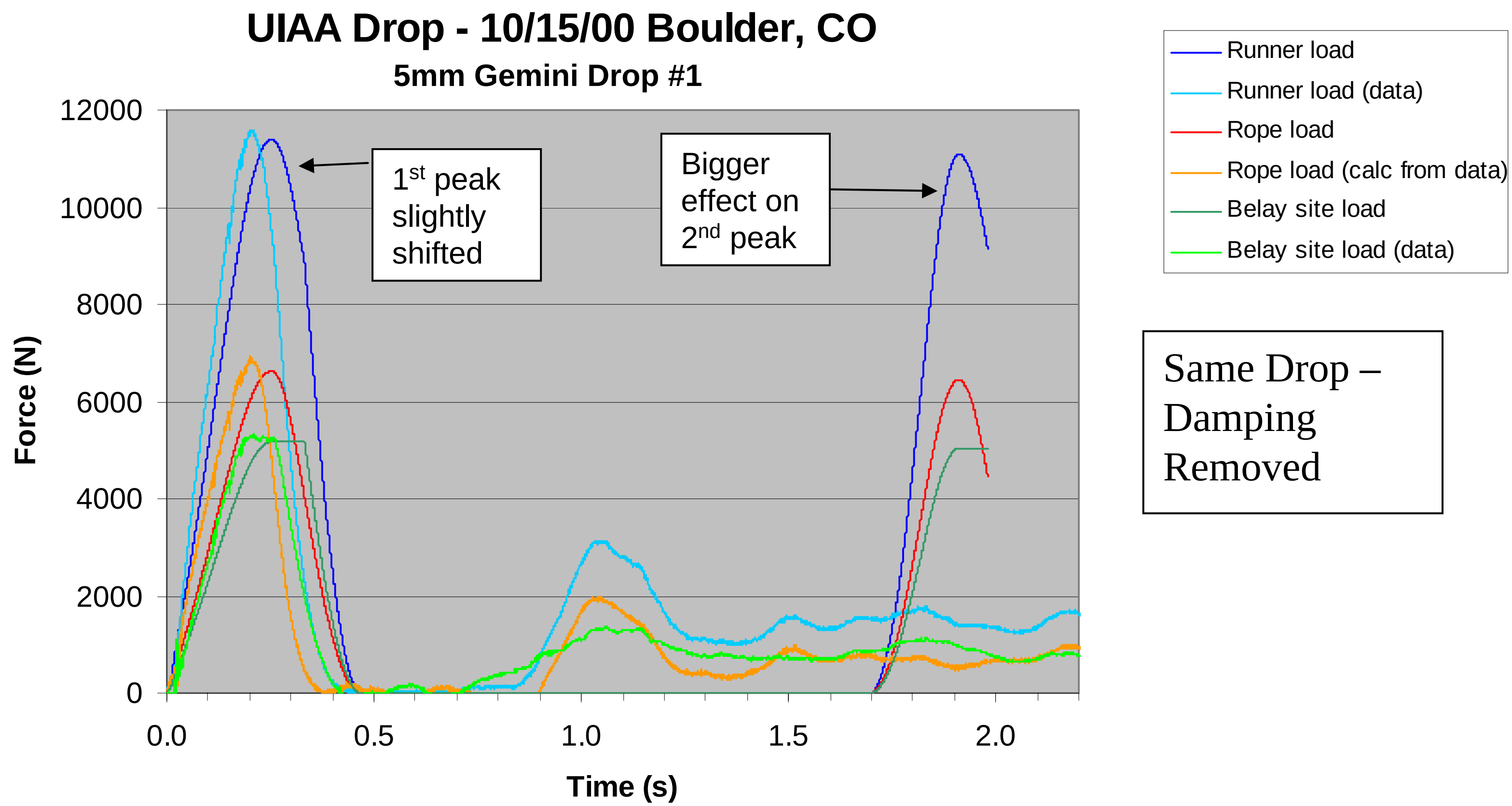
Black Diamond 10.5mm rope - rated impact force of 8.4 kN (1888 lb)

Comparison to Moyer Cordelette Testing

Comparison to Moyer Cordelette Testing

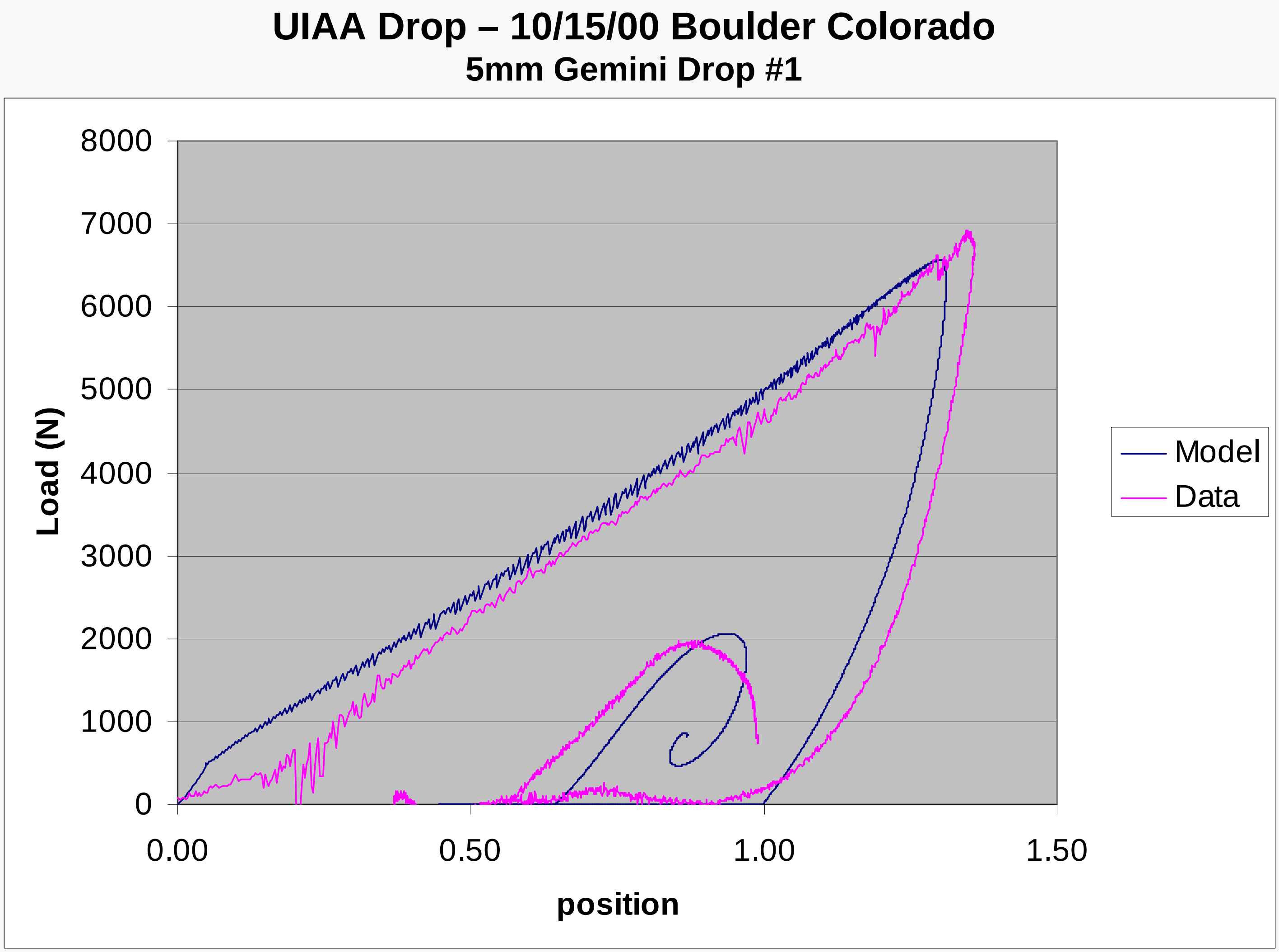


The Effect of Damping



Same Drop – Damping Removed

Comparison to Moyer Cordelette Testing



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

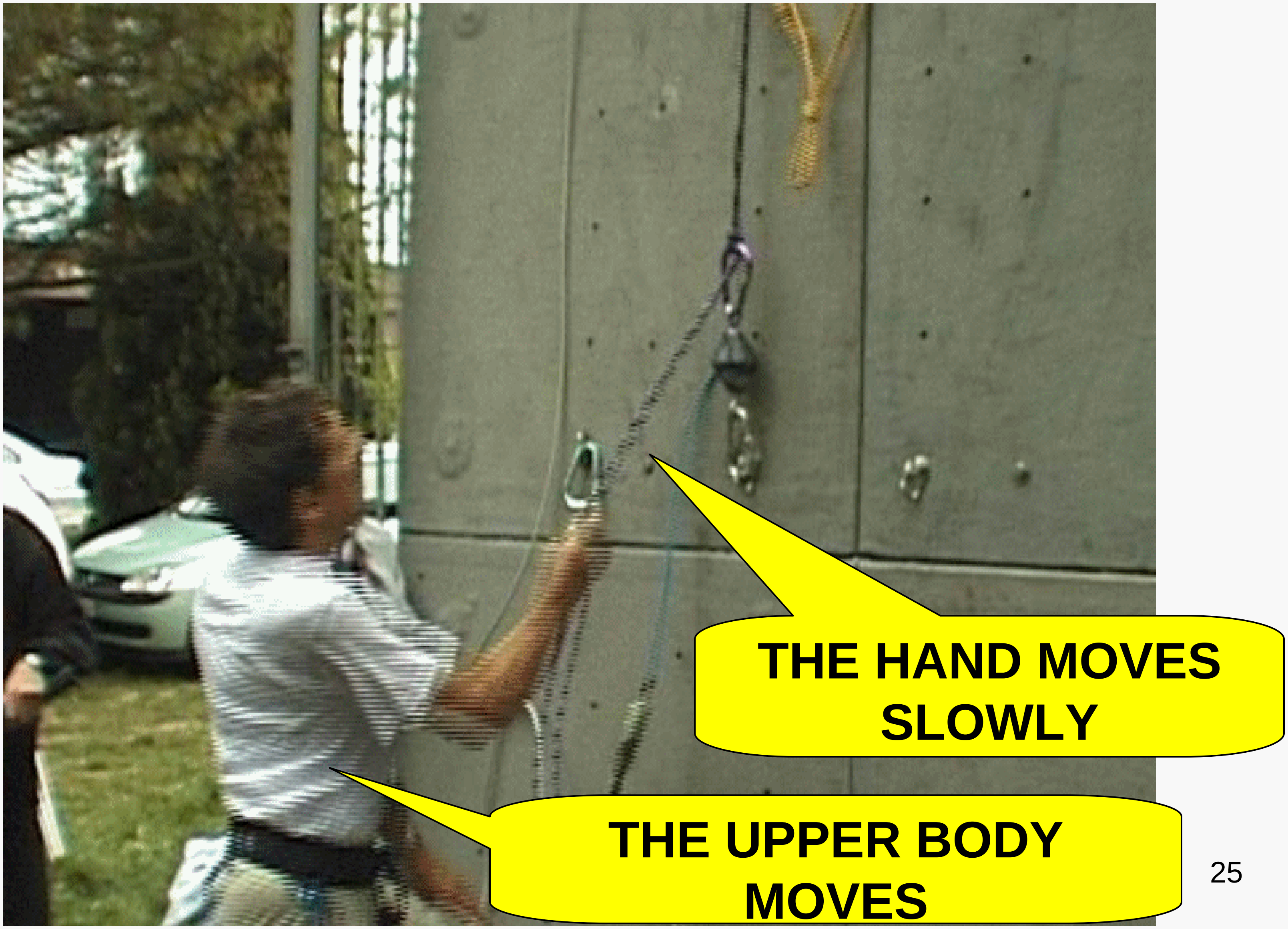
- Three phases of belay-hand behavior identified
    - Inertial Phase
    - Muscular Phase
    - Slipping Phase

“INERTIAL” PHASE

The hand moves fast

"MUSCULAR" PHASE

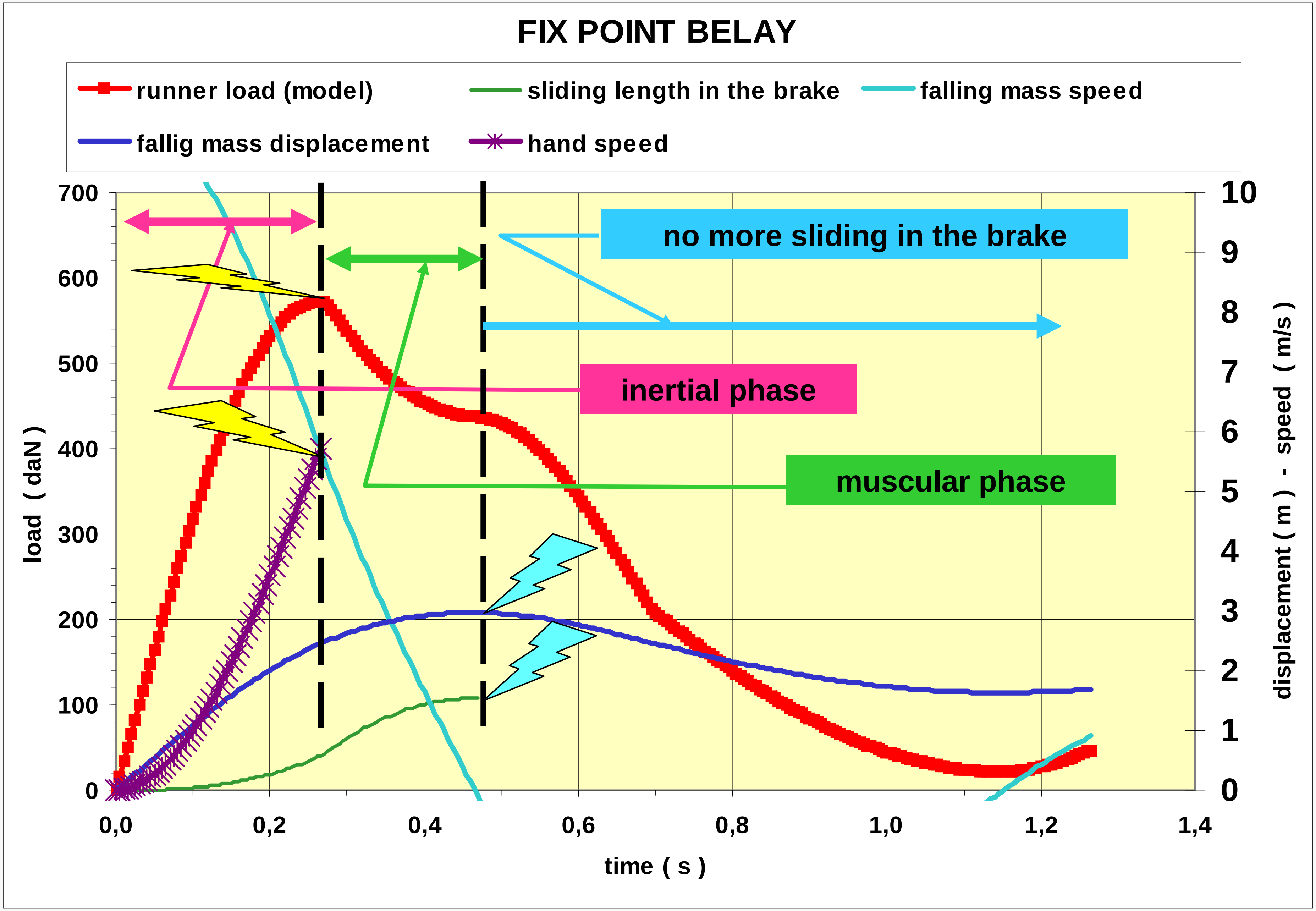
The hand moves slowly



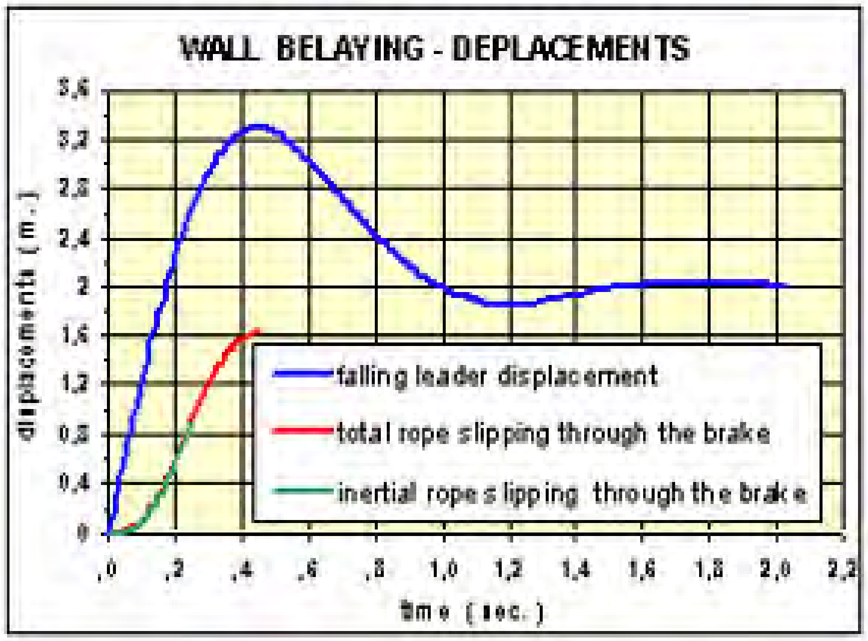
"HAND SLIPPING" PHASE

Possible rope slipping in the operator's hand

FIX POINT BELAY



Comparison to CMT Belay Simulation and Data

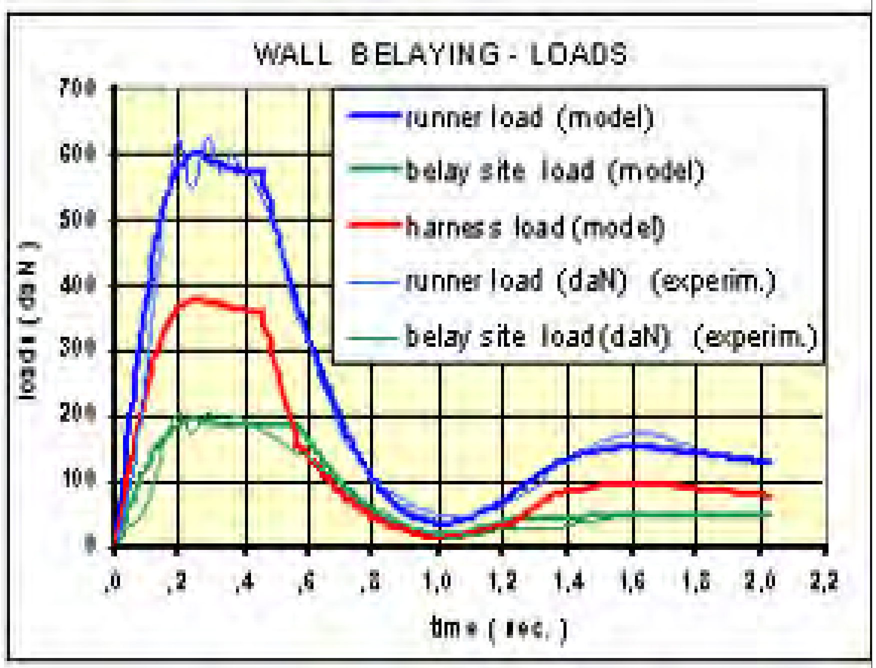


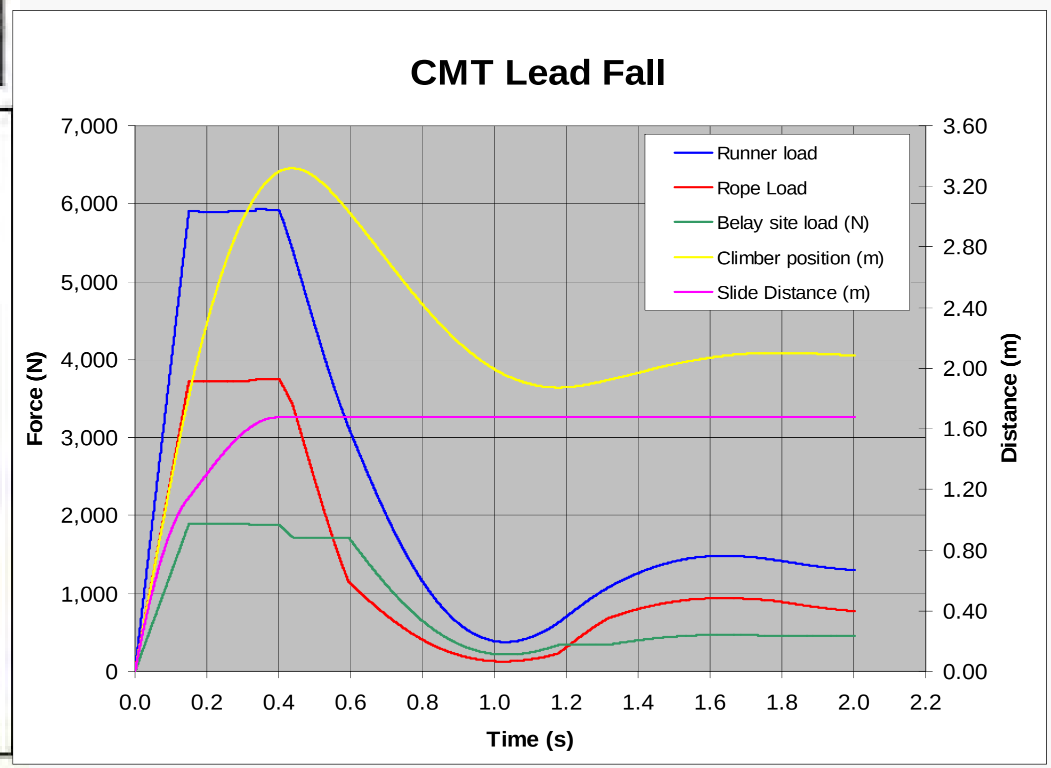
CMT Fall Parameters given:

- 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 Lead Fall

80	m_c
0.0005	dt
7.15	L_1
4	d
11.15	L
0.58	η
0	B
20920	A
3000	λ
50	k_ratio
0.15	T_r
7.5	FMF
290	grip
8	h
0.717	F





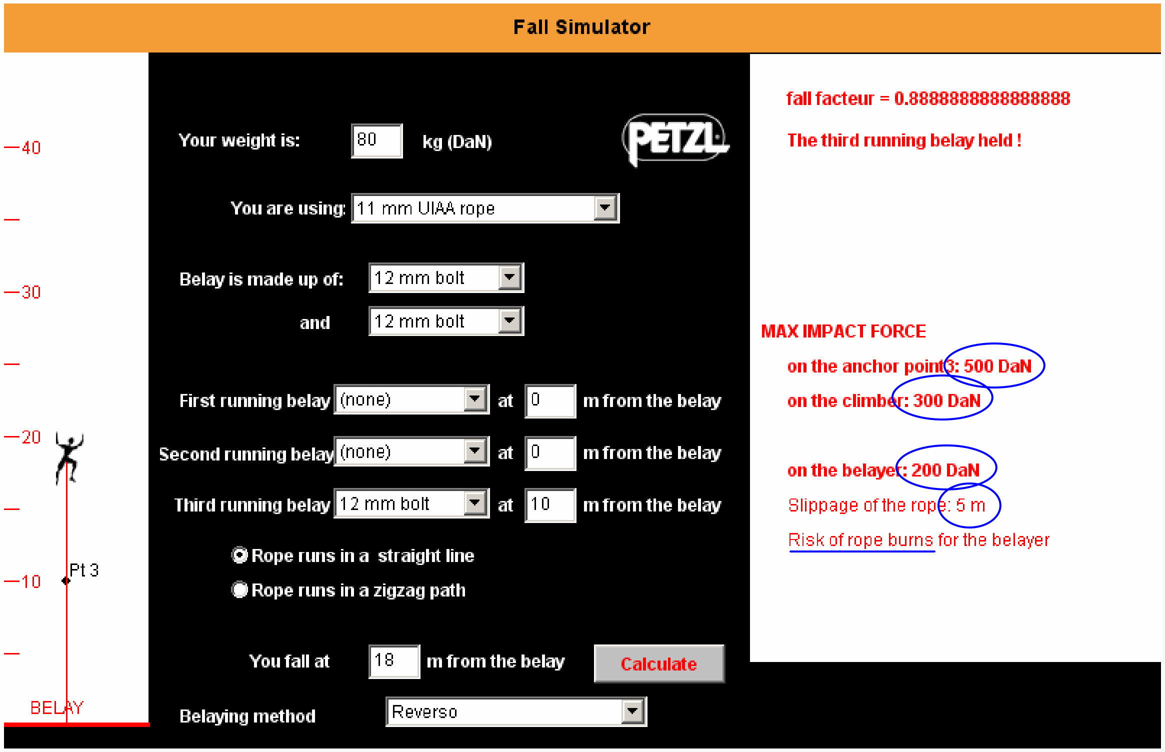
CMT Conclusions on Belaying

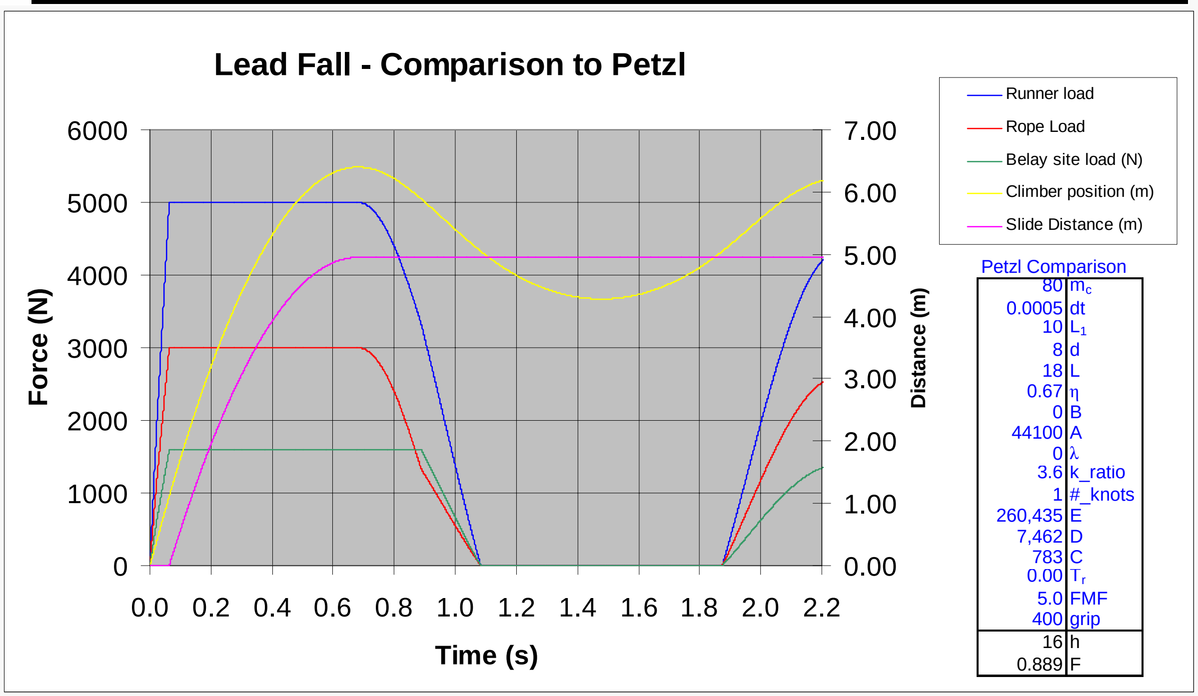
• Hand acts as an inertial load for the first few hundred milliseconds.

• 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:

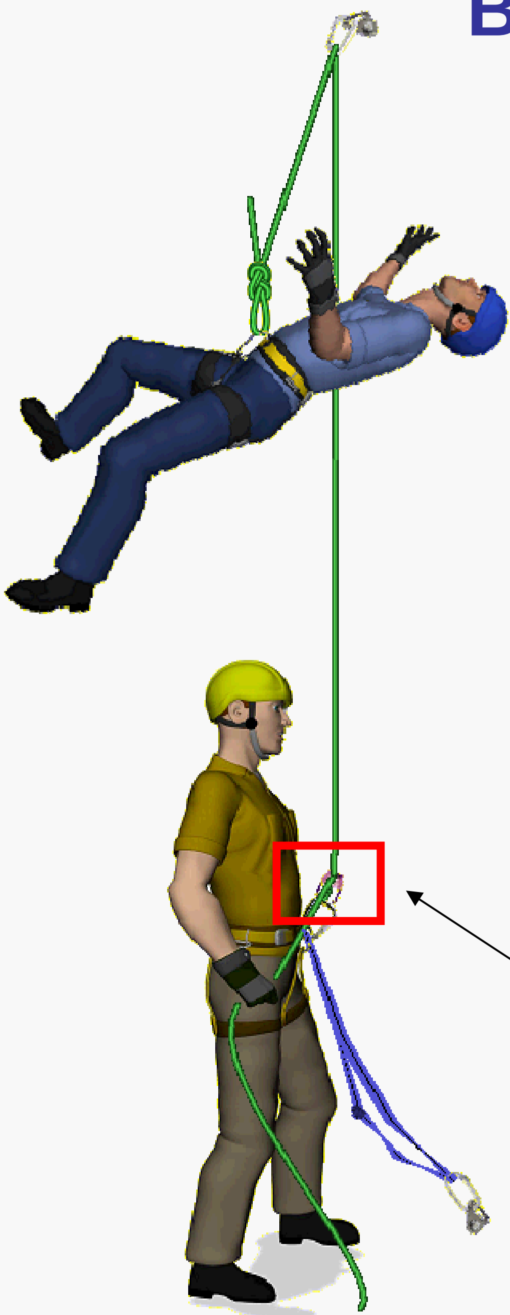
- Hand Grip = 400N
- Rope Burn Warning = 1800J
- Reverso FMF = 5.0
- Munter Hitch FMF = 7.5
- Grigri FMF = ∞ (no slipping)

- 11mm rope modulus ≈ 44.1 kN
- Carabiner efficiency = 66.6%
- Knot elongation included

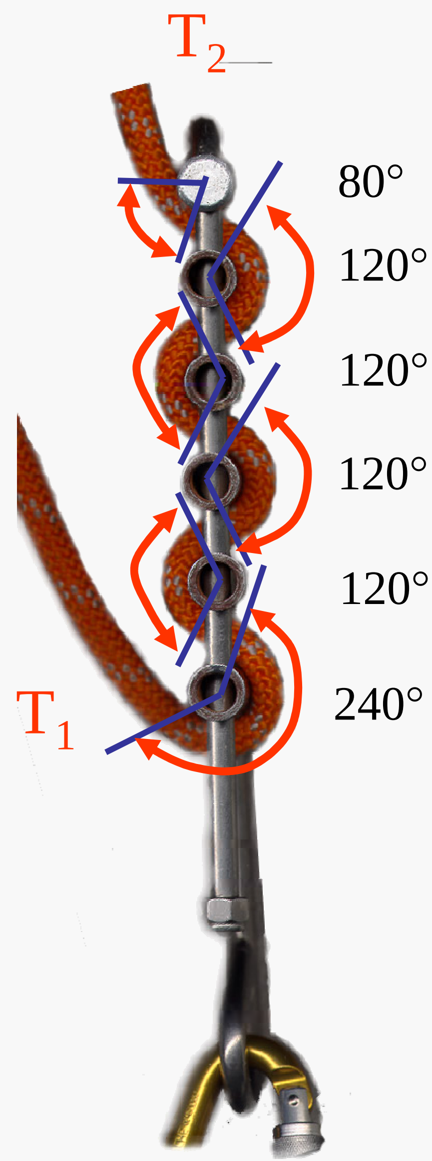
- No rope damping
- No lifting of belayer

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

Belay Device Details - FMF Values



Friction device properties are very important to the model predictions



Attaway Friction Analysis

$T_2/T_1 = e^{\mu\beta}$

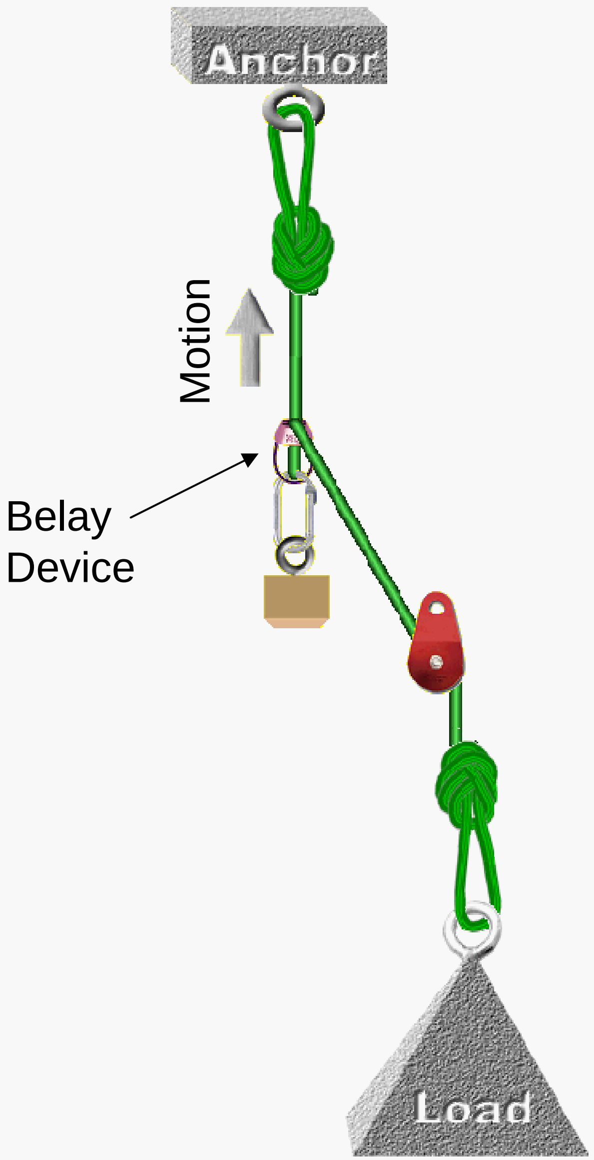
Total = 800°

4.4π

$\boxed{T_1 = T_2/31}$

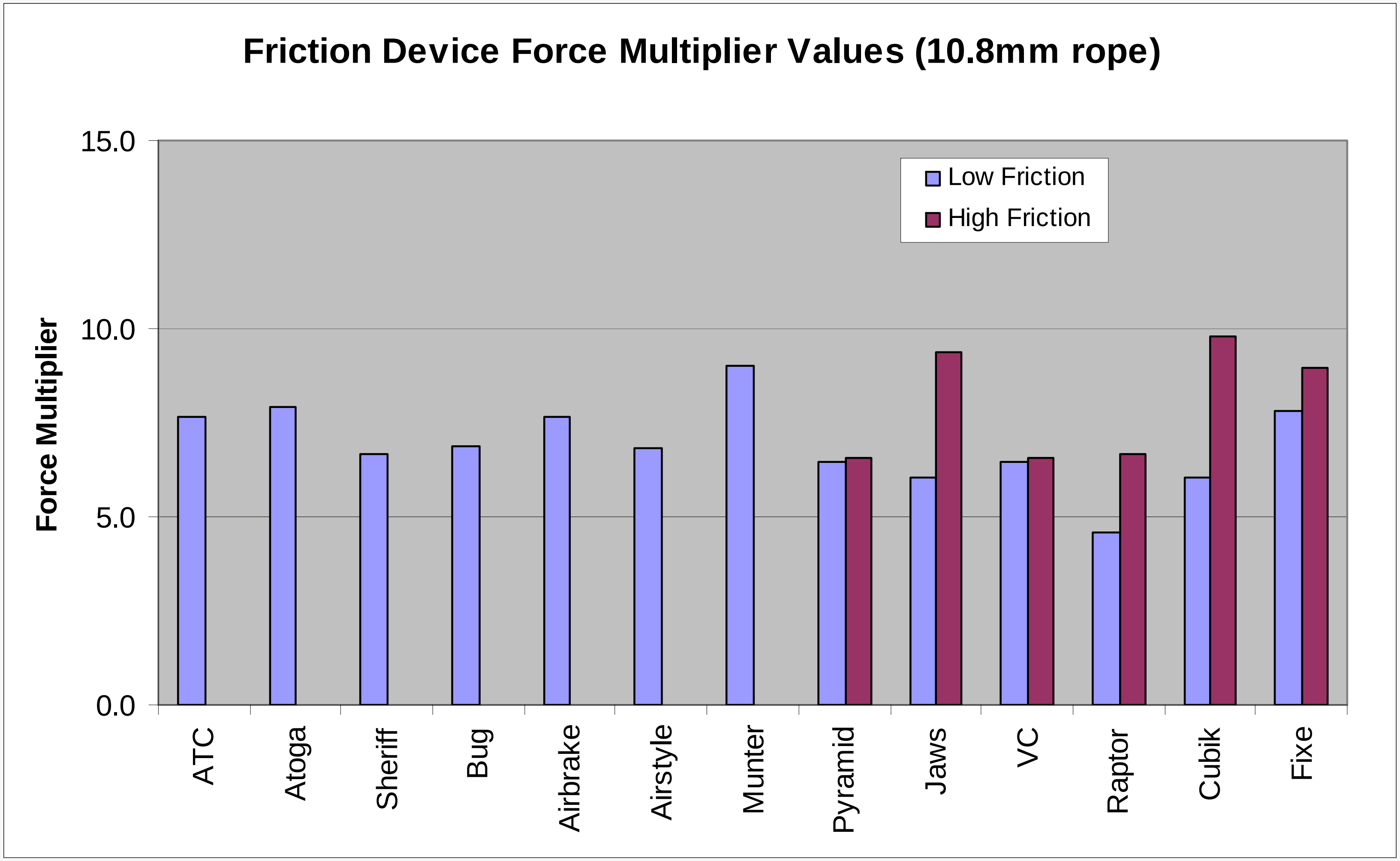
Belay Device FMF Values

Black Diamond Testing



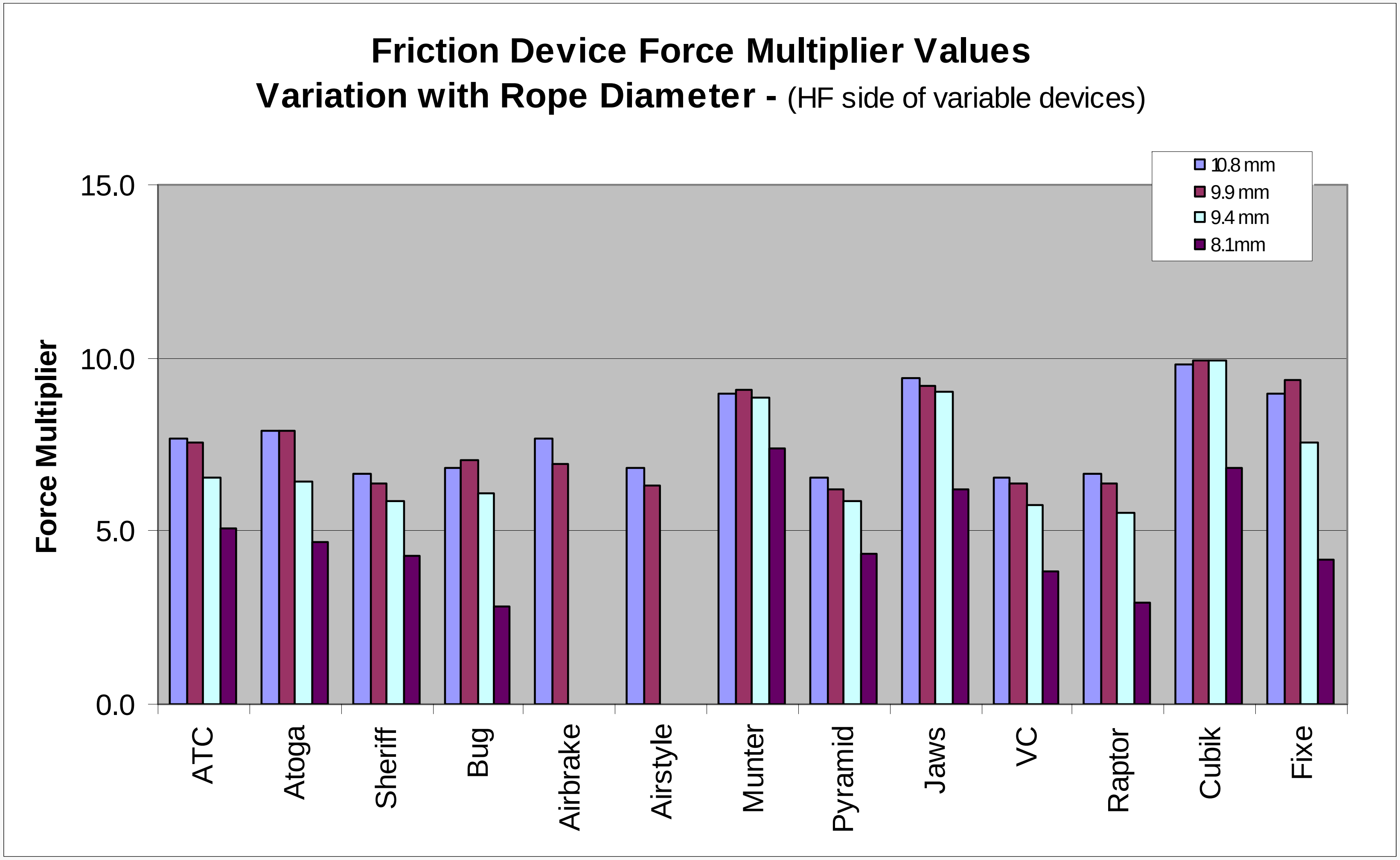
Belay Device FMF Values

Black Diamond Test Data



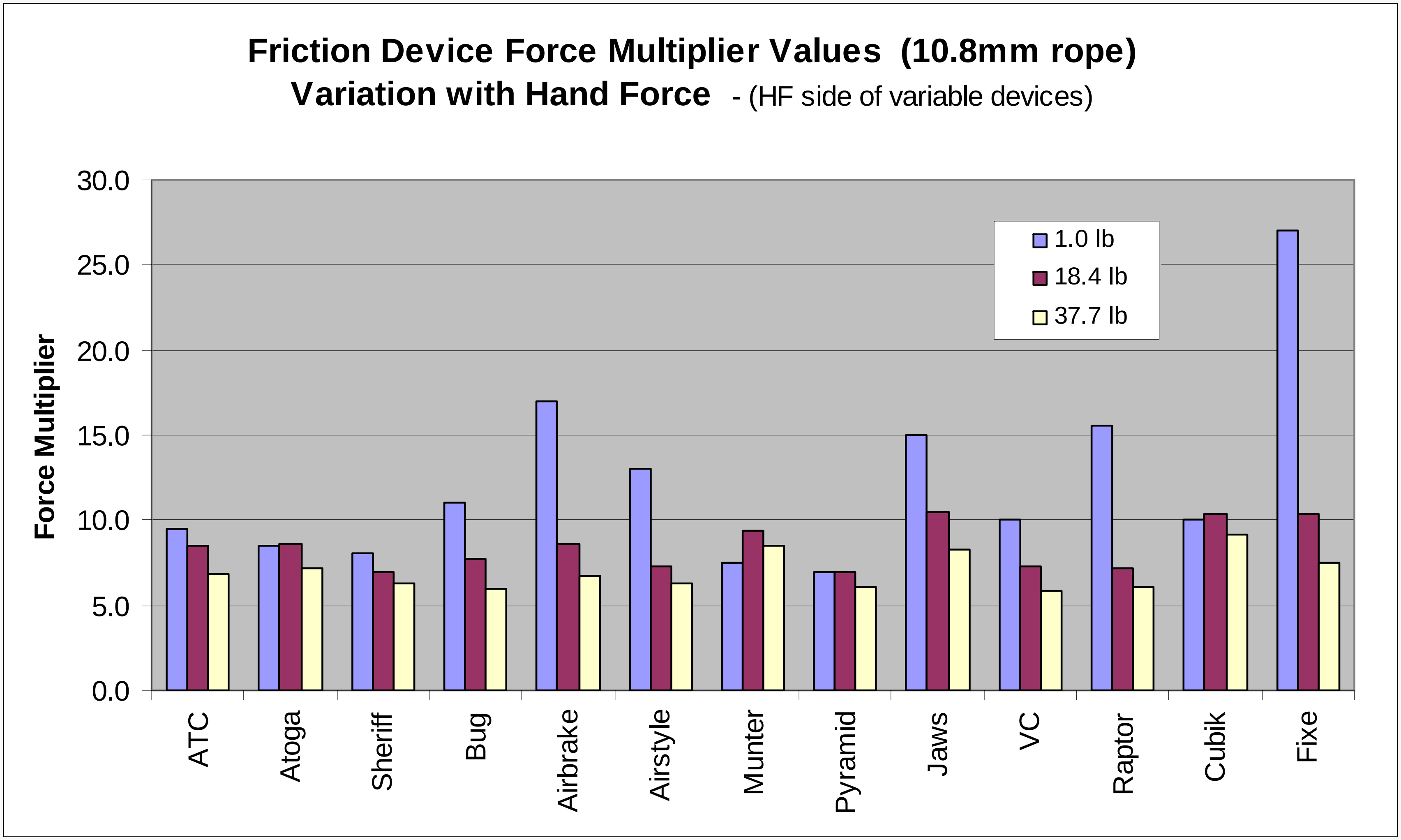
Belay Device FMF Values

Black Diamond Test Data



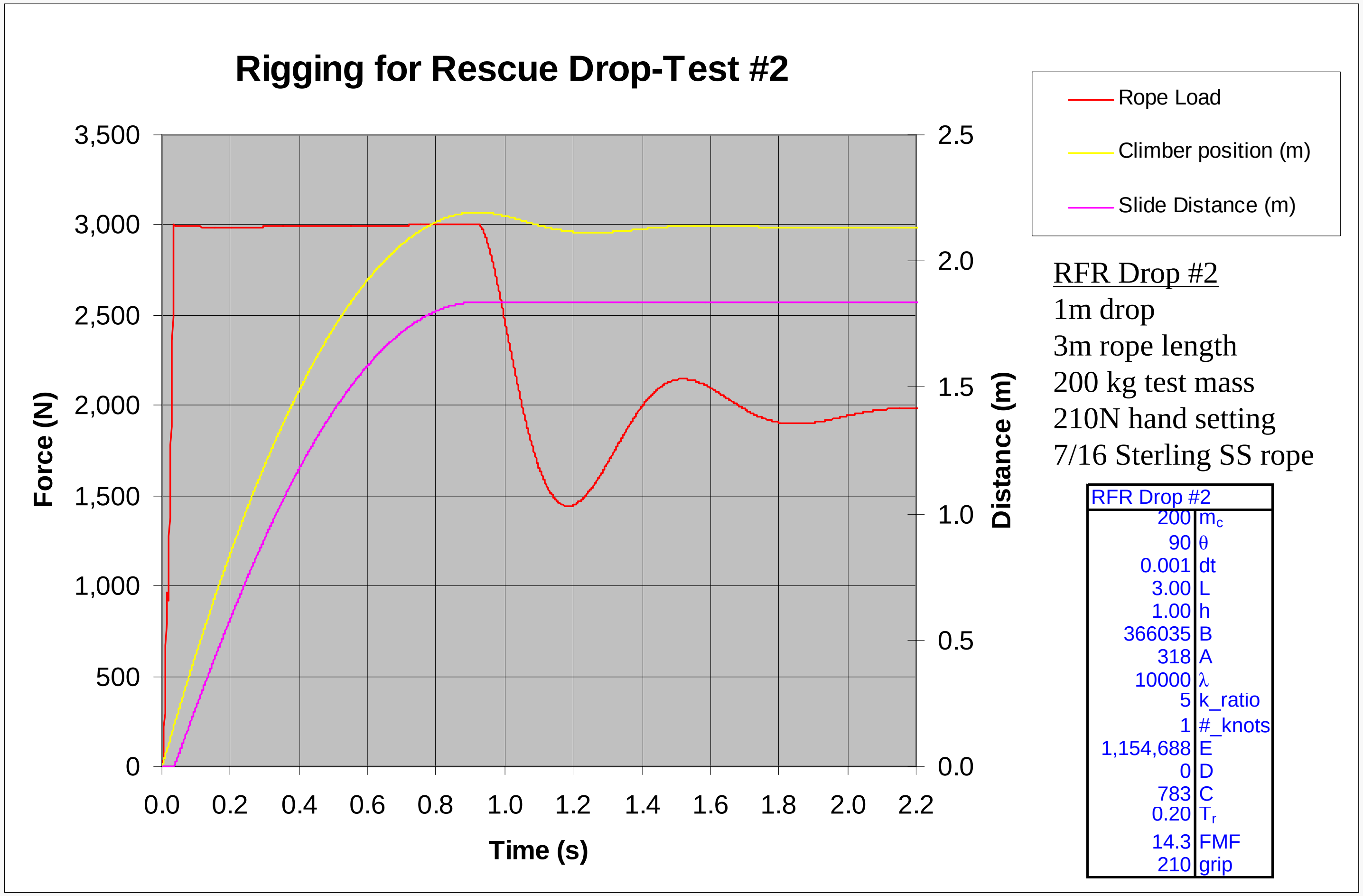
Belay Device FMF Values

Black Diamond Test Data



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

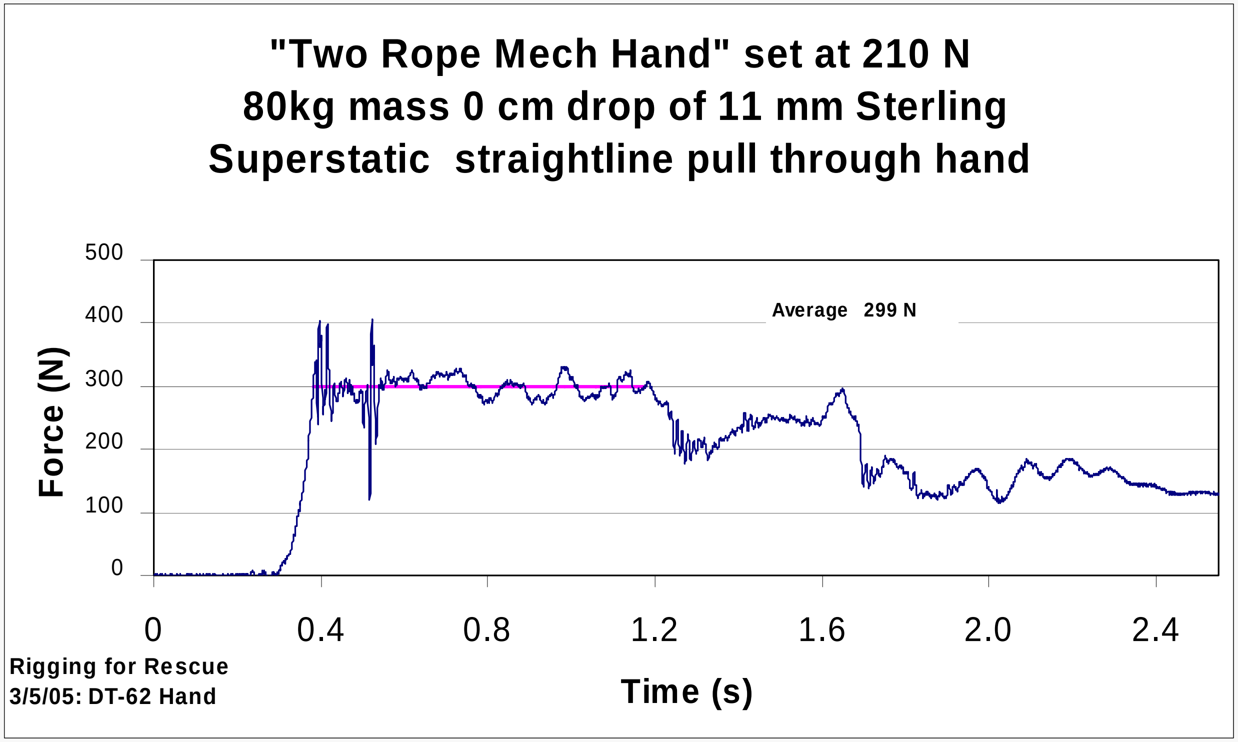
- Model values:

  3003 N Peak Force, 184 cm slide distance, 219 cm FAS extension

Comparison to Rigging for Rescue Drop-Test Data

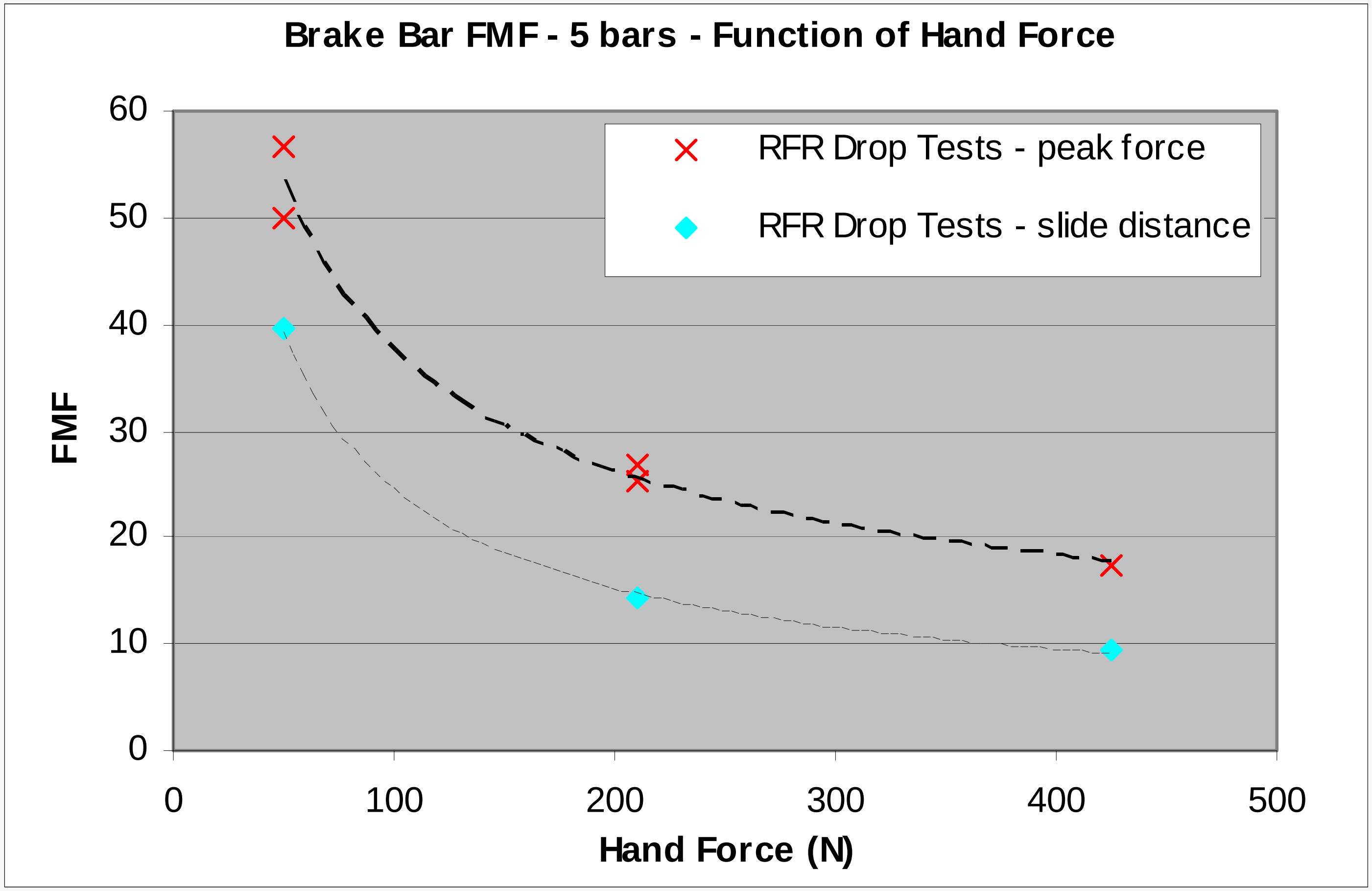
Rigging for Rescue Data – ITRS 2005

- 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.

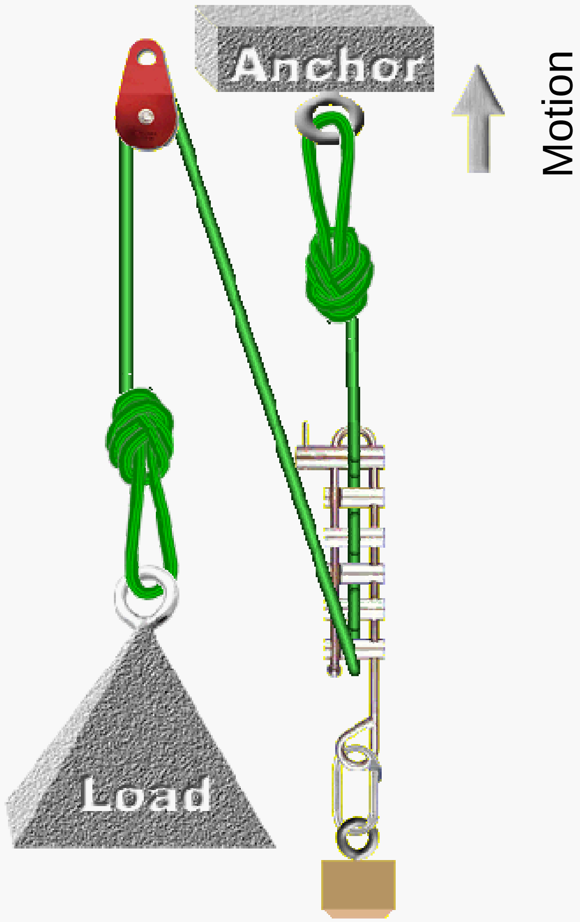


Comparison to Rigging for Rescue Drop-Test Data

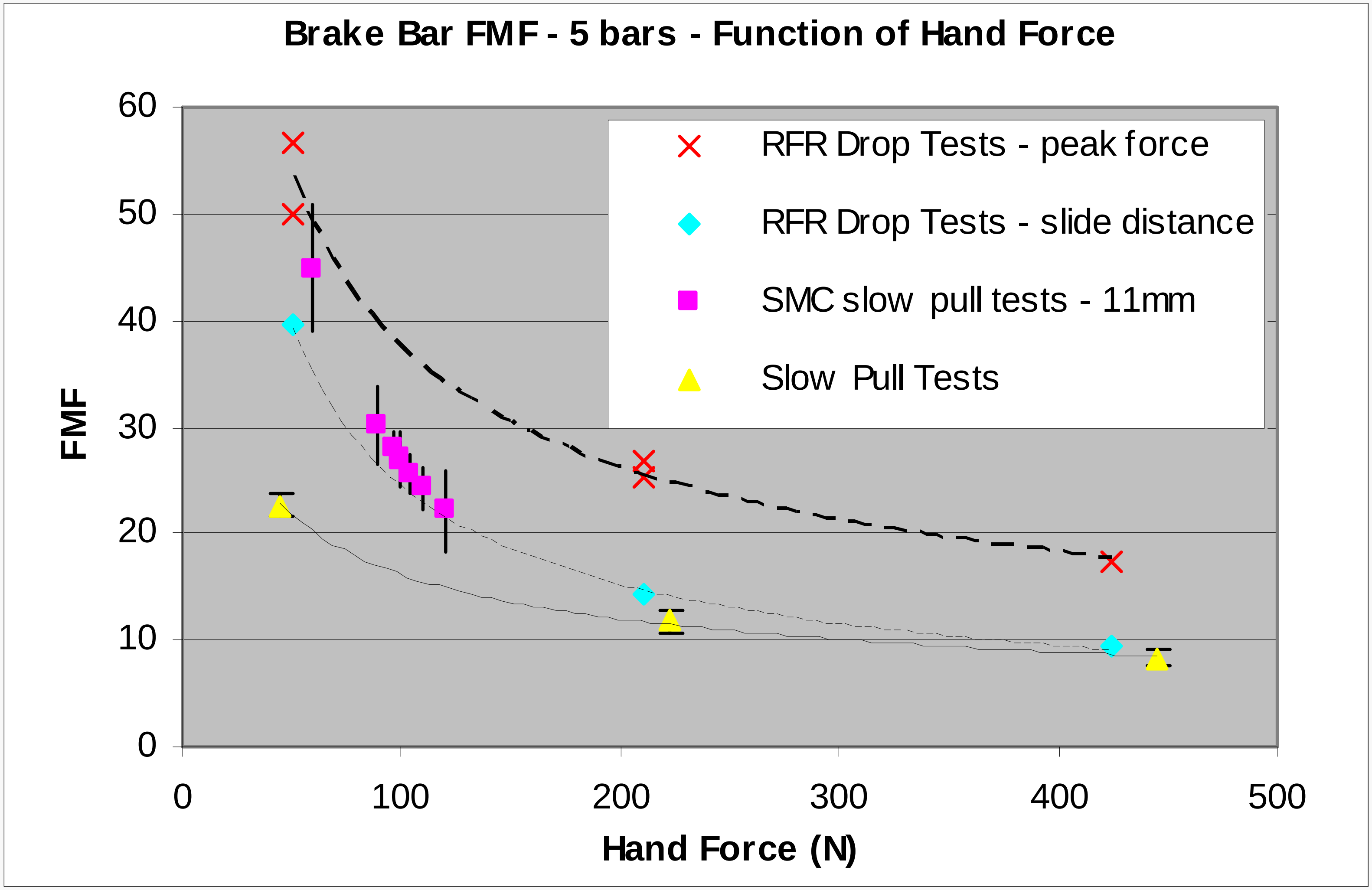
Brake Bar FMF varies with Hand Force



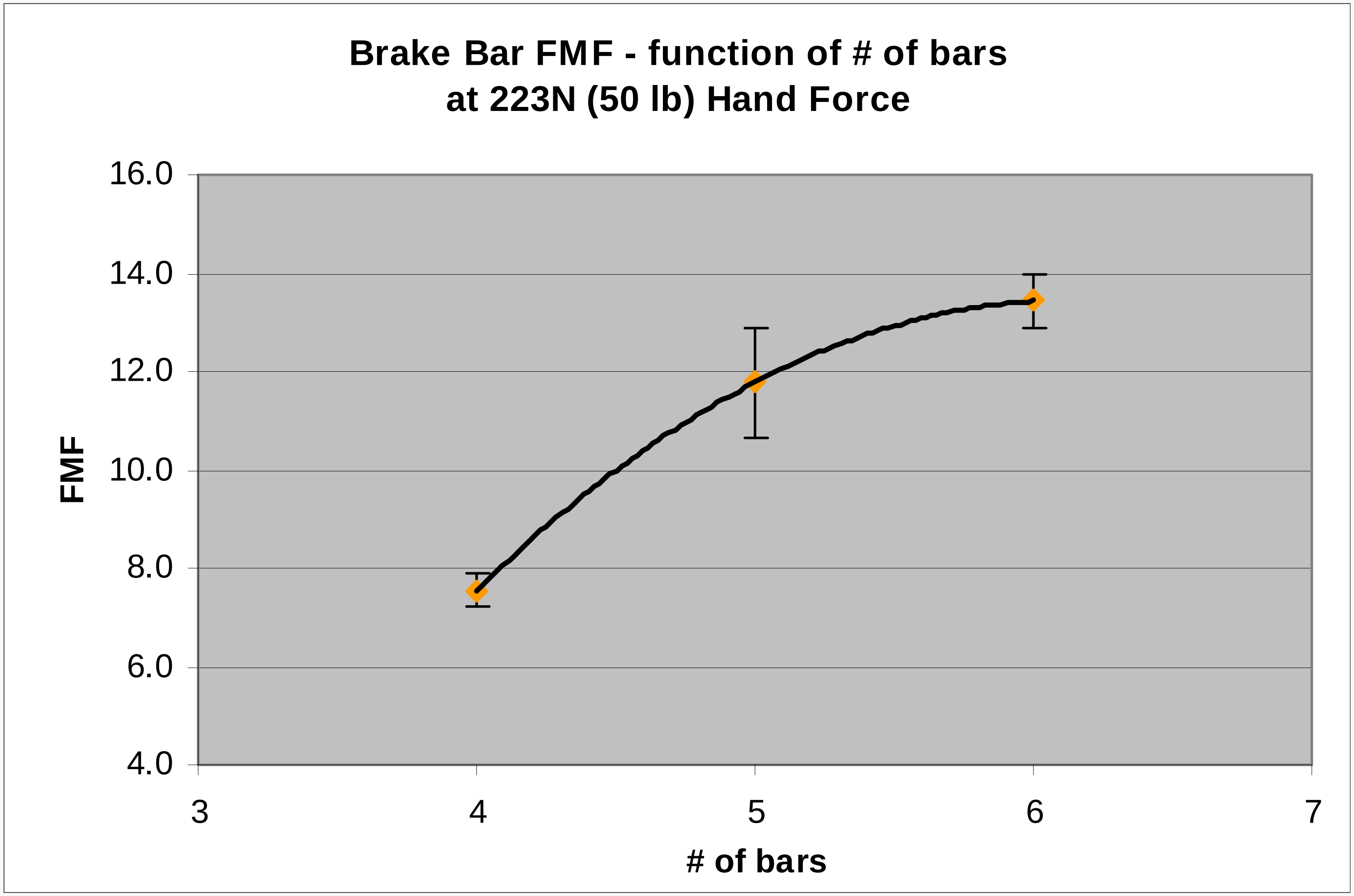
Brake Bar FMF Testing at Black Diamond

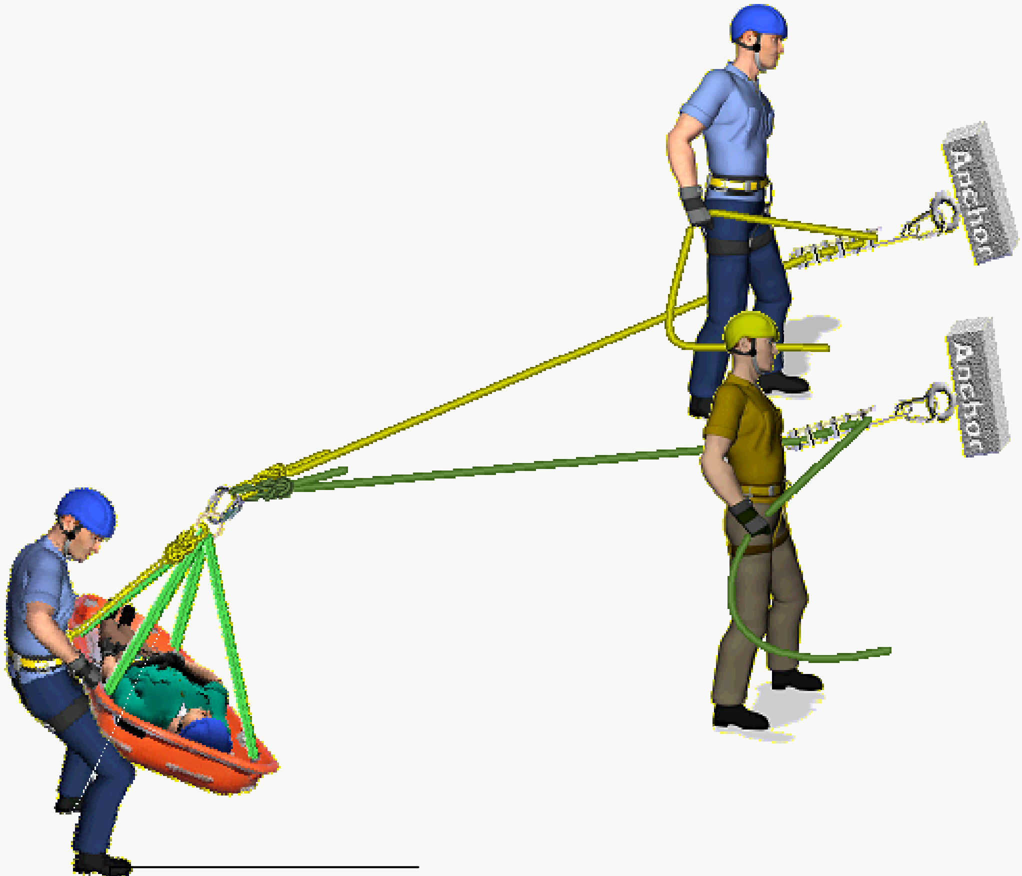


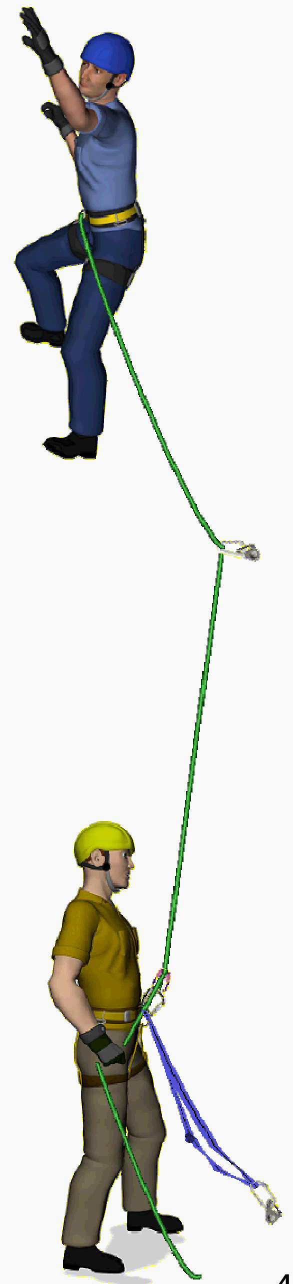
Brake Bar FMF Testing at Black Diamond



Brake Bar FMF Testing at Black Diamond







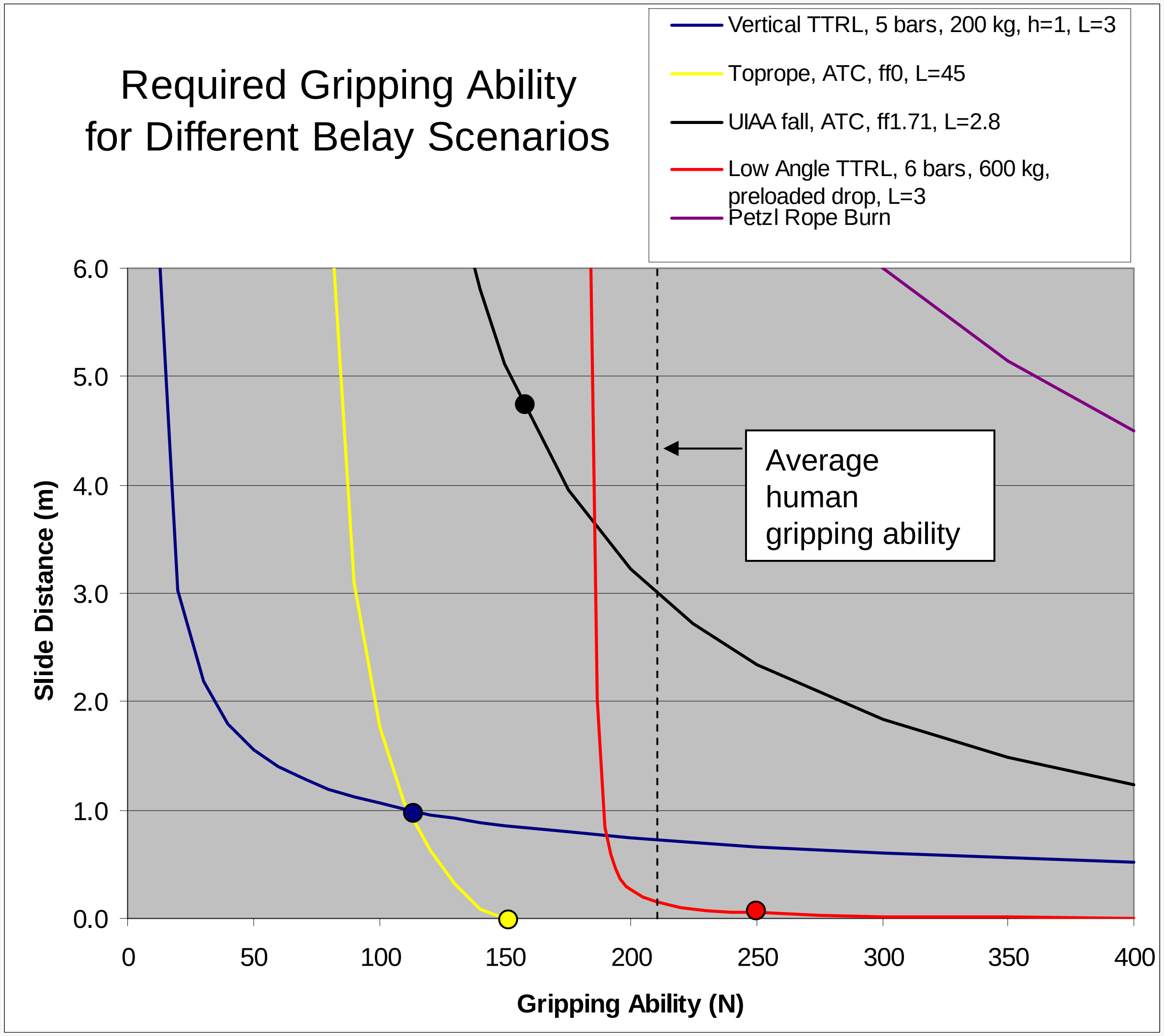
Back to the Original Question

How do TTRL belays compare to climbing belays?

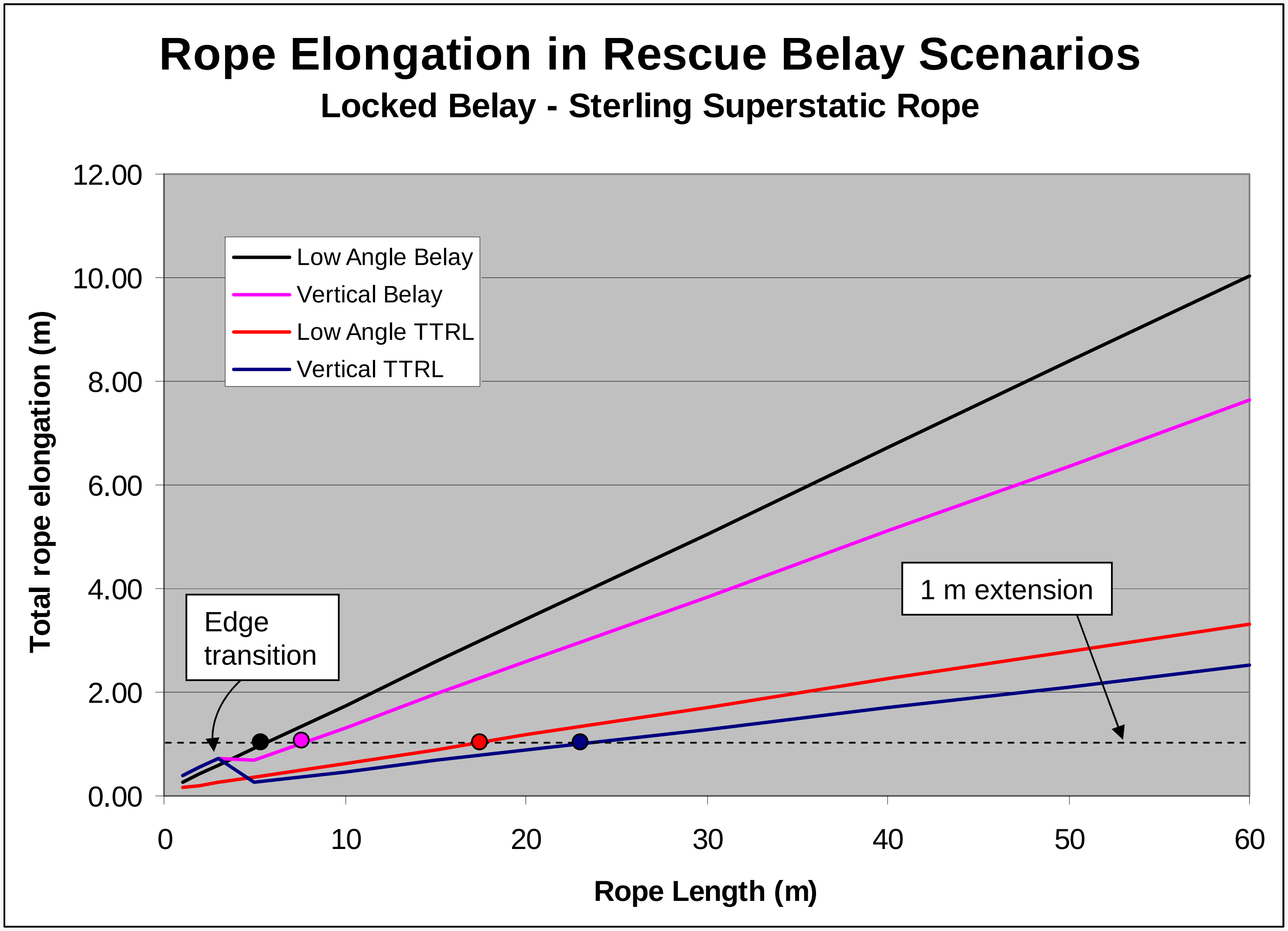
Gripping Ability Required for Climbing and Rescue Scenarios

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

- Chuck Weber – PMI
- Paul Tusting and Kolin Powick – Black Diamond Equipment
- Carlo Zanantoni - CMT
- Mike Gibbs – Rigging for Rescue
- Dave Custer – UIAA
- Steve Achelis – RescueRigger
- Garin Wallace – SMC
- Marc Beverly and Steve Attaway