Climbing Equipment and Friction

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- SAMME @ Bundoora EAST Campus
SportzEdge Program @ RMIT University

- The Sports Engineering and Technology (SportzEdge) research program is focussed on Sports Technology Innovation

- with key research areas in
  - *Performance enhancement with smart solutions*;
  - *Design customisation*;
  - *Injury prevention*;
  - *Growth in sports participation*; and
  - *Sustainable design and manufacturing*
Key Areas of Expertise
SportzEdge @ RMIT University

• **Smart Equipment**
  Smart balls, wheelchairs, shoes, gloves, etc.
  Sensor-less sensing, advanced signal processing, fractal dimensions

• **Advanced manufacturing**
  3D printing / metal, polymers

• **Non-linear engineering**
  Friction, VE, vibrations, E-transfer, foam mechanics, FEM

• **Sports Aerodynamics**
  Skiing, surfaces, garments, helmets, balls, bikes

• **Sustainable Engineering**
  Eco-design, life-cycle assessment, sustainable manufacturing, carbon footprint of sports products

• **Design optimisation**
  Wheelchairs, sports shoes, etc.
SPORTS TECHNOLOGY JOURNAL

- **Editors-in-Chief:** FK Fuss, A Subic, R Mehta

- **Publisher:** www.tandf.co.uk/journals/rtec

Acceptance ratio: 60%

Upcoming issue:
Asia-Pacific Conference on Sports Technology

- Founded by Aleks Subic
- 2003 – Melbourne
- 2005 – Tokyo
- 2007 – Singapore
- 2009 – Hawaii
- 2011 – Melbourne
- 2013 – Hong Kong
- 2015 - Barcelona

Biennial conference alternating with the ISEA Conference
Conference books published
MC190 MSc Int‘I Sports Technology

- 1st sports engineering / technology in the southern hemisphere
- 2 yrs / 4 sems
- Double degree options with European unis
  - UAS Vienna (Technikum)
  - German Sports Uni Cologne
Routledge Handbook of Sports Technology and Engineering

- Editors: Tino, Aleks, Martin, Rabi
- Routledge / Taylor & Francis
- 1st comprehensive Sports Engineering Book ever
- Postgraduate level
- published Nov 2013
- RMIT Superbike on the cover
PULLEY MECHANICS
Pulley - Tendon System

- Broad A2 and A4 pulleys are located between joints
- Narrow A1 and A3 pulleys are positioned over joints (A1 @ MCP, A3 @ PIP)

Figure from: Andreas Schweizer, M.D, The A2 pulley and the flexor tendon sheath
Mechanics of the Pulley - Tendon System

- Pulleys ensure that the flexor tendons remain close to the joint axes and maintain a constant tendon moment relationship

- Bowstringing occurs in the absence of pulleys
Bowstringing

- Increases moment arm and muscle moment
- Increases muscle stroke → limits range of force production (via force-length relationship)
Components of the Pulley System
Fp (pulley force)

Ft

axial view

side view

Fp
tendon
Ft
Pulley Model
Derivation of Equations
Derivation of Equations

\[ F_{P_{1x}} = \frac{(c_1 - x_1)}{l} F_{P_1} \]
\[ F_{P_{1y}} = \frac{(d_1 - y_1)}{l} F_{P_1} \]
\[ F_{\mathbf{f}_{1x}} = \left( \frac{(a_1 - x_1)}{\sqrt{(a_1 - x_1)^2 + (b_1 - y_1)^2}} \right) \cdot F_{\mathbf{f}} \]
\[ F_{\mathbf{f}_{1y}} = \left( \frac{(b_1 - y_1)}{\sqrt{(a_1 - x_1)^2 + (b_1 - y_1)^2}} \right) \cdot F_{\mathbf{f}} \]
\[ F_{\mathbf{f}_{2x}} = \left( \frac{(a_2 - x_1)}{\sqrt{(a_2 - x_1)^2 + (b_2 - y_1)^2}} \right) \cdot F_{\mathbf{f}} \]
\[ F_{\mathbf{f}_{2y}} = \left( \frac{(b_2 - y_1)}{\sqrt{(a_2 - x_1)^2 + (b_2 - y_1)^2}} \right) \cdot F_{\mathbf{f}} \]
3 constitutive equations per pulley fibre

\[
\left( \frac{(a_1 - x_1)}{\sqrt{(a_1 - x_1)^2 + (b_1 - y_1)^2}} \right) \cdot R_l + \left( \frac{(a_2 - x_1)}{\sqrt{(a_2 - x_1)^2 + (b_2 - y_1)^2}} \right) \cdot R_l + \frac{(c_1 - x_1)}{l} \cdot F_{P_1} = 0
\]

\[
\left( \frac{(b_1 - y_1)}{\sqrt{(a_1 - x_1)^2 + (b_1 - y_1)^2}} \right) \cdot R_l + \left( \frac{(b_2 - y_1)}{\sqrt{(a_2 - x_1)^2 + (b_2 - y_1)^2}} \right) \cdot R_l + \frac{(d_1 - y_1)}{l} \cdot F_{P_1} = 0
\]

\[ (c_1 - x_1)^2 + (d_1 - y_1)^2 = (l)^2 \]
ELASTIC PULLEY
(with spring constant)

\[
\left( \frac{(x_{i-1} - x_i)}{\sqrt{(x_{i-1} - x_i)^2 + (y_{i-1} - y_i)^2}} \right) \cdot F_t + \left( \frac{(x_{i+1} - x_i)}{\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}} \right) \cdot F_t + \frac{(c_i - x_i) \cdot Fp_i}{l_i + \frac{Fp_i}{k}} = 0 \quad (1)
\]

\[
\left( \frac{(y_{i-1} - y_i)}{\sqrt{(x_{i-1} - x_i)^2 + (y_{i-1} - y_i)^2}} \right) \cdot F_t + \left( \frac{(y_{i+1} - y_i)}{\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}} \right) \cdot F_t + \frac{(d_i - y_i) \cdot Fp_i}{l_i + \frac{Fp_i}{k}} = 0 \quad (2)
\]

\[
(c_i - x_i)^2 + (d_i - y_i)^2 = \left( l_i + \frac{Fp_i}{k} \right)^2 \quad (3)
\]
ANNULAR PULLEY – equations for the \( i \)th fibre

\( n \) fibres

3 eqns per fibre

UNKNOWNS:
1) \( x_i \) – x-coordinate of free end of fibre
2) \( y_i \) – y-coordinate of free end of fibre
3) \( F_{pi} \) – force of fibre

3\( n \) equations (algebraic, 2\(^{nd}\) order)

3\( n \) unknowns

2\(^n\) possible results (19 fibres \( \rightarrow \) 524288 results)

1 true result (all unknowns must be positive)
Tendon Angle

- Change in Tendon Angles affects force distribution in the pulley system
- Colours describe the magnitude of the forces. Red → maximum Blue → minimum
- Force concentrations may be located at the marginal or central fibres
Smart Climbing Holds and Walls
National Championship
National Climbing Championship 2002
National Climbing Championship

Colour-coded Vector Diagrams

TIME
3 Phases of Contact

The contact time was divided into 3 phases (**set-up, crank, and lock-off**). The two transitions (borders) between the 3 phases were defined as:

1) set-up / crank: first major rise of the resultant force
2) crank / lock-off: turning point of the COP, when the COP moves off the wall
Vector Diagrams

Phase 1

Phase 2

Phase 3

mean vector
World Cup
Climbing World Cup 2002
World Cup Hold
Sensor mounting

frame

washer

wall

gap

handhold
Climbing World Cup

NAGAKAI Hoshiko (JP)
Handhold surface – polynomial function

\[ Y = 0.04835000082 - 1.3211798 \times X - 401.5132744 \times X^2 + 50394.75096 \times X^3 - 2697802.565 \times X^4 + 82418487.53 \times X^5 - 1548606012 \times X^6 + 1.820585185 \times 10^{10} \times X^7 - 1.306439741 \times 10^{11} \times X^8 + 5.238094305 \times 10^{11} \times X^9 - 9.001212133 \times 10^{11} \times X^{10} \]

\[ Y = 0.08058923162 - 1.937357548 \times X - 65.24065762 \times X^2 - 3414.531177 \times X^3 - 145431.33 \times X^4 - 3495822.81 \times X^5 - 47296490.57 \times X^6 - 359751331.8 \times X^7 - 1437328874 \times X^8 - 2345394205 \times X^9 \]
• Moment equilibrium

$$M_z - Xe^* f(X) + Ye^*X=0$$

$$Mz-Xe^*(0.04835000082-1.3211798*X-401.5132744*pow(X,2)+50394.75096*pow(X,3)-2697802.565*pow(X,4)+82418487.53*pow(X,5)-1548606012*pow(X,6)+1.820585185E+010*pow(X,7)-1.306439741E+011*pow(X,8)+5.238094305E+011*pow(X,9)-9.001212133E+011*pow(X,10)) + Ye^*X=0$$

• roots solved with Matlab (MathWorks).

• vector diagrams together with the handholds were reconstructed in AutoCAD 2000 (Autodesk).
"Root Management"

- Polynomials $> 2^{\text{nd}}$ order: Matlab required
- Solving polynomials up to the $10^{\text{th}}$ order $\rightarrow$ maximally 3 (!) roots within the limits of the instrumented sports equipment
- Root1 in $\sim 94\%$, root2 in $\sim 44\%$, root3 in $\sim 0.03\%$
- How to decide which root is the correct one?
- Assumption of continuous ICP motion on the surface
Performance Parameters

less experienced

more experienced

impending slippage
Vector Diagrams – World Cup

17

more experienced

25

less experienced
Vector Diagrams – World Cup
Pinch Grip
Instrumented Hold – Pinch Grip
Vector Diagrams
Performance
Performance Parameters

• The better the climber, the

• 1) smaller the mean and max force
• 2) shorter the contact time
• 3) smaller the impulse
• 4) higher the mean & max coefficient of friction
• 5) higher the smoothness factor (less chaotic)
• 6) the smaller the fractal dimensions
Smoothness factor

Body weight divided by the mean of the absolute difference (in N) between the y-force-time graph and a parabolic curve of the same impulse. The parabolic curve serves as a model for the ideal force-time graph of the handhold contact.

\[ F_t = \left[ \frac{t}{T} - \left( \frac{t}{T} \right)^2 \right] (6 \ J/\ T) \]

\( T = \) contact time

\( J = \) impulse

Parabolic curve, initial and final conditions:

\( T,F: 0,0 \) & \( T,0 \)

**Force:** \( F_t = at^2 + bt \)  
**Impulse:** \( J = at^3/3 + bt^2/2 \)

at final condition \( t = T \):

**Force:** \( 0 = aT^2 + bT \)  
**Impulse:** \( J = aT^3/3 + bT^2/2 \)

**Force:** \( 0 = -3aT^2 - 3bT \)  
**Impulse:** \( 6J/T = 2aT^2 + 3bT \)

SUM: \( 6J/T = -aT^2 \rightarrow a = -6J/T^3 \)

\(-aT^2 = bT \rightarrow -T^2(-6J/T^3) = bT \rightarrow b = 6J/T^2 \)

**Force:** \( F_t = (-6J/T^3)t^2 + (6J/T^2)t \)

**Force:** \( F_t = (6J/T)(-t^2/T^2 + t/T) \)
Fractal Dimensions

- Force-time signals
- Hausdorff-Besicovitch Dimension

- The generalized fractal dimensions of a given time series with the known probability distribution are defined as:

  $$D_q = \lim_{N \to +\infty} \frac{1}{q-1} \log \sum_{i=1}^{N} p_i^q$$

- where the parameter $q$ ranges from $-\infty$ to $+\infty$.
- The fractal dimension $D_0$, nothing else than the Hausdorff-Besicovitch dimension.

$$D_0 = -\frac{\log N}{\log \delta V}$$
Performance Analysis

- Hausdorff dimension depends on:
  - 1) Amplitude of signal
  - 2) Length (duration) of signal
  - 1+2) Impulse
  - 3) Frequency and chaoticness of signal
- \( \Rightarrow \) all 4 parameters are performance indicators \( \Rightarrow \) smaller Hausdorff dimension in better climbers
Training
Training

- Influence of training on performance parameters
WALL AND HANDHOLD

- Force Transducer
- Threaded Hole
- Front Plate
- Back Plate
- Handhold
- Unthreaded Hole
- 44.70 mm boundary
- 2mm boundary

Wall and Handhold
Training

- decrease of the contact time, impulse, and maximal force, and Hausdorff dimension
- increase of the maximal friction coefficient and smoothness factor
Difficulty 1
Difficulty of a Climbing Route

• Route Grading
• Quantification of “Difficulty”
Route Grading

- no grading standard
- difficulty scales
- depending on *perception* \(\rightarrow\) experience of route setter

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<th>YDS</th>
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<td>9a+</td>
<td>5.15b</td>
<td>12-</td>
<td>36</td>
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Difficulty of Climbing

Inclination of the wall - overhang
Identification of difficulty parameters

- Resultant force and contact time: increase - decrease
- Fractal dimension (resultant) – angle: slight increase
- Fractal dimension (Fx) – angle: clear increase
Identification of difficulty parameters

- Better climbers reach higher angles
- Fractal dimension – Impulse: power law
- Normalised fractaldimension (Fx) \(\rightarrow\) increase with angle (significant)
Difficulty 2
Curved (non-linear) surface circular

- experimental climbing hold, grip surface shaped as a quarter cylinder (radius $r = 80$ mm)
- cavity for housing two force transducers
- depth of grip surface reduced by wooden panels
Instrumented Hold

- number of wooden panels attached to the wall represents the increasing grip difficulty
• radius $r$ of the grip surface: 0.08 m.
• origin of the handhold’s coordinate system at the axis of the cylindrical grip surface.
• centre of the upper transducer at horizontal and vertical distances of $m = -0.008$ m and $n = -0.010$ m
• centre of the lower transducer at horizontal and vertical distances of $m$ and $n + d$, where $d = -0.052$ m, corresponding to the distance between the centre of the two transducers
FBD

- force equilibrium

\[ \sum F_x = 0 \]
\[ \sum F_y = 0 \]

- geometrical identity of the hold’s surface

- moment equilibrium

\[ \sum M = 0 \]

\[ COP_x^2 + COP_y^2 = r^2 \]

\[ COP_x \ E_y - COP_y \ E_x + n \ S_x - (m + d) \ S_2z - m \ S_1z = 0 \]
Mathematical analysis

• Replacing Ex, Ey, and COPy in the moment equilibrium Eqn by S1z, S2z, Sx and COPx (from Eqns 1-3) reduces the number of unknowns to 1 (COPx)
• S1z, S2z, and Sx are measured (known values)
• New moment equilibrium Eqn is a 2\textsuperscript{nd} order Eqn \rightarrow 2 solutions: COPx\textsubscript{1}, COPx\textsubscript{2}

\[
COPx_{1,2} = \frac{-C_3 \pm \sqrt{C_5}}{2C_2}
\]

where \(C_5\) is the discriminant

\[
C_5 = C_3^2 - 4C_2C_4
\]

\[
C_2 = Sx^2 + (S1z + S2z)^2
\]

\[
C_3 = 2SxC_1
\]

\[
C_4 = C_1^2 - r^2 (S1z + S2z)^2
\]

\[
C_1 = (m + d) S2z + m S1z - n Sx
\]
Mathematical analysis

\[
COP_x^2 + COP_y^2 = r^2
\]

• Once COPx1 and COPx2 are determined, calculate COPy from
  \[
  COP_y = \pm \sqrt{r^2 - COP_x^2}
  \]
  • \(2\) solutions each, as COPy can be positive and negative
  • \(\rightarrow\) in total \(4\) solutions
  • But only \(2\) solutions are correct \(\rightarrow\) check via moment equilibrium
  • Furthermore: C5 must be positive for real COPx numbers; COPx must be negative, COPy must be positive
Mathematical analysis

- slope angle $\theta$ of the surface at the centre of pressure ($COP_x, COP_y$)
- external forces $E_x$ and $E_y$ from Eqns (1,2), the resultant force $F_R$ of which is
- angle $\varphi$ of $F_R$
- components, $E_t$ and $E_n$, of the external forces applied tangentially ($E_t$) and perpendicularly ($E_n$) to the centre of pressure
- coefficient of friction $COF$

\[
\theta = \tan^{-1} \frac{-COP_x}{COP_y}
\]

\[
F_R = \sqrt{E_x^2 + E_y^2}
\]

\[
\varphi = \text{ATAN2}(E_y, E_x)
\]

\[
E_t = E_x \cos \theta + E_y \sin \theta
\]

\[
E_n = -E_x \sin \theta + E_y \cos \theta
\]

\[
COF = \left| \frac{E_t}{E_n} \right| = \left| \frac{E_x COP_y - E_y COP_x}{E_x COP_x + E_y COP_y} \right|
\]
\[ \theta = \tan^{-1} \left( -\frac{COP_x}{COP_y} \right) \]

\[ \tan \theta = \frac{\sin \theta}{\cos \theta} = -\frac{COP_x}{COP_y} \]

\[ Et = Ex \cos \theta + Ey \sin \theta = Ex \sin \theta \frac{COP_y}{-COP_x} + Ey \cos \theta \frac{-COP_x}{COP_y} \]

\[ En = -Ex \sin \theta + Ey \cos \theta = -Ex \cos \theta \frac{-COP_x}{COP_y} + Ey \sin \theta \frac{COP_y}{-COP_x} \]

\[ Et = \frac{Ex \sin \theta COP_y^2 + Ey \cos \theta COP_x^2}{-COP_x COP_y} \]

\[ En = \frac{-Ex \cos \theta COP_x^2 + Ey \sin \theta COP_y^2}{-COP_x COP_y} \]

\[ \frac{Et}{En} = \frac{\frac{Ex \sin \theta COP_y^2 + Ey \cos \theta COP_x^2}{-COP_x COP_y}}{\frac{-Ex \cos \theta COP_x^2 + Ey \sin \theta COP_y^2}{-COP_x COP_y}} = \frac{Ex COP_y - Ey COP_x}{Ex COP_x + Ey COP_y} \]
Accuracy

- compare actual COP location to calculated one
- sufficiently accurate
Results

• Vector diagrams
• Vertical force decreases
• Horizontal force changes direction ??
Results

• COF increases with increasing distance between COP and wall
• more COF = route more difficult
Results

- Resultant force changes direction $\rightarrow$ dynamic move (= route more difficult)
Results

- Contact time decreases (climbing faster → dynamic move → route more difficult)
- Resultant force decreases (→ forcing the climber to climb more economically → route more difficult)
- Horizontal force decreases and changes direction
Finger Force Distribution
Grip Types and finger forces

- Closed crimp (thumb on index)
- Open crimp
- Open hand
Smart Hold

- Finger key board
- Each finger key instrumented with piezo-electric force transducers
**Results**

- CC: I>M>R>L
- OC, OH: M>I=R>L
Fatigue
Fatigue

• Change of performance parameters due to fatigue
### Fatigue

- Assessment of fatigue: BORG Scale

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<th>Verbal Anchor</th>
<th>%MVC</th>
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<td>Nothing at all</td>
<td>0</td>
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<tr>
<td>0.5</td>
<td>Extremely weak (just noticeable)</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>Very weak</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Weak (light)</td>
<td>20</td>
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<tr>
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<td>Moderate</td>
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<td>Strong (heavy)</td>
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<td>90</td>
</tr>
<tr>
<td>10</td>
<td>Extremely strong (almost maximal)</td>
<td>100</td>
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</table>
Fatigue

• once fatigue sets in, the vertical and horizontal forces at the holds drop by more than 10% when comparing BORG < 5.5 and BORG > 5.5
• a fatiguing climber exert less force on the handholds and climbs more economically, which, in turn, leads to a lower injury risk during fatigue.
Speed Climbing
X Games Asia’06, Kuala Lumpur, 12 - 14 May 2006

MEN SPEED CLIMBING

Gold: Maxym Styenkovyy / Ukraine
Silver: Muhammad Zaki bin Ramli / Singapore
Bronze: Erianto / Indonesia

A slip at the last cost Singapore's Zaki the gold medal in Men's Speed Climbing

“I didn’t expect to get the gold medal because he was leading all the way, but when I saw him slip, I grabbed my chance to win it,” said Maxym Styenkovyy
Instrumented Holds

Manufacturing of holds:
- Moulded holds,
- 6 parts sand
- 2 parts epoxy resin
- 1 part hardener
Climbing Route

Average climbing velocity:
1.2 m / (time from hold 3 to hold 5)
Aim of the Study

- 1) correlation between velocity and contact time
- 2) correlation between velocity and reaction forces
- 3) influence of the hold shape
Experimental Procedure

- Trial runs + warm-up
- Hold 3 and 5: jug type
- Hold 4: jug or sloper
- 2 climbs at max. velocity
- 2 climbs at medium velocity
- 2 climbs at slow velocity
- Change of hold 4
- Another 6 climbs at 3 different velocities
Average climbing velocity:
1.2 m / (time from hold 3 to hold 5)
Vector Diagrams - climber 3
Velocity and Contact Time

The regressions are non-linear and follow a power fit. 
Hold 1: \( t = 0.953 \, v^{-1.109} \)  
\( r = 0.999 \)
Hold 2: \( t = 1.135 \, v^{-0.887} \)  
\( r = 0.936 \)

Better correlation of 1st contact time: 
1st contact provides impulse for subsequent velocity (+ foot impulse)

Fastest climb: mean contact time on the 2nd instrumented handhold is significantly longer, 
\( p<0.001 \), if hold 4 is a sloper (1.45 s) compared to a jug (1.15 s).
Velocity and Forces

Resultant forces vs. velocity: (normalised forces in xBW)

- \(a\) = maximal value at 1st hold
- \(b\) = maximal value at 2nd hold
- \(c\) = mean value at 1st hold
- \(d\) = mean value at 2nd hold

logarithmic fit

\[ r = 0.825 - 0.92 \]
**Velocity and Shock Spikes**

Shock spikes vs. velocity

\( a = \) resultant shock spike at 2nd hold,
\( b = \) resultant shock spike at 1st hold,
\( c = \) shock spike in x-direction at 1st hold,
\( d = \) shock spike in x-direction at 2nd hold

The shock spikes in the x-axis direction are negative because the direction of the shock spikes forces is into the wall.

\[ r = 0.8 - 0.884. \]
Conclusions

• contact time decreases with increasing climbing speed,
• forces including shock spike increase with speed
• jug holds result in a higher velocity than sloper holds

• this is comparable to running on flat ground. Even the shock spike, which is a crucial factor for joint arthroses and appears during walking and running, is present during speed climbing.
Double Dyno
Experimental Procedure
Terminology
Results

The graph shows the changes in force over time for different body parts. The x-axis represents time in seconds, and the y-axis represents force in Newtons (N). The graph includes lines for total force, body weight, hands, and feet. Points 1, 2, and 3 indicate specific moments in time where significant changes in force occur.
\[ h = \frac{v^2}{2g} \]
Results
Finger Forces

- The closer to the deadpoint, the higher are the finger forces
CONCLUSION

- The preferable technique for dynamic move is:
  - 1) to overshoot, i.e., to jump higher than required, and
  - 2) to grab the handhold as early as possible (before the dead point).
- This results in a high success rate and a minimal finger injury risk.
- The dead-point technique should be revised and abandoned for sport climbing
Fully Instrumented Wall

- 8 holds connected to 6-DOF transducers
Climber 1
“Chalk” is the minimum standard equipment a climber needs. In free soloing, all equipment the climber relies on is chalk and special climbing shoes. Chalk increases the friction between rocks and artificial handholds and absorbs sweat.

• usually made from magnesium carbonate (MgCO₃); only for sandstone, climbers prefer rosin (colophony, pine tree sap), which does not pollute the rock.

• Magnesium-based chalk is available in powder form (“chalk bag”) or in liquid form. The latter is a suspension of powder chalk in alcohol; when left to dry, the alcohol evaporates and the remaining chalk coats the hand and fingers like a glove.
CHALK

• Better climbers produce a higher friction coefficient $COF$ (up to 1, measured during a Climbing World Cup on a hold of a downward slope of at least $22^\circ$, because they are confident to approach the limit from their experience.

• Using chalk, climbers can hold slopers of an angle of up to $47^\circ$ which requires a minimal $COF$ of 1.072 in order to prevent slippage. In fact, the maximal $COF$ measured in this study was 1.175 (corresponds to a slope of $49.6^\circ$).
CHALK

- **Use of 'chalk' in rock climbing: sine qua non or myth?**
  Li F.X., Margetts S., Fowler I.
  Perception Action Laboratory, School of Sport and Exercise Sciences, The University of Birmingham, Edgbaston, UK.

- Friction coefficient with chalk: **2.5**
- Friction coefficient without chalk: **3.0**

- **Conclusion**: chalk decreases the friction coefficient: DON'T USE CHALK !!!! Leave the chalk bag at home !!!
- **Attention**: the authors are sport scientists and not engineers!

- Such high *COFs* are unrealistic and would correspond to freely hanging on a sloper of $68.2^\circ$ and $71.6^\circ$, respectively, without slippage.

- Wrong study design and method!!!
Experiment was repeated with an artificial hold:

1) USE CHALK!!!! No myth!!!

2) powder chalk is better than dry hand w/o chalk (increases the friction coefficient)

3) no difference between dry hand (w/o chalk), wet hand, and liquid chalk

4) chalk on hold (polluted hold) + dry hand has the same effect as powder chalk on hand + clean hold

5) chalk on hold (polluted hold) + powder chalk on hand REDUCES the friction coefficient
CHALK

- Liquid chalk is **NOT** exceptional
- … *does not* last twice as long
- … *does* pollute the rock

---

**MAGNESIE LIQUIDE "PURE GRIP"**

This new generation chalk is better suited to the needs of climbers whether indoors or bouldering. On indoor walls the Pure Grip makes no dust and lasts twice as long. When bouldering, the grip obtained with Pure Grip, compared to powder chalk, is exceptional.

**STRONG POINTS:**
- Does not pollute the rock
- Does not make dust
- Very good capacity: 250 ml + 5l
Angular semiautomatic brakes
Angular semiautomatic brakes

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- Cinch
- Grigri
- Eddy
- Sum
Static Rope Brakes

(a) Diagram of brake design

(b) Forces acting on brake components

(c) Free body diagram showing forces

(d) Schematic of forces and their components

(e) Calculations of forces and tensions

(f) Additional calculations for different scenarios

Symbols used:
- $F_N$: Normal force
- $F_F$: Friction force
- $T_1$: Tension force
- $T_2$: Tension force
- $R$: Resultant force
- $F_M$: Force applied by mechanism
- $v$: Velocity
- $\theta$: Angle
Angular Semiautomatic Brakes
**COF experiment**

- $\mu_s = 0.2$ at 3000N
- Force weakening regime
- Nylon rope on steel (2 and 4 strands)
- polished Nylon6 block on steel

\[ \mu_s = A \ln(\log F) + B \]
Angular Semi-automatic Brakes

- Moment arms
Angular Semiautomatic Brakes

Cinch

Grigri

Eddy

Sum
Angular Semiautomatic Brakes

\[ \frac{T_1}{T_2} = e^{COF_B \theta} \]

- If \( T_2 = T_1 \), then \( COF_B = 0 \); before the point of impending slippage, \( COF_B < \mu_B \); at the point of impending slippage, \( COF_B = \mu_B \); if the rope slips through the brake, \( COF_B > \mu_B \).

- \( F_1, F_2 \) = friction at rope compression zone, \( F_1 \) between cam and rope (inside FBD), \( F_2 \) between rope and housing

\[ \frac{T_2}{T} = F_1 + F_2 \]

\[ \frac{F_2}{N} = COF_T \]

\( B = \text{belt}, \ T = \text{translational} \)
Static Semiautomatic Brakes

- FBD of cam+rope
Static Semiautomatic Brakes

- Moment equilibrium

- if $F_1 = F_2 = F$ (i.e., equal compression effects on either side of the rope)

$$T_1 L_1 = F_2 L_2 + N L_3$$

$$T_2 e^{COF_B \theta} L_1 = COF_T N L_2 + N L_3$$

$$2COF_T e^{COF_B \theta} L_1 = COF_T L_2 + L_3$$

$$e^{COF_B \theta} = \frac{COF_T L_2 + L_3}{2COF_T L_1} = \frac{L_2}{2L_1} + \frac{L_3}{2COF_T L_1}$$

$$COF_B = \ln\left(\frac{L_2}{2L_1} + \frac{L_3}{2COF_T L_1}\right)$$
Static Semiautomatic Brakes

\[
COF_B = \ln\left(\frac{L_2}{2L_1} + \frac{L_3}{2COF_T L_1}\right)
\]

- \(COF_B\) = function of \(COF_T\) for which the moment equilibrium is valid, for the given design parameters of \(\theta, L_1, L_2,\) and \(L_3,\) irrespective of what the actual magnitudes of \(\mu_T\) and \(\mu_B\) are \(\to\) friction equilibrium curve
• Depending on the known actual magnitudes of $\mu_T$ and $\mu_B$, three conditions can be defined.

• 1) Within the equilibrium curve, a segment of specific length can be defined, within which stable conditions occur; inside this segment, the brake blocks, whereas outside of it, the rope slips.

• 2) If the length of the segment of stable conditions reduces to zero, the critical coefficient of friction, $\mu_{\text{crit}}$, is defined, and the brake always operates at the point of impending slippage.

• 3) The 3rd condition is defined by the fact that, for a certain set of design parameters or given actual $\mu_T$ and $\mu_B$, no stable condition exists.
Static Semiautomatic Brakes

- **Optimisation**
- Reduce $L_2 \to 0 \to$ negative value
- positive $L_2$: $FL_2$ moment has same sense as $T_1L_1$
- negative $L_2$: $FL_2$ moment has opposite sense to $T_1L_1$
- If $L_2 = 0$: $COF_T = \mu_T = COF_B = \mu_B = \mu_{crit}$

$$2\mu \ e^{\mu \theta} L_1 = L_3$$

- $W = \text{Lambert function}: \text{if } y = xe^x, \text{then } x = W(y)$.
- In order to prevent the worst case, i.e. the point of impending slippage at $\mu_{crit}$, the actual $\mu$ must be larger than $\mu_{crit}$, i.e., $\mu_{\text{actual}} > \mu_{crit} \cdot \frac{W \left( \frac{L_3 \theta}{2L_1} \right)}{\theta}$
- Stable condition: curve segment inside rectangle
- Bottom left corner of rectangle: critical coefficient of friction, $\mu_{\text{crit}}$
Safety Factors

- Design goal is to have $\mu > \mu_{\text{crit}}$, by applying a safety factor. The selected design safety factor (DSF), however, is smaller than the actual safety factor (ASF),
- This is due to the fact that $COF_B = \mu$ on full loading, whereas $COF_T < \mu$.
- $COF_{T-\text{actual}}$ is determined from the equilibrium curve at $COF_B = \mu$. The safety factors are defined as follows:

\[
DSF = \frac{\mu}{\mu_{\text{crit}}} \quad \text{and} \quad ASF = \frac{\mu}{COF_{T-\text{actual}}}
\]
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![Graph showing COF vs COF$_T$ for different makes.](image)
"There are only 3 real sports: bull-fighting, car racing and mountain climbing. All the others are mere games."

Ernest Hemingway