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Estimation of finger muscle tendon tensions and pulley forces during specific sport-climbing grip techniques

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Abstract

The present work displayed the first quantitative data of forces acting on tendons and pulleys during specific sport-climbing grip techniques. A three-dimensional static biomechanical model was used to estimate finger muscle tendon and pulley forces during the "slope" and the "crimp" grip. In the slope grip the finger joints are flexed, and in the crimp grip the distal interphalangeal (DIP) joint is hyperextended while the other joints are flexed. The tendons of the flexor digitorum profundus and superficialis (FDP and FDS), the extensor digitorum communis (EDC), the ulnar and radial interosseus (UI and RI), the lumbrical muscle (LU) and two annular pulleys (A2 and A4) were considered in the model.

For the crimp grip in equilibrium conditions, a passive moment for the DIP joint was taken into account in the biomechanical model. This moment was quantified by relating the FDP intramuscular electromyogram (EMG) to the DIP joint external moment. Its intensity was estimated at a quarter of the external moment. The involvement of this parameter in the moment equilibrium equation for the DIP joint is thus essential. The FDP-to-FDS tendon-force ratio was 1.75:1 in the crimp grip and 0.88:1 in the slope grip. This result showed that the FDP was the prime finger flexor in the crimp grip, whereas the tendon tensions were equally distributed between the FDP and FDS tendons in the slope grip. The forces acting on the pulleys were 36 times lower for A2 in the slope grip than in the crimp grip, while the forces acting on A4 were 4 times lower. This current work provides both an experimental procedure and a biomechanical model that allows estimation of tendon tensions and pulley forces crucial for the knowledge about finger injuries in sport climbing.

Keywords: Climbing; Biomechanical finger model; Muscle tendon tension; Joint hyper-extension; Intra-muscular electromyography; Optimization

1. Introduction

Sport-climbing has been a popular activity for approximately 25 years and is now recognized as a modern competitive sport as well as a mode of fitness exercise (Watts and Drobish, 1998). The most common climbing grip techniques are the 'crimp' grip and the 'slope' grip (Schweizer, 2001). The crimp grip refers to the use of small edges with the proximal interphalengeal (PIP) joint flexed from 90° to 100° and a hyper-extended distal interphalengeal (DIP) joint. The slope grip is used when grasping wide handholds whereas the DIP joint is flexed from 50° to 70° and the PIP joint is flexed just slightly. The high forces applied to the fingertips result in acute solicitations of the flexor tendon pulley system (Bollen, 1990; Rooks, 1997; Schöffl et al., 2003), which acts to maximize tendon excursion with flexion. Doyle (1989) and Bollen and Gunson (1990) showed that ruptures of the second (A2) and fourth (A4) annular pulleys were observed in more than 40% of competition

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climbers. Because these injuries can seriously compromise a climber's ability and safety, proper diagnosis, treatment, rehabilitation, and prevention are essential. In order to understand the pathomechanics of pulley injuries, it is crucial to determine the tensions in the extrinsic finger flexor muscle tendons (i.e. Flexor Digitorum Superficialis and Profundus, FDS and FDP) (Hume et al., 1991; Marco et al., 1998; Roloff et al., 2005).

Biomechanical properties of the crimp grip were assessed by Schweizer (2001) using two devices to measure the force and the distance of bowstringing during simulated rock climbing. Results have confirmed that the crimp grip places a tremendous demand on the pulley system. Nevertheless, no biomechanical model (Chao and An, 1978; Weightman and Amis, 1982; Brook et al., 1995, Valero-Cuevas et al., 1998, Sancho-Bru et al., 2001) provided any satisfactory mean to determine the tendon tensions in FDP, and subsequently in FDS, when the DIP joint is hyper-extended as in the crimp grip. When the DIP joint is hyperextended, joint contact forces, ligament forces, and soft connective tissue loads produce a net passive moment for the DIP joint (Dennerlein et al., 1998; Leijnse, 1998). This moment is involved in the joint mechanical equilibrium for low fingertip force intensity without requiring FDP involvement although this muscle is the only flexor that is inserted at the distal phalanx. It is not obvious that this will hold true for maximal efforts as in rock climbing, but when assessing accurate tendon tensions, the passive moment for the DIP joint must be considered. Direct measurement of the passive moment cannot be performed currently and no published data is available. Nevertheless, it is possible to develop estimates of the DIP passive moment by relating the FDP muscle electromyogram (EMG) to muscle mechanical moments through the moment balance equations. In this study, we used the linear EMG-force relation during FDP isometric contraction (Valero-Cuevas et al., 1998) and our assessment was based on the two following ideas: (1) as long as the DIP joint remains balanced by the passive moment, no FDP moment production is needed and no significant EMG in FDP should be observed, and (2) a significant pattern in EMG should be observed when the moment equation for the DIP joint requires a significant FDP muscle moment production to obtain mechanical equilibrium.

2. Materials and methods

2.1. Subjects

The subjects of this study were six expert climbers (national competitive level, USA 5.13b on sight). The mean (standard deviation (SD)) values for age, height, body mass of subjects were 27 (5.5) years; 177.4 (4.5) cm; 65.6 (2.0) kg, respectively. The procedure was approved by the Consultative Committee for the Protection of Persons in Biomedical Research (CCPPRB, Grenoble, France) and all subjects signed an informed consent.

2.2. Experimental device

The subjects were sitting with the right forearm placed on a horizontal table. The upper arm was approximately at 45° of abduction, the elbow joint flexed at 90° and the wrist placed at 0° of flexion, palms down. A vice stabilized the upper arm and a clamp stabilized the palm of the hand. The middle finger gripped a hold (1 cm deep) while the other fingers were folded and were not in contact with the experimental set up. The point of application of the fingertip force was located at half the length of the distal phalanx. The subjects were instructed to place their middle finger in the crimp grip (Fig 1a) and in the slope grip (Fig. 1b). A digital camera (Sony, CD-S70) located 0.7 m to the left of the subjects recorded the sagittal posture of the finger during each force production. Two passive markers per phalanx were used. The markers were aligned with the longitudinal axis of the phalanx. In the crimp grip, the joint angles was $-22.6°$ (5.0) for the DIP joint (α_1), 106.5° (7.2) for the PIP joint (α_2) and $-2.6°$ (14.4) for the MCP

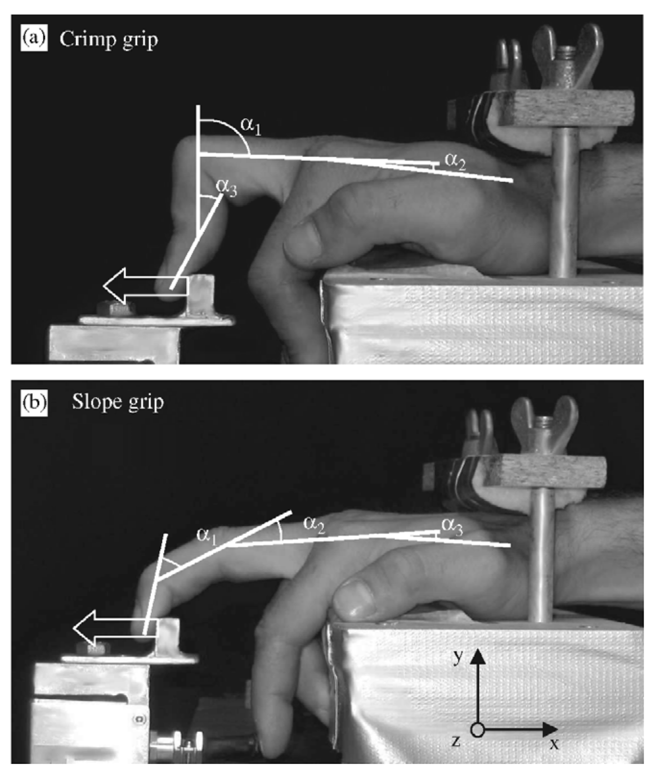

Fig. 1. Finger grip techniques tested in the experiment. A vice stabilized the wrist and a clamp stabilized the palm of the hand in order to ensure an isometric contraction of the finger flexor muscles.

joint (α_3). In the slope grip, α_1 was 38.8° (9.4), α_2 was 25.9° (11.8) and α_3 was −2° (11.7). The angle of MCP joint adduction/abduction was set to 0° for the computing procedure. Thorough experimental precautions were taken by using the vice and the clamp in order to insure that the joint angle was constant during the experimental session.

2.3. Procedure

In rock climbing, the force at the fingertip may be generated by a beginning eccentric contraction of the FDS and FDP muscles as the hand is not fixed. In these conditions, the friction force generated between pulleys and flexor tendons may increase around 10% the maximum force at the fingertip. Friction force depends on the joint angle of the PIP joint and is different in the crimp and in the slope grip (Schweizer et al., 2003). In order to control this effect, the test consisted in producing a maximal voluntary grip force (MVF) with the middle finger in isometric conditions, with the hand position maintained by the vice and the clamp. The force generated resulted only from the isometric contraction of the finger flexor muscles.

The subjects were instructed to increase the force along the horizontal axis in three steps as depicted in Fig. 2. The requirements of isometric testing included (a) low, midrandge (50% of MVF), and maximal effort (100% of MVF) recordings, and (b) fixed joint positions. The subjects underwent three tests for each grip technique. The peak force of each test was considered as input data for the estimation of tendon tensions and forces acting on pulleys.

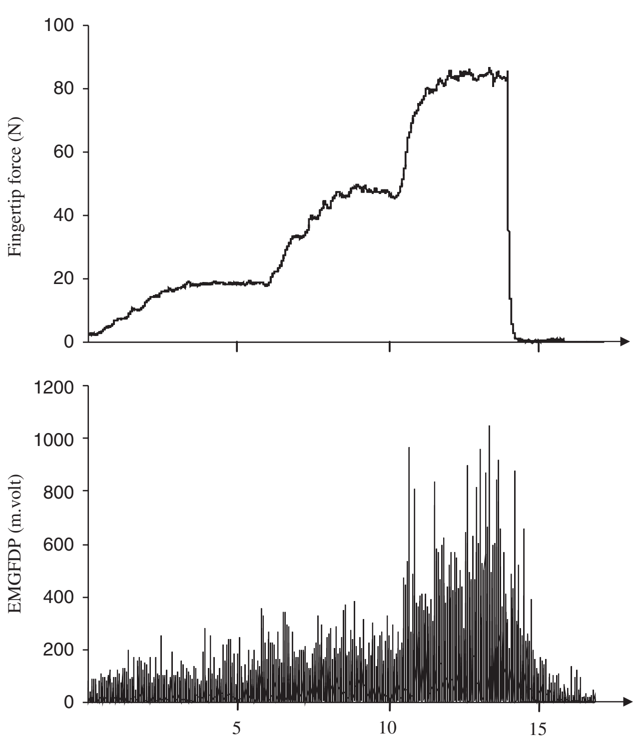

Fig. 2. Recordings of applied fingertip force and intra-muscular EMG of FDP muscle during a typical test. The force was increased in three steps (low, 50% MVF, and 100% MVF). EMG was full wave rectified before plotting.

2.4. Signal recordings

A three-axial force sensor (load of range: 0–1 kN, 0.5 N resolution for all axes, ENSIEG, INPG, France) was used to record the external fingertip force. The force signals were amplified (PM instrumentation, Ref. 1965, Orgeval, France) and recorded at 1024 Hz using MYODATA acquisition system (Mazet Electronique, model Biostim 6082, France).

Monopolar needle electrodes (Medtronic type DCN25, shaft diameter 0.46, core area 0.07 mm^2) recorded intra-muscular EMG of FDP and FDS muscles. Electrodes were located according to the recommendations made by Burgar et al. (1998) and Reilly and Schieber (2003). A cross-correlation analysis was performed after each experimental session. The results showed a cross-correlation inferior to 0.3 for all the tests. This reflects the accurate placement of needles and the absence of cross talk. Pre-tests performed on three subjects showed that the presence of needles did not significantly affect the fingertip force intensity. The raw EMG signals, were amplified to 3 db (common mode rejection ratio: $>$90 dB), sampled at 5 kHz and recorded (bandpass from 10 Hz to 10 kHz) on the Keypoint workstation (Medtronic, Skovlunde, Denmark). EMG signals were filtered using a Butterworth filter (order 4, bandpass from 20 to 600 Hz). EMG of FDP was quantified using root mean square (FDP–RMS) computed in 0.1 s windows following prior substraction of the background activity level with a time constant fixed at 0.1 s (Chao et al., 1989) and used to estimate the magnitude of the passive moment for the DIP joint.

2.5. Estimation of the passive DIP joint moment magnitude

Many investigators agree that there is a linear relationship between EMG and tension within a muscle, provided that the contraction is isometric, in the mid-range of exertion, and that the muscle length remains unchanged (Lippold, 1952; Long and Brown, 1964; Valero-Cuevas et al., 1998). From a physiological point of view, if there is no EMG activity, there will be no active tension created by the muscle and thus no muscular active moment at the joint (Chao et al., 1989). Therefore, in equilibrium conditions, it is possible to establish a simple relation between

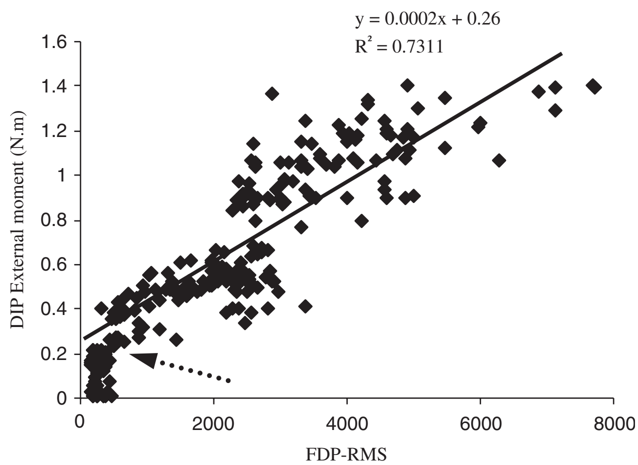

Fig. 3. Example of the relationship between the external DIP joint moment and the FDP–RMS for a subject. The point at which FDP–RMS value exceeded the preset threshold (i.e. >3 SD beyond baseline) is marked with the arrow. From this point, a linear regression equation was calculated and the value of the Y-intercept was identified as the passive DIP joint moment (e.g. 0.26 Nm).

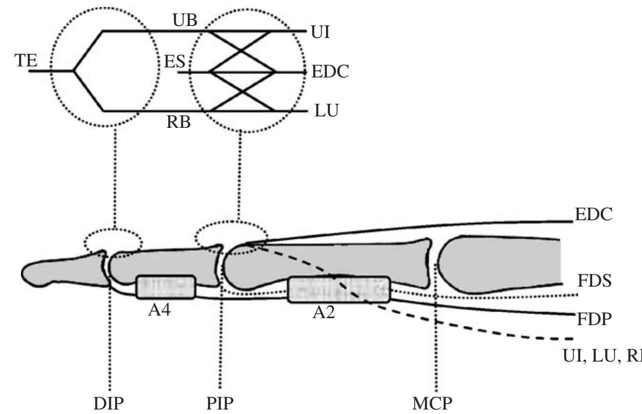

Fig. 4. Finger muscle tendons acting on finger joints (FDP, FDS, EDC, UI, LU, RI). The extensor mechanism connects muscle tendons (EDC, UI, LU) and extensor bands (RB, UB, TE, ES) as represented in the upper insert (Dorsal view).

the DIP joint passive moments and the fingertip external moment before a significant EMG activity is detected in the FDP muscle. The identification of a significant FDP activity on the EMG corresponds to the point for which the FDP–RMS reaches three standard deviations beyond mean of baseline activity (Hodges and Bui, 1996). In the model for the DIP external moment and FDP–RMS relationship (Fig. 3), the constant term (i.e. the Y-intercept) in the linear regression analysis can be considered to accurately depict the mean value that must be added to the moment equation in order to balance the DIP joint without significant FDP moment. These estimated values of the passive moment for the DIP joint were determined for each subject (i.e. three tests per subject) and then expressed in percentage of the external DIP moment.

2.6. Biomechanical finger model

The biomechanical model consists in 4 rigid segments: proximal, middle, and distal phalanx and metacarpal bone (Fig. 4). DIP and PIP joints were modelled as frictionless hinges with one degree of freedom in flexion/extension. The MCP joint was modelled with two degrees of freedom in flexion/extension and in abduction/adduction. The ulnar and radial ligaments (UL and RL, respectively) of the MCP joint were included as proposed by Sancho-Bru et al. (2001). The tension of each ligament (t_{lig}) was estimated using a quadratic function relating the force developed by the ligament to its elongation (Mommersteeg et al., 1996). In order to represent the non-linear behaviour of the ligament, a characteristic constant of the ligament (K) was set to $750\,\text{N/cm}^2$ according to Minami et al. (1985) as:

$$t_{\text{lig}} = K(L_{\text{lig}} - L_0)^2, \tag{1}$$

where L_{lig} is the length of the ligament and L_0 is the unstrained length of the ligament. The data for the ligament moment arms and insertion points were obtained from Chao et al. (1989).

Newton's laws of static equilibrium for forces ($\vec{F}$) and moments ($\vec{M}$) were used, considering that the external forces and moments were balanced by tendon, ligament, and passive moments:

$$\sum \vec{F} = \vec{0} \tag{2}$$

$$\sum \vec{M} = \vec{0} \tag{3}$$

Moments of tendons were computed from:

$$\overrightarrow{M_{i|j}} = \overrightarrow{B_{i,j}} \wedge \vec{t_i} \tag{4}$$

where $\overrightarrow{M_{i|j}}$ and $\overrightarrow{B_{i,j}}$ are the moment vector and the moment arm of the i tendon ($i =$ FDP, FDS, extensor digitorum communis:EDC, lumbrical: LU, ulnar interosseus: UI, radial interosseus: RI, terminal extensor tendon: TE, extensor slip: ES, radial band: RB and ulnar band: UB) over the j joint ($j =$ DIP, PIP, MCP), and $\vec{t_i}$ represents the tension of the i tendon.

The moment arms of tendons were estimated using An et al. (1979) and An et al. (1983). Adapting Eq. (3) to the four degrees of freedom of the finger model provides a four moment equilibrium equation system:

$$
\begin{aligned}
&(\mathrm{Mz}_{\mathrm{FDP|DIP}} + \mathrm{Mz}_{\mathrm{TE|DIP}}) + \mathrm{Mz}_{\mathrm{Fext|DIP}} + \mathrm{Mz}_{\mathrm{passif}} = 0\\
&(\mathrm{Mz}_{\mathrm{FDP|PIP}} + \mathrm{Mz}_{\mathrm{FDS|PIP}} + \mathrm{Mz}_{\mathrm{UB|PIP}} + \mathrm{Mz}_{\mathrm{RB|PIP}}\\
&\quad + \mathrm{Mz}_{\mathrm{ES|PIP}}) + \mathrm{Mz}_{\mathrm{Fext|PIP}} = 0\\
&(\mathrm{Mz}_{\mathrm{FDP|MCP}} + \mathrm{Mz}_{\mathrm{FDS|MCP}} + \mathrm{Mz}_{\mathrm{LU|MCP}} + \mathrm{Mz}_{\mathrm{UI|MCP}}\\
&\quad + \mathrm{Mz}_{\mathrm{RI|MCP}} + \mathrm{Mz}_{\mathrm{EDC|MCP}})\\
&\quad + \mathrm{Mz}_{\mathrm{Fext|MCP}} + \mathrm{Mz}_{\mathrm{LLI}} + \mathrm{Mz}_{\mathrm{LLU}} = 0\\
&(\mathrm{My}_{\mathrm{FDP|MCP}} + \mathrm{My}_{\mathrm{FDS|MCP}} + \mathrm{My}_{\mathrm{LU|MCP}} + \mathrm{My}_{\mathrm{UI|MCP}}\\
&\quad + \mathrm{My}_{\mathrm{RI|MCP}} + \mathrm{My}_{\mathrm{EDC|MCP}})\\
&\quad + \mathrm{My}_{\mathrm{Fext|MCP}} + \mathrm{My}_{\mathrm{LLI}} + \mathrm{My}_{\mathrm{LLU}} = 0,
\end{aligned}
\tag{5}
$$

where $\mathrm{Mn}_{i|j}$ represents the moment of the i tendon over the n degree of freedom ($n = x,\ y,\ z$) of the j joint. $\mathrm{Mz}_{\mathrm{passif}}$ represents the passive moment of the DIP joint in the crimp grip. $\mathrm{Mn}_{\mathrm{Fext}|j}$ is the moment of the external fingertip force at the n degree of freedom of the j joint.

The moment equilibrium system contains 6 unknown muscle tendon tensions (FDP, FDS, LU, UI, RI, EDC) and 4 unknown extensor mechanism tendon tensions (TE, RB, UB, ES).

2.6.1. Extensor mechanism

The extensor mechanism (Fig. 4, upper insert) is a deformable tendon hood which connects muscle tendons (LU, UI, EDC) and tendon bands (ES, RB, UB and TE) (Landsmeer, 1961; Garcia-Elias et al., 1991; Brook et al., 1995; Leijnse, 1998; Valero-Cuevas et al., 1998). The model presented by Brook et al. (1995) was used to determine the fraction of force transmitted by each tendon to the extensor bands:

$$
\begin{aligned}
t_{\mathrm{TE}} &= \chi_{\mathrm{RB}} t_{\mathrm{RB}} + \chi_{\mathrm{UB}} t_{\mathrm{UB}}\\
t_{\mathrm{RB}} &= \alpha_{\mathrm{EDC}} t_{\mathrm{EDC}} + \alpha_{\mathrm{LU}} t_{\mathrm{LU}}\\
t_{\mathrm{UB}} &= \alpha_{\mathrm{EDC}} t_{\mathrm{EDC}} + \alpha_{\mathrm{LU}} t_{\mathrm{LU}}\\
t_{\mathrm{ES}} &= (1-\alpha_{\mathrm{UI}}) t_{\mathrm{UI}}\\
&\quad + (1-\alpha_{\mathrm{LU}}) t_{\mathrm{LU}}\\
&\quad + (1-2\alpha_{\mathrm{EDC}}) t_{\mathrm{EDC}},
\end{aligned}
\tag{6}
$$

where t_{EDC}, t_{UI} and t_{LU} represent the tendon tensions of EDC, UI and LU. t_{TE}, t_{RB}, t_{UB} and t_{ES} represent the tensions of TE, RB, UB, and ES. χ_{RB} and χ_{UB} are cosine terms accounting for the convergence angles of the RB and UB on to the TE equal to 0.992 and 0.995, respectively (An et al., 1979). The α coefficients were determined together with the unknown tendon tensions using the non-linear optimization process described in Section 2.6.3 *Resolution*.

The mechanical properties of the extensor mechanism were well described by Landsmeer (1961) and Leijnse (1998). Furthermore, Leijnse (1998) showed that when the PIP joint is flexed (flexion angle $>70^{\circ}$) while the DIP joint remains extended, RB and UB bands become slack and no active extensor force will run through the lateral bands. Consequently, in the crimp grip, even with maximally active extensor and intrinsic muscles, no force will be transferred to the DIP joint extensor tendon (i.e. $t_{\mathrm{TE}} = 0$, $t_{\mathrm{RB}} = 0$ and $t_{\mathrm{UB}} = 0$). Accurate measuring passive moment magnitude for DIP joint equilibrium equation may be considered under this condition.

2.6.2. Resolution

Combining Eqs. (4)–(6), gives the following vector equality:

$$
\begin{bmatrix}
r_{11} r_{12} r_{13} r_{14} r_{15} r_{16}\\
r_{21} r_{22} r_{23} r_{24} r_{25} r_{26}\\
r_{31} r_{32} r_{33} r_{34} r_{35} r_{36}\\
r_{41} r_{42} r_{43} r_{44} r_{45} r_{46}
\end{bmatrix}
\cdot
\begin{Bmatrix}
t_{\mathrm{FDP}}\\ t_{\mathrm{FDS}}\\ t_{\mathrm{LU}}\\ t_{\mathrm{RI}}\\ t_{\mathrm{UI}}\\ t_{\mathrm{EDC}}
\end{Bmatrix}
+
\begin{Bmatrix}
\mathrm{Mz}_{\mathrm{Fext|DIP}}\\ \mathrm{Mz}_{\mathrm{Fext|PIP}}\\ \mathrm{Mz}_{\mathrm{Fext|MCP}}\\ \mathrm{My}_{\mathrm{Fext|MCP}}
\end{Bmatrix}
+
\begin{Bmatrix}
\mathrm{Mz}_{\mathrm{passif}}\\ 0\\ \mathrm{Mz}_{\mathrm{LLI}} + \mathrm{Mz}_{\mathrm{LLU}}\\ \mathrm{My}_{\mathrm{LLI}} + \mathrm{My}_{\mathrm{LLU}}
\end{Bmatrix}
=
\begin{Bmatrix}
0\\ 0\\ 0\\ 0
\end{Bmatrix}
\tag{7}
$$

or in the simplified form:

$$[R]\cdot\{T\} + \{F\} + \{L\} = \{0\}, \tag{8}$$

where the matrix $[R]$ is the 4×6 moment arms matrix obtained from moment arms of tendons and from Eq. (6) using the α coefficients. $\{T\}$ is a 6-element vector containing the six unknown muscle tendon tensions. $\{F\}$ is a 4-element vector representing moments of external force at each degree of freedom. $\{L\}$ is a 4-element vector containing the passive moment over DIP joint and the ligament moments of UL and RL over MCP joint. $\mathrm{Mz}_{\mathrm{passif}}$ was included only for the crimp grip.

The resolution consisted in solving the following optimization problem:

$$\text{find}:\quad t_i (i = \{\mathrm{FDP}, \mathrm{FDS}, \mathrm{LU}, \mathrm{UI}, \mathrm{RI}, \mathrm{EDC}\})$$

and

$$\alpha_{\mathrm{EDC}}, \alpha_{\mathrm{LU}}, \alpha_{\mathrm{UI}}$$

that minimizes:

$$G(t) = \sum_{1}^{i} \left(\frac{t_i}{\mathrm{PCSA}_i}\right)^2 \tag{9}$$

$$\text{subject to}:\quad t_i \geqslant 0\,, \tag{10}$$

$$0 \leqslant \alpha_{\mathrm{LU}} \leqslant 1;\ 0 \leqslant \alpha_{\mathrm{UI}} \leqslant 1;\ 0 \leqslant \alpha_{\mathrm{EDC}} \leqslant 0.5 \tag{11}$$

and subject to the equilibrium constraints expressed in Eq. (8).

$PCSA_i$ is the physiological cross-sectional area of the i muscle as described by An et al. (1983). Eq. (10) was added to obtain positive tendon tensions. Eq. (11) states that fraction of force transmitted by the tendons to the extensor mechanism bands ranging from 0 to 1.

2.6.3. Force acting on pulleys

Forces acting on A2 and A4 pulleys (Fig. 5) were estimated using the method described by Roloff et al. (2005):

$$F_{A2} = 2(t_{FDP} + t_{FDS})\cos\left(\frac{\beta_{A2}}{2}\right), \tag{12}$$

$$F_{A4} = 2(t_{FDP})\cos\left(\frac{\beta_{A4}}{2}\right), \tag{13}$$

where F_{A2} and F_{A4} are the force acting on the A2 and A4 pulleys. β_{A2} and β_{A4} stand for the angle between the tendon and the A2 or A4 pulleys. The localisation of pulleys was accomplished using An et al. (1979) data. Since tests were performed in static conditions, we have neglected the friction forces between pulleys and tendons according to Roloff et al. (2005) and Schweizer et al. (2003).

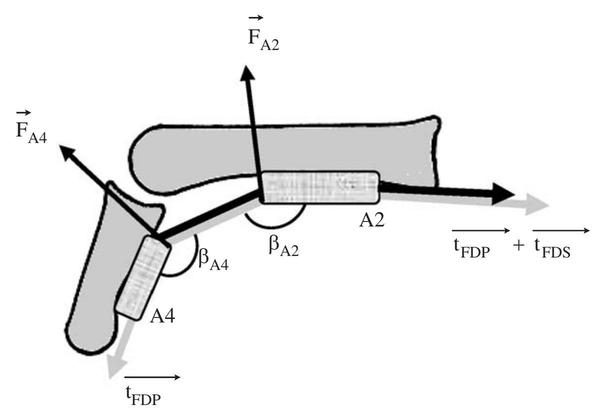

Fig. 5. Finger pulley model. Calculation of the force acting on A2 ($\overrightarrow{F_{A2}}$) or A4 ($\overrightarrow{F_{A4}}$) pulley depends both on the angle between the pulley and tendon (β_{A2} or β_{A4}) and on the tension of FDP and FDS tendons.

2.7. Data analysis

All computations were performed using Matlab (The MathWorks, Natick, MA) and its optimization toolbox (*fmincon*). Descriptive statistics are means and SD. *t*-tests for dependant samples were used to determine statistical differences between the two grip techniques. All comparisons were made on the data by mean subject result ($n = 6$). The level of significance was set at $p < 0.05$ for all statistical analysis.

3. Results

3.1. External forces and moments

The mean external fingertip force was 95.6 N (26.4) in the crimp grip and 97 N (21.8) in the slope grip

Table 2
Estimates of the passive moment for the DIP joint (Mz_{passif}) in each subject

Subject	Mz_{passif}	
	N.m	% $Mz_{Fext\|DIP}$
1	0.26	24.5 (3.6)
2	0.11	15.6 (0.5)
3	0.25	16.0 (0.4)
4	0.28	18.4 (1.3)
5	0.26	21.0 (0.5)
6	0.38	37.6 (2.6)
Mean	0.26(0.08)	22.2 (8.2)

Values were expressed in Nm and in percentage of DIP external moment ($\%Mz_{Fext|DIP}$).

Table 1
Fingertip force (F_{ext}, N) and external moments (Nm) for the DIP ($Mz_{Fext|DIP}$) and PIP ($Mz_{Fext|PIP}$) joints in both crimp and slope grips

Subject	F_{ext}		$Mz_{Fext\|DIP}$		$Mz_{Fext\|PIP}$	
	Crimp	Slope	Crimp	Slope	Crimp	Slope
1	86.0 (12.7)	100.1 (10.1)	−1.07 (0.16)	−1.14 (0.12)	−5.35 (0.14)	−4.96 (0.14)
2	58.1 (12.5)	68.3 (2.4)	−0.75 (0.15)	−0.89 (0.04)	−2.28 (0.38)	−2.14 (0.15)
3	126.9 (3.8)	119.1 (4.0)	−1.58 (0.05)	−1.08 (0.02)	−3.52 (0.55)	−2.63 (0.34)
4	121.4 (8.8)	123.5 (6.9)	−1.55 (0.11)	−1.56 (0.08)	−5.53 (0.51)	−4.30 (0.36)
5	102.8 (2.4)	92.3 (3.5)	−1.26 (0.03)	−1.09 (0.11)	−4.32 (0.26)	−3.57 (0.01)
6	78.6 (5.6)	78.9 (10.2)	−1.01 (0.07)	−1.01 (0.14)	−3.61 (0.24)	−2.69 (0.42)
Mean	95.6 (26.4)	97.0 (21.8)	−1.21 (0.05)	−1.13 (0.23)	−4.10 (1.23)*	−3.38 (1.09)

*Indicates a significant difference between the crimp and the slope grips ($p < 0.05$).

(Table 1). No significant difference was observed ($t = -0.35$, $p = 0.74$). The mean external moment for the DIP joint was -1.21 Nm (0.05) in the crimp grip and –1.13 Nm (0.23) in the slope grip. No significant difference was observed ($t = -0.82$, $p = 0.44$). The mean external moment for the PIP joint was -4.1 Nm (1.23) in the crimp grip and -3.38 Nm (1.09) in the slope grip. These values were statistically different ($t = -4.42$, $p < 0.05$).

3.2. Passive moment for the DIP joint

A representative DIP joint external moment/FDP–RMS graph from one subject during the crimp grip is displayed in Fig. 3. Data for each subject was reported in Table 2. The values ranged from 0.11 to 0.38 Nm for all subjects. The mean value was 0.26 Nm (0.08) which accounted for 22.2% (8.2) of the external moment for the DIP joint.

3.3. Tendon tensions

The tensions of the extrinsic muscle tendons (i.e. FDP, FDS, and EDC muscles) and of the intrinsic muscles (i.e. UI, RI, and LU muscles) are, respectively, presented in Tables 3 and 4 and illustrated in Fig. 6.

The FDP tendon tension ranged from 159 to 373 N in the crimp grip (mean: 257.5 N (81.2)) and from 140 to 236 N in the slope grip (mean: 189.8 N (37.7)). The FDS tendon tension ranged from 83 to 260 N in the crimp grip (mean: 147.6 N (60.5)) and from 107 to 458 N in the slope grip (mean: 214.8 N (128.8)). The mean EDC tendon tension was 40.7 N (71.2) in the crimp and 30.3 N (41.3) in the slope grip. It should be noted that EDC tendon tension was set at zero for four subjects in the crimp grip and for two subjects in the slope grip.

Concerning the intrinsic muscles of the hand, the mean UI tension was 50.9 N (28.4) in the crimp grip and 61.9 N (82.3) in the slope grip. The mean RI tension was 29.3 N (21.3) in the crimp grip and 36.6 N (63.2) in the slope grip. Tendon tension was calculated at zero for the LU muscle, in both grip techniques.

3.4. A2 and A4 pulley forces

The estimated forces acting on pulleys are reported in Table 5 and Fig. 6. The mean force acting on A2 pulley was 254.8 N (87.2) in the crimp grip and 8.1 N (5.7) in the slope grip. The mean force on A4 pulley was 220.9 N (116.2) in the crimp grip and 57.4 N (22.8) in the slope grip.

Table 3
Estimated tendon tensions (N) in FDP (t_{FDP}), FDS (t_{FDS}), and EDC (t_{EDC}) tendons

Subject	t_{FDP}		t_{FDS}		t_{EDC}	
	Crimp	Slope	Crimp	Slope	Crimp	Slope
1	226.0 (45.0)	190.7 (19.6)	112.1 (7.4)	107.4 (18.8)	0	86.6 (6.0)
2	186.5 (52.9)	140.3 (11.0)	83.6 (58.1)	165.6 (29.3)	70.4 (61.2)	79.5 (27.9)
3	373.1 (13.4)	214.5 (4.9)	134.8 (2.3)	458.0 (16.7)	0	0
4	312.6 (33.6)	236.1 (18.3)	144.7 (43.1)	249.5 (20.5)	0	1.3 (2.2)
5	287.5 (17.6)	207.7 (17.5)	260.6 (72.9)	179.1 (85.5)	174.2 (109.3)	0
6	159.2 (22.8)	149.7 (17.5)	149.9 (8.1)	129.2 (23.6)	0	14.3 (9.5)
Mean	257.5 (81.2)	189.8 (37.7)	147.6 (60.5)	214.8 (128.8)	40.7 (71.2)	30.3 (41.3)

Table 4
Estimated tendon tensions (N) in LU (t_{LU}), UI (t_{UI}), and RI (t_{RI}), intrinsic muscles

Subject	t_{LU}		t_{UI}		t_{RI}	
	Crimp	Slope	Crimp	Slope	Crimp	Slope
1	0	0	67.5 (13.0)	7.2 (2.3)	44.2 (10.8)	0
2	0	0	26.0 (37.7)	8.4 (1.4)	17.6 (30.5)	0
3	0	0	54.7 (11.04)	220.3 (10.5)	25.0 (9.4)	159.1 (8.6)
4	0	0	93.3 (30.05)	40.2 (16.3)	61.5 (29.7)	9.6 (12.3)
5	0	0	14.22 (7.0)	80.2 (1.2)	0	51.0 (3.7)
6	0	0	49.8 (6.9)	82.4 (3.7)	27.4 (6.4)	0
Mean	0	0	50.9 (28.4)	61.9 (82.3)	29.3 (21.3)	36.6 (63.2)

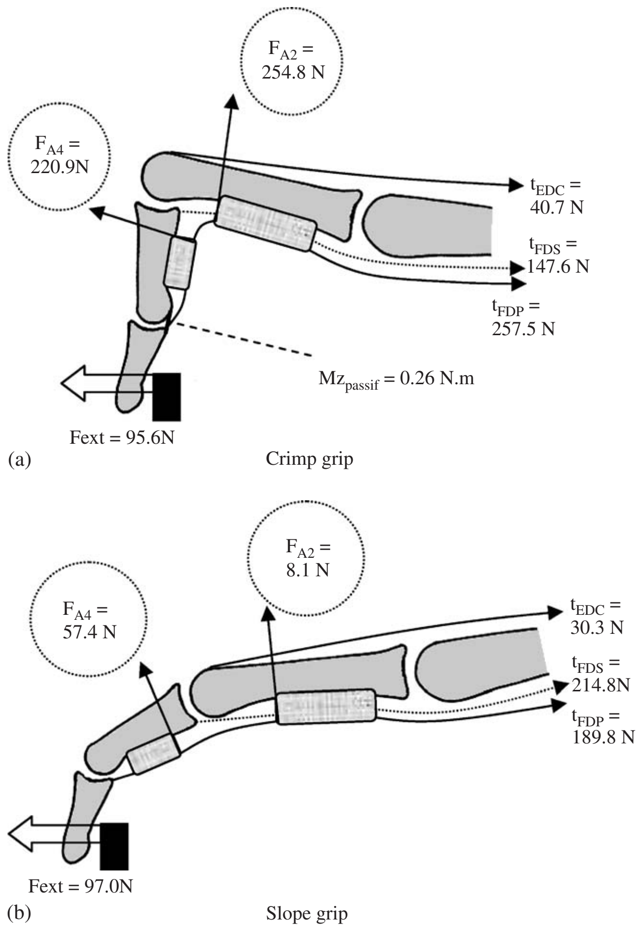

Fig. 6. Mean estimated tendon tensions and mean forces acting on A2 (F_{A2}) and A4 (F_{A4}) pulleys in the crimp grip (a) and in the slope grip (b). The intrinsic muscles were not presented to make the chart clearer.

Table 5
Forces (N) acting on A4 (F_{A4}) and A2 (F_{A2}) finger pulleys

Subject	F_{A4}		F_{A2}	
	Crimp	Slope	Crimp	Slope
1	183.5 (36.5)	56.7 (5.9)	217.6 (33.7)	3.17 (0.4)
2	197.3 (128.4)	19.0 (1.6)	190.0 (61.8)	16.7 (4.8)
3	302.9 (10.9)	63.8 (1.4)	327.0 (10.1)	7.2 (0.2)
4	183.2 (6.2)	66.9 (8.4)	212.6 (27.6)	6.2 (0.8)
5	398.4 (55.9)	87.9 (39.7)	397.6 (79.9)	13.0 (12.5)
6	60.1 (27.4)	49.9 (7.2)	183.9 (15.5)	2.0 (0.3)
Mean	220.9 (116.2)*	57.4 (22.8)	254.8 (87.2)*	8.1 (5.7)

*Indicates a significant difference between the crimp and the slope grips ($p<0.05$).

The A2 force-fingertip force ratio was 2.7 (0.8) in the crimp grip and 0.1 (0.1) in the slope grip. The statistical analysis showed a significant difference ($t = 9.26$, $p<0.05$). Concerning the A4 pulley, A4 force-fingertip force ratio was 2.4 (1.2) in the crimp grip and 0.6 (0.2) in the slope grip. These values were statistically different ($t = 3.73$, $p<0.05$).

4. Discussion

The current study was carried out in order to estimate tendon tensions and forces on pulleys when climbers grip a hold using various techniques.

The external fingertip force analysis indicates that grip techniques do not affect the external force magnitude. This result correlates to previous investigations (Quaine et al., 2003; Quaine and Vigouroux, 2004) and suggests using the slope grip preferentially to reduce risks of injury. However, the voluntary isometric one finger contraction described does not exactly simulate holding a grip during rock climbing, since the beginning eccentric contraction prior stabilisation of the hand is avoided. Therefore, the fingertip force may be superior during climbing since it results from the sum of the muscle forces and the friction forces due to the eccentric movement. Our results show that there was a passive moment for the DIP joint in the crimp grip with hyperextension of the distal joint, in all subjects. The magnitude of this moment was estimated at a quarter of the external moment. This moment is thus considerable and its involvement in the moment equilibrium equation for the DIP joint is essential, otherwise, the FDP tension will be overestimated. Concordant results have already been published in patients undergoing open carpal tunnel surgery with a gradually increasing fingertip force from 0 to 10 N (Dennerlein et al., 1998), but no quantitative data was presented.

Tendon tension estimations showed that the muscles were differently involved in the crimp or the slope grip. In the crimp grip, the tension in the FDP tendon was 60% higher than that of the FDS, whereas, in the slope grip it represented less than 90% of the FDS tension. Nevertheless, these results remain restricted to the testing set-up using a small ledge for the distal phalanx only. Further studies considering a bigger slope grip where the middle or the proximal phalanx is in contact with the hold should be performed. The FDP-to-FDS tendon–force ratio was 1.75:1 in the crimp grip and 0.88:1 in the slope grip. This means that the FDP is the prime finger flexor in the crimp grip, whereas the tensions are equally distributed between FDS and FDP tendons in the slope grip. In the crimp grip, the FDP-to-FDS tendon–force ratio needs to be included appropriately when determining the forces acting on the pulley system, especially for the A2 pulley (Roloff et al., 2005). However, the tendon–force ratio values used in the literature range from 1:1 to 3:1. We recommend using a ratio of 1.75:1 to accurately mimic load bearing as in rock climbing.

Our analysis shows that the forces acting on the pulleys are different in the crimp or the slope grip. The forces on the A2 pulley are 36 times lower in the slope grip than in the crimp grip, while the forces acting on the A4 pulley are 4 times lower. This correlates to clinical observations that ruptures of the pulley system are usually associated to the crimp grip (Bollen, 1990; Schöffl et al., 2003). In the crimp grip, we showed that the forces acting on pulleys were similar to the ones recorded by Marco et al. (1998). When comparing these forces with those reported by Lin et al. (1990), the A4 pulley is close to its maximal resistance while the A2 pulley can easily stand the exerted forces. This is in accordance with various studies which reported that the A4 pulley rupture occurs first (Marco et al., 1998; Warme and Brooks, 2000). Finally, Schweizer (2001) reported that at 25% of maximum strength in flexion, the A2 pulley load was 3 times superior to the force applied at the fingertip. Our results confirm this ratio for maximal fingertip force production.

A limitation of our model was that it did not include the effects of the A3 pulley. However, the restraining function of the A3 pulley is negligible on the basis of its high compliance compared to the A2 and A4 pulleys (Zhao et al., 2000; Roloff et al., 2005). Moreover, there may be some limits with the method proposed to assess the passive moment associated to the EMG signals. The probability of making a Type II error is evident with a threshold set at 3 SD from baseline activity. This Type II error indicates a failure to detect EMG activity when it is present, resulting in the possible underestimation of the FDP tension and in the subsequent overestimation of the FDS tension.

In conclusion, the present static biomechanical model of the finger yields satisfactory data on tensions applied in tendons and pulleys for activities involving a high risk of pulley rupture, such as sport climbing. The results for the DIP external moment and FDP–EMG relationship reveals the importance of considering the passive moment for the DIP joint equilibrium in order to accurately estimate the tension in FDP and FDS muscle tendons. Our analysis shows that the pattern of tendon tension distribution is largely due to the grip technique. The forces on the pulleys are particularly lower in the slope grip than in the crimp grip. Finally, data improves the knowledge about finger pulley injuries in sport climbing and are crucial for the clinicians and surgeons.

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