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ORIGINAL ARTICLE

Estimation of hand and wrist muscle capacities in rock climbers

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Abstract
Purpose This study investigated the hand and wrist muscle capacities among expert rock climbers and compared them with those of non-climbers. The objective was to identify the adaptations resulting from several years of climbing practice.
Methods Twelve climbers (nine males and three females) and 13 non-climber males participated in this study. Each subject performed a set of maximal voluntary contractions about the wrist and the metacarpo-phalengeal joints during which net joint moments and electromyographic activities were recorded. From this data set, the muscle capacities of the five main muscle groups of the hand (wrist flexors, wrist extensors, finger flexors, finger extensors and intrinsic muscles) were estimated using a biomechanical model. This process consisted in adjusting the physiological cross-sectional area (PCSA) and the maximal muscle stress value from an initial generic model.
Results Results obtained from the model provided several new pieces of information compared to the analysis of only the net joint moments. Particularly, the capacities of the climbers were 37.1 % higher for finger flexors compared to non-climbers and were similar for finger extensor and for the other muscle groups. Climbers thus presented a greater imbalance between flexor and extensor capacities which suggests a potential risk of pathologies.
Conclusions The practice of climbing not only increased the strength of climbers but also resulted in specific adaptations among hand muscles. The proposed method and the obtained data could be re-used to optimize the training programs as well as the rehabilitation processes following hand pathologies.

Keywords Sport climbing · Muscle capacities · Training · Hand modeling

Abbreviations

c_g	PCSA adjustment coefficient of the g muscle group
ECRB	Extensor carpi radialis brevis
EDC	Extensor digitorium superficialis
EMG	Electromyography
cm	Centimeter
$Diff_{EMG}$	Mean absolute difference between recorded EMG and estimated $a_{mech\|g}$ (task)
DIP	Distal interphalangeal joints
FCR	Flexor carpi radialis
FDP	Flexor digitorum profundus
FDS	Flexor digitorum superficialis
FE	Extrinsic finger extensor muscle group
FF	Extrinsic finger flexor muscle group
FI	Intrinsic finger muscle group
Hz	Hertz
$M_{max\|m}$	Muscle moment-generating capacities of the m muscle
$M_{max\|g}$	Muscle moment-generating capacities of the g muscle group
Imb_j	Muscle imbalance ratio of the j joint (j = MCP or wrist)

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M_{ergo}(task)	Measured net joint moments
$\overline{M_{ergo}}$(task)	Estimated net joint moments
MCP	Metacarpo-phalengeal joints
N	Newton
$a_{mech\|g}$ (task)	Mechanical participation of the g muscle group
PCSA	Physiological cross-sectional area
PIP	Proximal interphalangeal joints
r_m	Moment arm of the m muscle
RMS	Root mean square
SD	Standard deviation
σ_{max}	Maximal muscle stress
YDS	Yosemite decimal system
WE	Wrist extensor muscle group
WF	Wrist flexor muscle group

Introduction

One of the numerous originalities in sport climbing is the intense use of the upper limbs (fingers, hands, forearms and arms) to equilibrate and displace the entire body on inclined walls from vertical to fully overhang profile (Watts and Drobish 1998). This vertical "quadrupedy" generates high forces on the fingertips, in forearm muscles and in ligaments which are sometimes maintained for up to several minutes (Quaine et al. 1996; Mermier et al. 1997; Noé et al. 2001). As a consequence, expert climbers develop unusual prehensile capacities and are affected by specific pathologies (Cutts and Bollen 1985; Shea et al. 1992). In particular, because their practice requires the use of small-depth holds, climbers can generate higher force intensities at the fingertips than non-climbers (Grant et al. 2003; Quaine et al. 2003). Climbers are also able to maintain high levels of fingertip forces over longer periods than non-trained individuals; mainly thanks to an increase in their forearm muscles' vascularisation (Vigouroux and Quaine 2006; Philippe et al. 2012). In contrast to these capabilities, several studies observed that climbers do not necessarily present higher performances during non-climbing tasks such as handgrip exercises where the forces are applied on the entire surface of the finger pad, and during full power-grip tasks (Cutts and Bollen 1985; Ferguson and Brown 1997).

To grasp climbing holds, two finger techniques are commonly used by climbers: the slope and the crimp grips. The crimp grip consists in a hyper-extension of distal interphalangeal (DIP) joints combined with an important flexion of proximal interphalangeal (PIP) joints and is used to grasp sharp holds whose depths are smaller than the distal phalanx length. This particular finger posture has clearly been associated with finger pulley rupture which is one of the most common pathologies among climbers (Schweizer 2001). The slope grip corresponds to a large flexion of both the DIP and PIP joints and is typically used for holes or sloppy holds whose depths are larger than the distal phalanx length (Amca et al. 2012). Although the slope grip is not specific to sport climbing activities, the force levels produced at the fingertips were shown to be similar to those during the crimp grip for a 1 cm depth hold (Quaine and Vigouroux 2004; Schweizer 2001). To improve the understanding of these two grip techniques, Vigouroux et al. (2006, 2008) and Schöffl et al. (2009a) investigated the muscle forces exerted during maximal crimp grip forces and maximal slope grip forces. These studies estimated that during crimp and slope grips, the finger flexor tendons (*flexor digitorum superficialis* (FDS) and/or *profundus* (FDP)) can exert forces amounting to 250 N. Overall, these force levels are higher than the theoretical capacities of these muscles (around 150 N) which are generally evaluated using physiological cross-sectional area (PCSA) and the maximal muscle stress (σ_{max}) data from the literature (Chao et al. 1989; Valero-Cuevas et al. 1998). To produce such high intensities, climbers probably have to increase their muscle capacities compared to non-climber populations. Conversely, the forces developed in the extensor digitorium superficialis (EDC) tendon (amounting to 40 N during crimp grip and 30 N during slope grip) appear to be equivalent to those developed during other daily tasks such as pinch grip or cylindrical grip (Vigouroux et al. 2011; Goislard de Monsabert et al. 2012) and are in the range of their maximal capacities (around 60 N). From these results, it can be seen that, through their training, climbers seem to develop particular adaptations of their muscle force-generating capacities.

Although previous studies brought crucial information about climber hand performances and about patho-mechanisms of pulley ruptures, little is known about the climber characteristics in terms of muscle capacities. This lack of data is due to the fact that estimating such internal data is very complex and also that sport climbing is a relatively recent activity. Because of these difficulties, the design of training and prevention programs for climbers remains empiric. As an example, to train their finger performances, a majority of climbers use "hangboard" exercises which consist in sustaining the entire body mass with only their hands by grasping various types of holds. While this kind of exercise presents obvious advantages for the finger flexor enhancement, it cannot be used to target specific hand muscles. As presented above, the muscular capacities of climbers are probably highly specific and differ largely from other sporting populations who train their hands differently. The main objective of this study was to investigate the muscular particularities of climbers by estimating the capacities of five muscle groups of the hand (finger

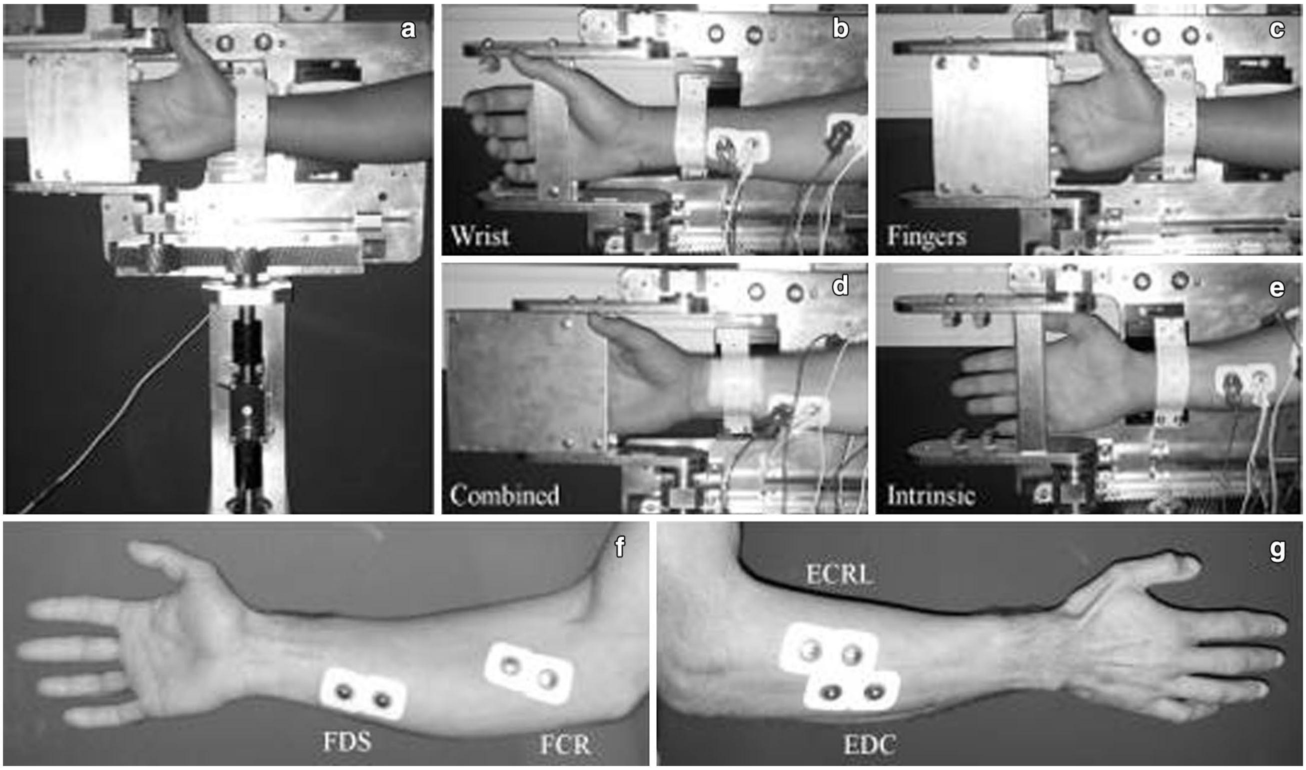

Fig. 1 Experimental setup. These pictures show the specially designed ergometer (**a**) as well as the modules and associated postures (**b**–**e**) used to realize the isometric maximal voluntary contractions. A representative electrode placement used for one subject is presented on bottom panels (**f**, **g**)

flexors, finger extensors, wrist flexors, wrist extensors, intrinsic). This estimation was based on the combination of various moment measurements and a biomechanical model.

Methods

Nine male climbers (age: 25.5 ± 10.2 years; height: 178.0 ± 6.5 cm; body mass: 73.0 ± 4.1 kg; hand length: 19.5 ± 0.5 cm) and three female climbers (age: 25.3 ± 7.6 years; height: 167.6 ± 2.1 cm; body mass: 54.3 ± 0.6 kg; hand length: 17.7 ± 0.6 cm) participated in this study. They were all experienced (more than 5 years) and well-trained climbers (French 8a, YDS: 5.13a grade level) and did not present any injury to the right hand or the right upper limb. For comparison purposes, 13 non-climbers with no specific training of hands or upper limbs were tested (age: 27.6 ± 4.0 years; height: 178.2 ± 5.1 cm; body mass: 70.2 ± 5.9 kg; hand length: 18.8 ± 0.9 cm). Prior to testing, subjects were informed about the testing procedure and signed a voluntary participation form according to the Aix-Marseille University Guidelines.

Joint moment measurement ergometer

A wrist and hand iso-kinetic dynamometer (Bio2 M, Compiegne, France) inspired from Schweizer et al. (2003) was used to measure the net joint moments with a 2000 Hz sampling rate. It consists of a torque sensor (DR 2112, SCAIM, Annemasse, France) to which specific modules are linked to mobilize specific hand and finger muscles. The measurement axis is connected to a servo-motor which controls the moment produced to mobilize the joint at a constant desired velocity (used in static condition for the current study). Specific modules were used for the measurement of maximum flexion/extension isometric joint moments (Fig. 1). These modules were designed to target at best one or several muscle groups during the mobilization of either the wrist or the MCP joints, although the actions of synergist and antagonist muscles could not be excluded. The testing of multiple joints and tasks was useful for guiding the modeling presented below. Overall, four modules were used. (1) The wrist module consisted of two 4-cm-large aluminum plates which wrapped the hand from the baseline of the thumb up to a line located below the metacarpophalangeal (MCP) head joint line (Fig. 1b). The fingers were not in contact with the surface of the module and did not exert any force. This module was specifically used to measure flexion/extension joint moments mainly produced by wrist muscles (further called Wrist task, Wflex and Wext) and it minimizes the actions of extrinsic finger muscles. (2) The wrist–fingers module was used to measure the simultaneous actions of extrinsic finger muscles and wrist muscles (Combined task, Cflex and Cext). It consisted of two 15-cm-large aluminum plates placed on both sides of the hand and fingers from the palm of the hand to the tips of the fingers (Fig. 1d). Measurements of maximum flexion/extension isometric joint moment were done around the wrist. (3) The third module (Finger task, Fflex and Fext) was used to measure maximal flexion/extension isometric moments around the MCP joints. With this module, the four fingers (index, middle, ring and little) were placed between two large 12-cm aluminum plates from the MCP joint line to the fingertips (Fig. 1c). This module was designed to target the finger flexor and extensor extrinsic muscles as well as the intrinsic muscles. (4) The fourth module was dedicated to measure the intrinsic muscle action (Intrinsic task, Fintdone in flexion only). It consisted of two 3-cm-large steel plates placed just distally to the MCP joint line with the DIP and PIP joints free. The measurement was done at the MCP joints axis (Fig. 1e).

The ergometer was fixed vertically on a wall and was positioned according to the subject's height to maintain the right forearm horizontally. Measurements were done with the finger joints positioned at 0° of flexion in an anatomical neutral posture. The wrist was in neutral flexion and abduction, the forearm mid-pronated, the elbow at 90° of flexion and the shoulder at 0°–15° of abduction and neutral rotation. Subjects were asked to apply a maximum isometric joint moment at the MCP joints or at the wrist for a 6 s period of effort (Pitcher and Miles 1997). Subjects exerted forces on the module surfaces and used the palmar side of the fingers for flexion and dorsal side for extension. Subjects were instructed to only mobilize their forearm to exert the moments and to prevent the participation of the trunk, the shoulder and the legs. This instruction was controlled visually and trials were re-done when subjects failed to respect it. For each condition, two consecutive trials were performed for both extension and flexion. A resting period of at least 1 min separated two trials to limit the effects of fatigue. In addition, four resting periods of at least 4 min were imposed during the entire experiment.

EMG recordings

A Biopac MP 150 system (Biopac Systems, Inc. Santa Barbara, CA, USA) was used for the acquisition of EMG at a sampling rate of 2000 Hz. EMG activities of the *extensor carpi radialis longus* (ECRL), *flexor carpi radialis* (FCR), EDC and FDS were recorded. After appropriate skin preparation, 9-mm-diameter surface electrodes Ag/AgCl (Oxford Instruments Medical, Surrey, UK) were applied to the skin over the muscles with a 20-mm interelectrode spacing. The placements of electrodes were determined using anatomical description, palpation and functional movements. Correct placement of the electrodes was controlled by recording signals during functional tests including wrist radial deviation, finger and wrist flexion, and finger and wrist extension. To measure the ratio of coactivation between forearm extensors and flexors, two trials of maximal co-contraction (Co) were also performed (Falconer and Winter 1985). During this task, the subjects were asked to maximally and statically co-contract all hand and forearm muscles with a similar arm, forearm and hand posture to the one used for moment measurements. Figure 2 represents typical signals recorded during the experiment.

Data analysis and estimations of the muscle capacities

For each condition, only the trial presenting the highest measured joint moment was considered for the analysis. EMG signals were filtered using a Butterworth filter (bandpass, order 4, zero-phase lag, bandwidth: 20–400 Hz). The maximum isometric joint moments were evaluated using a 750-ms window centered on the peak moment for each task. Within this time interval, the mean joint moment and the EMG root mean square (RMS) value were computed. For each muscle, the muscle activation was assessed by normalizing the RMS value during each task by the largest RMS value recorded among all trials. The maximal capacities of the five muscle groups (Wrist Flexors, WF; Wrist Extensors, WE; Finger Flexors, FF; Finger Extensors, FE; Intrinsic, FI) were evaluated using a biomechanical model of the hand (Table 1). The muscle moment-generating capacities of one muscle ($M_{\max|m}$) were classically evaluated according the Eq. 1 for a generic musculoskeletal model of the hand:

$$M_{\max|\mathrm{m}} = r_\mathrm{m} \cdot PCSA_\mathrm{m} \cdot \sigma_{\max}, \tag{1}$$

where the maximum muscle stress value ($\sigma_{\max}$), representing the maximal amount of Newtons which can be generated for 1 cm^{-2} of PCSA, is set at 35.4 N cm^{-2} for the hand muscles (Valero-Cuevas et al. 1998). r_m and $PCSA_\mathrm{m}$ are the flexion/extension moment arm and the PCSA of the m muscle. PCSA data were taken from Chao et al. (1989) for the fingers and from Ramsay et al. (2009) for the wrist. According to the posture adopted during this experiment, muscle moment arms were computed assuming a neutral position (0° in flexion–extension, abduction–adduction and pronation–supination) for all joints using the data from Chao et al. (1989) for the fingers and from Lemay and Crago (1996) for the wrist. Moment arms about the finger

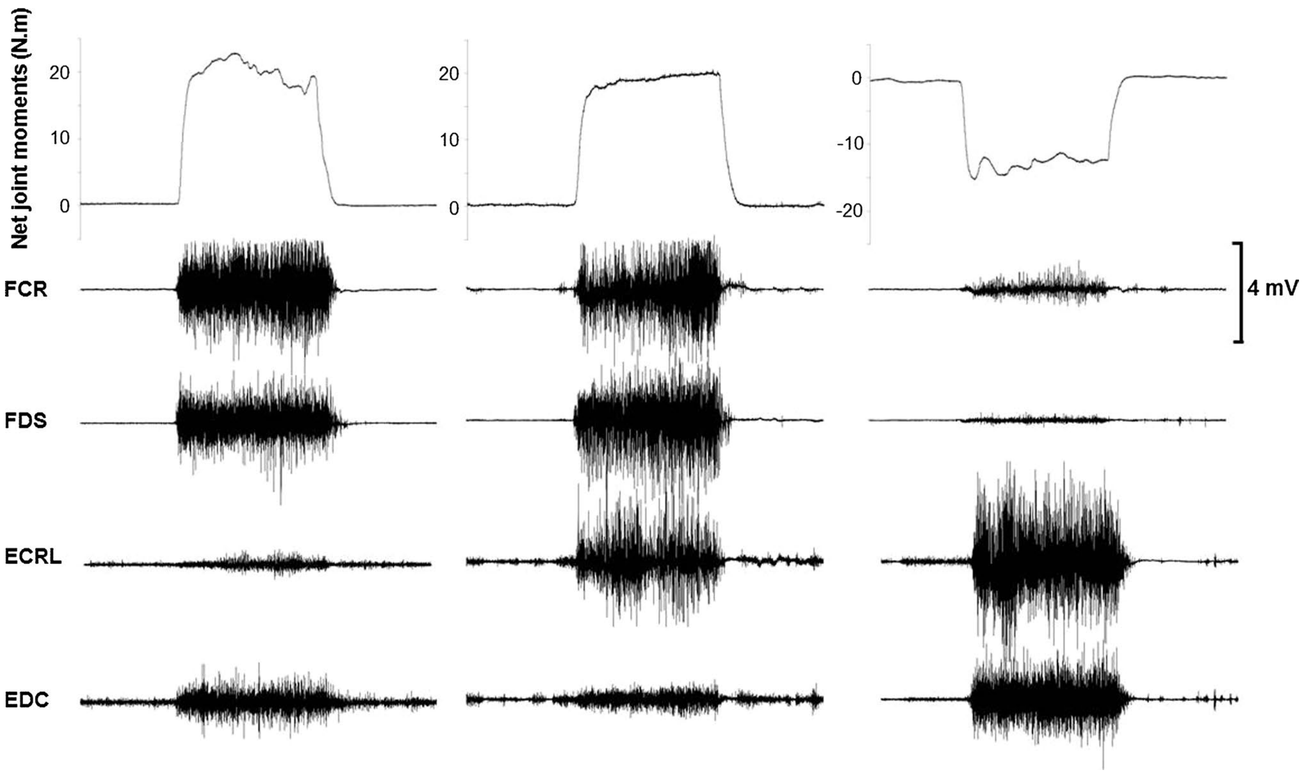

Fig. 2 Representative net joint moment data recorded by the ergometer (*top panels*) and associated EMG recordings of the four representative muscles (FCR, FDS, ECRL, EDC) during the wrist flexion task (*left panels*), the finger flexion task (*middle panels*) and the wrist extension task (*right panels*). The EMG recordings clearly indicate that the activation levels of synergist and antagonist muscles are non-negligible and therefore justify the need for a biomechanical model to estimate the capacities of specific muscle groups instead of only using the resultant net joint moments

Table 1 Muscle groups used in the optimization process

Muscle group	Included muscles
Wrist flexors, WF	Flexor carpi radialis; Flexor carpi ulnaris; Palmaris longus
Writs extensors, WE	Extensor radialis longus, extensor carpi ulnaris, extensor carpi radialis brevis
Finger flexors, FF	Flexor pollicis longus; FDP of index, middle, ring and little fingers; FDS of index, middle, ring and little fingers
Finger extensors, FE	Extensor pollicis longus and brevis; adductor pollicis longus; extensor digitorum communis of index, middle, ring and little fingers, extensor indicis proprius, extensor digiti quinti
Intrinsic, ID	First, second, third, fourth dorsal interossei; first, second, third palmar interossei; first, second, third lumbrical, flexor digiti quinti, abductor digiti quinti

joints were scaled for each participant using their hand length (Chao et al. 1989).

To assess the muscle capacities of each subject, the PCSA data and the $\sigma_{\max}$ value were adjusted using an optimization procedure. The procedure consisted of determining a new $\sigma_{\max}$ value and five PCSA coefficients for each participant. Each PCSA coefficient was used to multiply the PCSA of the muscles from one of the five muscle groups used in the procedure (WF, WE, FF, FE and FI). These values were adjusted to ensure that the muscle tensions estimated throughout the model are consistent with the force capacities measured with the ergometer. The adjustment of the PCSA coefficients and the $\sigma_{\max}$ value was done using a non-linear least-square constrained optimization (Fmincon, optimisation toolbox, Matlab, Natick, Massachusetts USA) with upper and lower bounds formulated as follows:
find

$$\sigma_{max}$$

$$c = \{c_{\mathrm{WF}}; c_{\mathrm{WE}}; c_{\mathrm{FF}}; c_{\mathrm{FE}}; c_{\mathrm{FI}}\}$$

$$a_{mech} = \{a_{mech}|WF; a_{mech}|WE; a_{mech}|FF; a_{mech}|FE; a_{mech}|FI\}$$

that minimize

$$f(\sigma_{max}, c, a_{mech}) = \sum_{task} \left[M_{ergo}(task) - \overline{M_{ergo}}(task)\right]^2 \tag{2}$$

subject to

$$\begin{cases} 15 < \sigma_{\max} < 60 \\ 0.5 < c < 8 \\ 0 < \boldsymbol{a}_{\text{mech}} < 1 \end{cases}, \tag{3}$$

where $M_{ergo}(task)$ is the net joint moment measured by the ergometer during one of the eight tasks with $\text{task} = \{W_{\text{flex}}; W_{\text{ext}}; C_{\text{flex}}; C_{\text{ext}}; F_{\text{flex}}; F_{\text{ext}}; F_{\text{int}}; Co\}$ and $\overline{M_{\text{ergo}}}(\text{task})$ is its estimation using the musculoskeletal model. This estimation consisted of summing the estimated moments produced by the five muscle groups:

$$\overline{M_{\text{ergo}}}(\text{task}) = \sum_{g} a_{\text{mech|g}}(\text{task}) \cdot M_{\text{max|g}}, \tag{4}$$

where $M_{\max|g}$ and $a_{\text{mech|g}}(\text{task})$ are the moment-generating capacity and the mechanical participation of the g muscle group with $g = \{\text{WF; WE;FF;FE; FI}\}$. The mechanical activation $a_{\text{mech|g}}(\text{task})$ is a value comprised between 0 and 1 which reflects at which percentage of its maximal capacity ($M_{\text{max|g}}$) a muscle group is producing a moment during the task. $M_{\text{max|g}}$ was expressed as the sum of the maximal moment capacity of all the muscles within a muscle group:

$$M_{\text{max|g}} = \sum_{\text{m}} r_{\text{m}} \cdot c_{\text{g}} \cdot PCSA_{\text{m}} \cdot \sigma_{\max} \tag{5}$$

The initial values of $\sigma_{\max}$ and c were, respectively, 35.4 N cm^{-2} and 1. The $a_{\text{mech|g}}(\text{task})$ initial values were set at the level of the EMG muscle activities of the corresponding control muscle recorded during the corresponding tasks. These initial values were carefully chosen to optimize at best the results provided.

Because the solution space of this optimization problem was large, the addition of constraints was necessary to eliminate non-physiological solutions that appeared for some subjects. These constraints consisted in ensuring that the muscle moment-generating capacities estimated through the optimization procedure did not demonstrate completely different trends than those observed for the net joint moment performances recorded with the ergometer:

$$0.7\frac{M_{\text{ergo}}(\text{C}_{\text{ext}})}{M_{\text{ergo}}(\text{C}_{\text{flex}})} \leq \frac{M_{\text{max|WE}} + M_{\text{max|FE}}}{M_{\text{max|WF}} + M_{\text{max|FF}}} \leq 1.3\frac{M_{\text{ergo}}(\text{C}_{\text{ext}})}{M_{\text{ergo}}(\text{C}_{\text{flex}})} \tag{6a}$$

$$0.7\frac{M_{\text{ergo}}(\text{F}_{\text{ext}})}{M_{\text{ergo}}(\text{F}_{\text{flex}})} \leq \frac{M_{\text{max|FE}}}{M_{\text{max|FF}} + M_{\text{max|FI}}} \leq 1.3\frac{M_{\text{ergo}}(\text{F}_{\text{ext}})}{M_{\text{ergo}}(\text{F}_{\text{flex}})} \tag{6b}$$

$$0.7\frac{M_{\text{ergo}}(\text{W}_{\text{flex}})}{M_{\text{ergo}}(\text{C}_{\text{flex}})} \leq \frac{M_{\text{max|WF}}}{M_{\text{max|WF}} + M_{\text{max|FF}}} \leq 1.3\frac{M_{\text{ergo}}(\text{W}_{\text{flex}})}{M_{\text{ergo}}(\text{C}_{\text{flex}})} \tag{6c}$$

$$0.7\frac{M_{\text{ergo}}(\text{W}_{\text{ext}})}{M_{\text{ergo}}(\text{C}_{\text{ext}})} \leq \frac{M_{\text{max|WE}}}{M_{\text{max|WE}} + M_{\text{max|FE}}} \leq 1.3\frac{M_{\text{ergo}}(\text{W}_{\text{ext}})}{M_{\text{ergo}}(\text{C}_{\text{ext}})} \tag{6d}$$

Once the maximal moment-generating capacities were computed, the imbalance ratio between extensor and flexor muscles (*Imb*) at the wrist and the MCP joints was computed as follows:

$$Imb_{\text{wrist}} = \frac{M_{\text{max|WE}} + M_{\text{max|FE}}}{M_{\text{max|WF}} + M_{\text{max|FF}}} \tag{7a}$$

are the moment-generating

$$Imb_{\text{mcp}} = \frac{M_{\text{max|FE}}}{M_{\text{max|FF}} + M_{\text{max|FI}}} \tag{7b}$$

To control the validity of the results provided, the absolute differences between the estimated mechanical activities ($a_{\text{mech|g}}(\text{task})$) and the recorded EMG activities were computed (Diff_{EMG}). For each muscle group, this value was averaged among all tasks and all subjects of a population. No Diff_{EMG} was computed for the intrinsic group for which no EMG was collected.

Statistical analysis

Mean and standard deviation (SD) were computed for the climbers and non-climbers results. The normality of results was controlled and t tests (Statistica, Statsoft, Tulsa, USA) were used to identify the significant differences between the two samples (male climbers and non-climbers) on the maximal joint moment of the seven tasks (Wflex, Wext, Cflex, Cext, Fflex, Fext, Fint), the estimated moment-generating capacities of the five muscle groups (WF, WE, FF, FE, FI) at the wrist and the MCP joints and the imbalance ratios at the wrist and MCP joints. The significance level was set at $p < 0.05$. The results of the three female climbers were presented for information but have not been included in the statistical analysis due to the low number of subjects and also because no female non-climbers were tested for comparison.

Results

Measured net joint moments

Measured net joint moments for climbers and non-climbers are presented in Fig. 3. Among all the subjects, the climbers presented significantly greater flexion performances

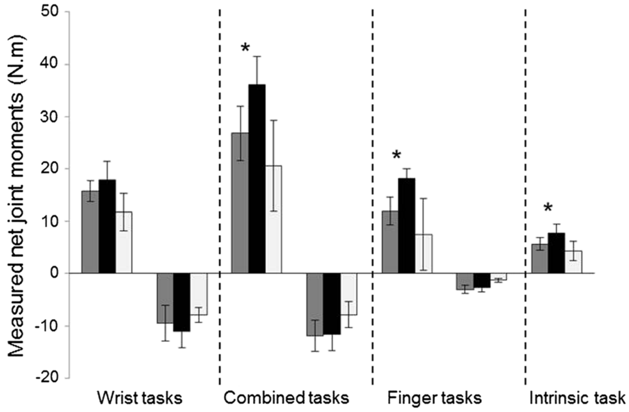

Fig. 3 Results of measured net joint moments. The *gray blocks* represent the non-climbers, the *black blocks* represent the male climbers and the *white blocks* represent the female climbers. *Positive values* represent flexion moments, *negative values* represent extension moments. *Asterisk* indicates a significant difference between non-climbers and male climbers

during the Combined task (climbers: 36.1 ± 5.4 N m, non-climbers: 26.8 ± 5.2 N m; $t(20) = 4.05$; $p < 0.001$), during the Finger task (climbers: 18.1 ± 1.9 N m, non-climbers: 11.9 ± 2.6 N m; $t(20) = 6.11$; $p < 0.001$) and during the Intrinsic task (climbers: 7.77 ± 1.7 N m, non-climbers: 5.7 ± 1.2 N m; $t(20) = 3.41$; $p < 0.01$). Conversely, no significant differences were observed for extension moments during the Combined task ($t(20) = 0.23$; $p = 0.82$) and during the Finger task ($t(20) = 0.98$; $p = 0.34$). These extension net joint moments amounted approximately to −12 N m during the Combined task and −3 N m during the Finger task for non-climbers and climbers. Concerning the Wrist tasks, no significant differences were observed for flexion moments ($t(20) = 1.81$; $p = 0.09$) and for extension moments ($t(20) = 1.15$; $p = 0.26$). Flexion moments were 17.85 ± 3.5 N m and 15.7 ± 2.0 N m for climbers and non-climbers, respectively. Extension moments amounted to −10 N m for these two groups of subjects. The female climbers produced net moments 42.0 ± 11.1 % lower than the male climbers and 31.2 ± 13.6 % lower than the non-climbers among all tasks tested.

Estimated moment-generating capacities

The estimated moment-generating capacities of each muscle group around the wrist joint are presented in Fig. 4. No significant differences were observed between climbers and non-climbers for both the wrist flexor and extensor groups (FC: $t(20) = 1.03$, $p = 0.32$; EC: $t(20) = -0.12$, $p = 0.9$) and the finger extensor group ($t(20) = 1.29$, $p = 0.21$). Mean values of wrist flexor moment-generating capacities amounted to 33.7 ± 6.8 N m for climbers and 31.2 ± 4.9 N m for non-climbers. The wrist extensor

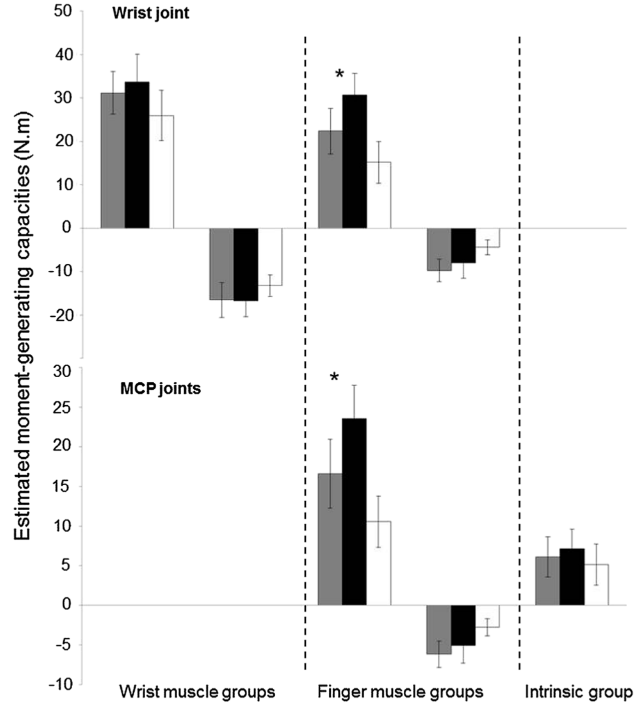

Fig. 4 Estimated muscle moment-generating capacities at the wrist joint level (*upper panel*) and MCP joints level (*lower panel*). Muscles included in the different muscles groups are detailed in Table 1. Non-climbers are in *gray*, male climbers are in *black* and female climbers are in *white*. *Asterisk* indicates a significant differences between non-climbers and climbers. Flexion and Extension are positive and negative values, respectively. No muscle capacities were presented for the intrinsic muscle group at the wrist joint and for the wrist muscle groups at the MCP joints since these muscles do not cross these respective joints

moment-generating capacities amounted to approximately −16.5 N m for both groups. Although no significant differences were found regarding finger extensor capacities, the climbers exhibited lower values (−8.0 ± 3.5 N m) than that of non-climbers (−9.7 ± 2.6 N m). Concerning the finger flexor capacities about the wrist joint, climbers (30.7 ± 3.5 N m) presented 37.1 % higher values ($t(20) = 4.14$; $p < 0.001$) than non-climbers (22.4 ± 5.2 N m).

The differences around the MCP joint level were similar to those concerning the wrist. The finger flexor moment-generating capacities of climbers (23.5 ± 2.8 N m) were significantly higher ($t(20) = 4.2$, $p < 0.001$) than those of non-climbers (16.6 ± 4.3 N m). No significant difference for the finger extensor group ($t(20) = 1.3$, $p = 0.21$) and the intrinsic muscle group ($t(20) = 1.0$, $p = 0.33$) was identified.

Concerning the female climbers, the moment-generating capacities around both joints were lower than the two other samples tested for all muscle groups. Interestingly, compared to the male climbers, the female climbers exhibited

Table 2 Outputs of biomechanical model

		Wrist flexors	Wrist extensors	Finger flexors	Finger extensors	Intrinsic
Non-climbers	Cg	5.2 ± 0.4	5.1 ± 0.9	1.4 ± 0.3	2.7 ± 0.8	2.0 ± 1.0
	σ_{max}	32.5 ± 4.6				
	$Diff_{EMG}$	0.14 ± 0.03	0.13 ± 0.07	0.14 ± 0.04	0.28 ± 0.03	/
Male climbers	Cg	5.7 ± 0.8	5.3 ± 1.0	2.0 ± 0.3	2.2 ± 0.9	2.2 ± 0.9
	σ_{max}	32.2 ± 4.9				
	$Diff_{EMG}$	0.14 ± 0.05	0.15 ± 0.07	0.15 ± 0.06	0.22 ± 0.05	/
Female climbers	Cg	5.0 ± 1.0	4.7 ± 0.5	1.1 ± 0.2	1.3 ± 0.3	1.9 ± 0.9
	σ_{max}	28.2 ± 4.8				
	$Diff_{EMG}$	0.12 ± 0.01	0.14 ± 0.04	0.17 ± 0.08	0.28 ± 0.07	/

Cg represents the PCSA coefficients adapted to each subject for each muscle group. σ_{max} represents the maximal muscle stress coefficient adapted for each subject and used for all muscle groups. $Diff_{EMG}$ represents the mean (among all tasks and all subjects of a population) of the differences between the estimated mechanical activity of each muscle group and the recorded EMG activity. No EMG was recorded for the intrinsic muscle group

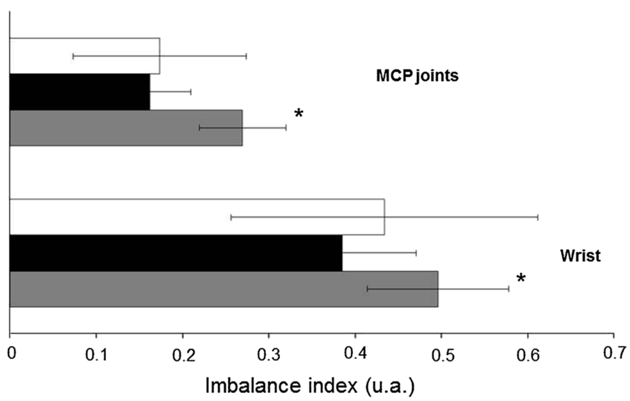

Fig. 5 Imbalance index at the Finger (MCP joints) and Wrist level. The imbalance index represents the ratio of the moment-generating capacities of finger and extensor muscle groups. Non-climbers, male and female climbers are represented by the *gray*, *black* and *white* blocks, respectively. A ratio value close to 1 means that extensor and flexors present similar moment-generating capacities

larger differences for the finger flexors and extensors (up to 45 %) than for the wrist and intrinsic muscles (around 25 %).

As additional information, Table 2 presents the averaged outputs of the model (Cg and σ_{max}) used to estimate the muscle moment-generating capacities. The variations among the tested populations of the Cg coefficients and the σ_{max} value globally lead to the same conclusions as when comparing the moment-generating capacities. This is not surprising as these variables are strongly related. The observed differences between the estimated implication of each muscle group and the EMG recordings during each task showed mean values between 0.12 and 0.28. The highest values were observed for the finger extensor muscle group with mean values ranging from 0.22 to 0.28. The lowest mean values are observed for the flexor carpi muscle group (approximately 0.13).

Estimated ratio of extensor–flexor moment capacities

The imbalance ratios at the wrist and the MCP level are presented in Fig. 5. When a ratio value is lower than 1, the joint presents an imbalance which indicates stronger capacities for flexors than for extensors. At both wrist and MCP level, the ratios were largely inferior to 1 for all subjects and significant differences were observed between climbers and non-climbers (wrist: $t(20) = 3.1$, $p < 0.01$; MCP: $t(20) = 4.9$; $p < 0.001$). For both joints, the non-climbers exhibited less imbalance (wrist: 0.50 ± 0.09 and MCP: 0.27 ± 0.05) than for climbers (wrist: 0.38 ± 0.08 and MCP: 0.16 ± 0.06).

The imbalance ratios of female climbers were comparable to those of climbers about the MCP level and were in between those of climbers and non-climbers about the wrist. Overall, large standard deviations were observed among female climbers.

Discussion

This study was designed to investigate the hand and wrist muscle capacities of climbers and to further characterize the specific adaptations resulting from the long-term practice of sport climbing. The net moment data measured during a set of wrist and finger ergometer tasks were used conjointly with a biomechanical model of the hand to estimate the capacities of five forearm muscle groups. Previously, several studies had analyzed the correlation between climbing expertise and the performances obtained during various tests such as dynamometry (Cutts and Bollen 1985;

Ferguson and Brown 1997; Grant et al. 2003; Quaine et al. 2003) or iso-kinetic exercises (Schweizer and Furrer 2007). These studies reported the results of external torques and forces measured during the tests and brought interesting knowledge. However, the obtained results were not representative of individual muscle capacities, since the measured performances corresponded to the resultant action of all the implicated muscles which includes synergistic and antagonistic actions. By using a biomechanical model, our study overcame this limitation and provided an estimation of individual capacities of the five main muscle groups of the hand.

The main conclusion of the present study is that the climbers presented significantly higher capacities for the finger flexor muscles. The many years of climbing practice, therefore, seem to have increased the finger flexors capacities by almost 40 %. This result was obviously expected given the numerous studies which demonstrated significant higher performances of climbers when grasping fingertip holds (Watts and Drobish 1998; Mermier et al. 1997; Cutts and Bollen 1985; Grant et al. 2003; Philippe et al. 2012). Nevertheless, this study brought new information by quantifying this improvement at the muscle level. In addition to this quantification, several unexpected results were highlighted by the current study. First, it is interesting to notice that the enhancement of the finger flexor capacities was not followed by a simultaneous enhancement of the antagonist finger extensor muscles. Although no significant effect was found, several climbers even presented lower finger extensor capacities than the non-climbers. This climber's characteristic is probably due to an underuse of the extensors during training and climbing which implies mostly a flexion action during hold grasping. This "weakness" may also be a consequence of the decrease in antagonist muscle activations which has been observed in numerous sport/movement expert reports (Griffin and Cafarelli 2005; Fouré et al. 2010). The second intriguing point is that the climbers presented similar wrist muscle group capacities to the non-climbers. This result is surprising since high intensity of wrist moments is required during climbing. It is plausible that these wrist joint moments are mainly produced by the finger extrinsic muscles which also cross the wrist joint. Consequently, it seems that the practice of climbing does not require important adaptations of wrist muscles. Further investigations are needed to determine if this conclusion is also valid for the wrist adduction–abduction and the forearm pronation–supination muscle groups. In a similar way, the capacities of climbers' intrinsic hand muscles were not significantly higher which is in accordance with the studies which demonstrated that climbers do not achieve higher performances for non-specific climbing tasks such as hand dynamometer tests (Ferguson and Brown 1997). To sum up, this study demonstrates that current climbing practice and training methods do not result in homogeneous improvements of muscle capacities, since only finger flexors are enhanced without modifications of other hand and wrist muscles. Given this conclusion, it could be interesting to develop new training tools and new methods to improve the forearm performances.

Consequent to the stronger enhancement of finger flexors, climbers exhibited higher imbalances between flexors and extensors around both the wrist and MCP joints than non-climbers. This point is of great importance from a pathological point of view, since it is well known in the literature that the co-activation of antagonist muscles and the associated mechanical actions are crucial for articulations in order to protect them from excessive shear forces and excessive involuntary torques by increasing joint rigidity (for review, see Remaud et al. 2007). Moreover, the role of antagonist muscles is particularly important for the hand and finger musculoskeletal system where the co-contraction is necessary to the equilibrium of the entire chain of segments from the forearm to the tip of fingers (Snijders et al. 1987; Goislard de Monsabert et al. 2012). Given that climbers present a stronger imbalance, it is probable that they have more difficulties in controlling and protecting their joints and are, therefore, more exposed to joint instability, joint surface over-use and/or ligament tears (Centomo et al. 2008; Stokes and Gardner-Morse 2003). This finding could explain why wrist medio-carpal instability (Garcia-Elias 2008; Lichtman et al. 1981; Lichtman and Wroten 2006) is often observed in climbers, although no medical reports have been published recently. This important imbalance may also be implicated in finger pulley ruptures, since the extensor muscle action is also required during the crimp grip technique (Vigouroux et al. 2006). Additional biomechanical investigations are, however, required to validate this idea and to understand how this imbalance could contribute to these specific pathologies.

Concerning the female climbers, the results showed that their performances were weaker than both the male climbers and the non-climbers. Furthermore, the imbalance ratios indicate that this weakness is amplified for finger flexor muscles, therefore suggesting that female climbers have a different capacity profile than male climbers. This may indicate that the improvement of the finger muscle capacities is harder to develop for women and/or that the women do not need this improvement for climbing. In spite of this, the female climbers showed similar imbalances at the MCP level to those observed for male climbers. However, additional subjects and one non-climber female sample should be tested to confirm this trend. One interesting point is that normalizing the moment-generating capacities with the body mass of each individual, as it is generally done to highlight the performance of climbers (Philippe et al. 2012), does not change the results significantly.

The conclusions remain similar both for the comparison between male and female climbers and for the comparison between climbers and non-climbers. This could be explained by the fact that the two samples of males presented similar body weights and this may confirm the fact that the female climbers presented a different type of muscle capacity adaptation.

Overall in this study, several limitations should be considered when interpreting our results. First, the use of a biomechanical model leads to inherent limits associated with the optimization resolution problems, the use of generic anthropometric data for muscle moments arms and the consideration of joints with perfect rotation axes. Moreover, in our model, the results obtained did not take into account the muscle force–length and the force–velocity relationships as well as the pulley-tendon frictions which could influence the performances during climbing (Schweizer et al. 2003; Schöffl et al. 2009b). Despite these limits, our model quantified the muscle capacities of climbers and showed that climbers present improved finger flexor capacities and increased imbalances at both wrist and MCP level. These results could be re-used by trainers and clinicians to prevent climbing injuries and improve training programs. In particular, our data indicate that training on finger extensors would be valuable to re-equilibrate the imbalance ratio of climbers. Already now, the method presented here is operational in the evaluation of specific muscle capacities of any climbers to design individual training programs. Further studies should focus on developing the proposed method to study muscle capacities and its dependence on joint positions and movement velocities and to further individualize the force–length and force–velocity relationships of the Hill-type muscle model (Hill 1953; Winter and Woo 1990).

Conflict of interest The authors declare that they have no conflict of interest. This experiment complies with the current laws of France in which it was performed.

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