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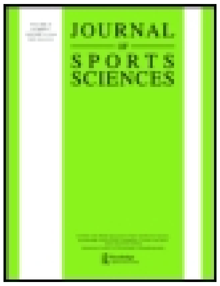

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Abstract

The aim of this study was to understand how the commonly used climbing-specific grip techniques and hold depths influence the finger force capacities. Ten advanced climbers performed maximal voluntary force on four different hold depths (from 1 to 4 cm) and in two force directions (antero-posterior and vertical) using three grip techniques (slope, half crimp and full crimp). A specially designed platform instrumented with a 6-degrees-of-freedom (DoF) force/torque sensor was used to record force values. Results showed that the maximal vertical forces differed significantly according to the hold depth and the grip technique (ranged from 350.8 N to 575.7 N). The maximal vertical forces increased according to the hold depth but the form of this increase differed depending on grip technique. These results seemed to be more associated with finger-hold contact/interaction than with internal biomechanical factors. Similar results were revealed for antero-posterior forces (ranged from 69.9 N to 138.0 N) but, it was additionally noted that climbers have different hand-forearm posture strategies with slope and crimp grip techniques when applying antero-posterior forces. This point is important as it could influence the body position adopted during climbing according to the chosen grip technique. For trainers and designers, a polynomial regression model was proposed in order to predict the mean maximal force based on hold depth and adopted grip technique.

Keywords: *Sport climbing, crimp grip, slope grip, hold depth, finger forces*

Introduction

Rock climbing has become an increasingly popular sport as a recreational activity and a competitive event. Also, there has been enormous progress in climbing standards over recent years. Nowadays, most of the hardest routes are on overhanging walls and/or they contain really small holds. During rock climbing moves, the majority of body weight is carried by relatively small muscle groups which control the hands and fingers with only partial support from the legs. The importance of finger strength was shown by Watts, Newbury, and Sulentic (1996). When climbing routes get steeper, less body weight is supported by the legs and the importance of the arms and grip strength increases (Grant et al., 2003; Noé, Quaine, & Martin, 2001). The inability to generate the necessary finger force to maintain contact with the handhold is defined as one of the main reasons of failure (Watts, Daggett, Gallagher, & Wilkins, 2000).

There are many different grip techniques to grasp holds with hand and fingers, but the most commonly used ones are the slope and the crimp grips (Figure 1). These two techniques are well described in literature: the crimp grip is characterised by a hyper-extension of the distal interphalangeal (DIP) joint while the slope grip is characterised by flexed finger joints. The slope grip is usually performed on large handholds while the crimp grip is used on small sharp edge handholds to optimise the contact area between the fingertips and the hold (Schöffl et al., 2009; Shea, Shea, & Meals, 1992). Furthermore, the crimp grip allows climbers to use their thumb above the other fingers (full crimp grip), thus applying additional forces (Quaine, Vigouroux, Paclet, & Colloud, 2011). In addition, it was shown that crimp and slope grips have different muscular coordination and pathology risks (Schöffl et al., 2009; Schweizer, 2001; Schweizer & Hudek, 2011). In spite of the pathology risk and even if the thumb is not used, the crimp grip is the one most often preferred by

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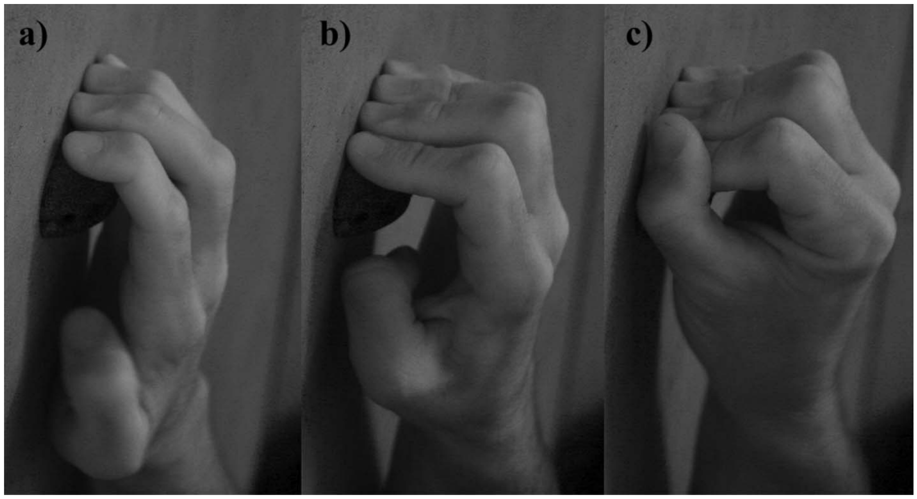

Figure 1. Illustration of the slope (a), half crimp (b) and full crimp (c) grip techniques used during rock-climbing. The slope grip is characterised by a flexion of the finger joints. The half crimp is characterised by a hyper extension of the distal joints and the full crimp grip is characterised by the addition of the thumb on the other fingers.

climbers (Schweizer, 2001). However, the reason for this choice is still unclear.

Several studies have been done to analyse the differences between the crimp and the slope grip techniques for maximal finger strength (Quaine et al., 2011; Quaine, Vigouroux, & Martin, 2003a; Quaine & Vigouroux, 2004; Schweizer, 2001; Vigouroux, Quaine, Labarre-Vila, & Moutet, 2006). Most of these studies showed that the maximal forces applied on a same depth hold are not significantly different between each grip. However, in all these studies, measurement of the maximal force was considered on a specially standardised finger grip apparatus instrumented with force sensors. The shape and depth of used holds were thus similar for both grip techniques but until now, no study has investigated the relationship between the different grip technique and various hold depths. In these previous studies participants were also required to pull the hold in the vertical direction and minimise the force exerted in the antero-posterior direction. However during rock climbing, climbers choose the appropriate grip techniques according to the movement which has to be performed and/or the body posture. Since force direction is important to perform and maintain a vertical quadrupedic posture (Quaine, Martin, Leroux, Blanchi, & Allard, 1996), analysing only vertical forces may not be enough to explain the differences between grip techniques.

The purpose of this study was thus to analyse the effect of commonly used grip techniques (slope, half crimp and full crimp) and hold depths on maximal voluntary contraction values exerted in both vertical and antero-posterior directions. Our hypothesis was that hold depth as well as force direction could explain the preference of climbers to use one or another grip technique. Based on our data, a regression model was constituted in order to predict the average forces based on the hold depth for each grip technique.

Methods

Ten male climbers (anthropometric measurements presented in Table I) participated in this study. They were all experienced and well trained climbers (French 7b, YDS: 5.12c grade level) and did not present any injury to the right hand and right arm. Participants were asked not to train the day before the experiment. Prior to testing, they were informed about the testing procedure and signed a voluntary participation form according to the University guidelines.

Measurement system

A specially designed wall mounted platform was used to fix the hand holds and measure the forces (Figure 2) using a 6-degrees-of-freedom (DoF) force/torque sensor (Delta F/T sensor, ATI, Industrial Automation, Apex, NC). The sensor was positioned in a horizontal plane and the axes were defined as x: antero-posterior, y: lateral and z: vertical axis. The force sensor was amplified (ATI 9105-PS-1) and connected to a computer via an analogue-digital converter card (NI PCI-6620, 16 Bit, National Instruments, Austin, TX). A Labview (National Instruments, Austin, TX) program was used to record and process the force signals at a sample rate of 1000 Hz. Hand and forearm kinematics were measured (100 Hz) using a camcorder (Basler A602fc) in the sagittal plane. Four reflective markers were attached to anatomical landmarks (lateral epicondyle, ulnar styloid process and both distal and proximal end of the middle finger metacarpals). An external trigger was used to synchronise force and kinematics data. Kinematic data was analysed with SIMI Motion movement analysis software.

The participants were positioned in the upright posture facing the wall and parallel to the hold plane.

Table I. Descriptive characteristics of participants.

	mean ± *s*
Age (years)	22.3 ± 4.5
Body mass (kg)	72.7 ± 5.7
Height (cm)	177.60 ± 5.25
Hand size (cm)	19.50 ± 0.73
Forearm length (cm)	28.34 ± 1.36

Note: Body mass and height were measured according to the standards by scales and measure. All the other anthropometric measurements were taken from the right side of the body using a tape measure. Forearm length was measured from the head of the radius to the tip of the radial styloid (Grant et al., 1996). Hand length was considered as the distance from the tip of the middle finger to the midline of the distal wrist crease when the forearm and hand are supinated horizontally (Clerke, Clerke, & Adams, 2005).

At the beginning of each trial, their upper arm was at approximately 90° of flexion (near horizontal position) and 60° of abduction with their elbow joint flexed at approximately 90°. The positioning of the hand hold was adjusted for each participant according to their height. The participants were allowed to block the left hand on a fixed vertical frame only to maintain the body position during trials. But they were not allowed to use the left hand to counter the force of the right hand laterally. This was controlled by asking participants to minimise lateral forces.

Experimental protocol

Experimental tests were performed on four different hold depths and in three different hand positions: slope, half crimp (crimp without thumb) and full crimp (crimp with thumb). Special wooden handholds with flat grip surfaces were used in this study. They had a rounded edge to prevent finger pain and injury (Figure 2). The depths of the holds were from 1 cm to 4 cm and they were labelled as Hold 1, Hold 2, Hold 3 and Hold 4 respectively. Before test trials participants warmed up and did some contractions on the test apparatus to familiarise themselves with

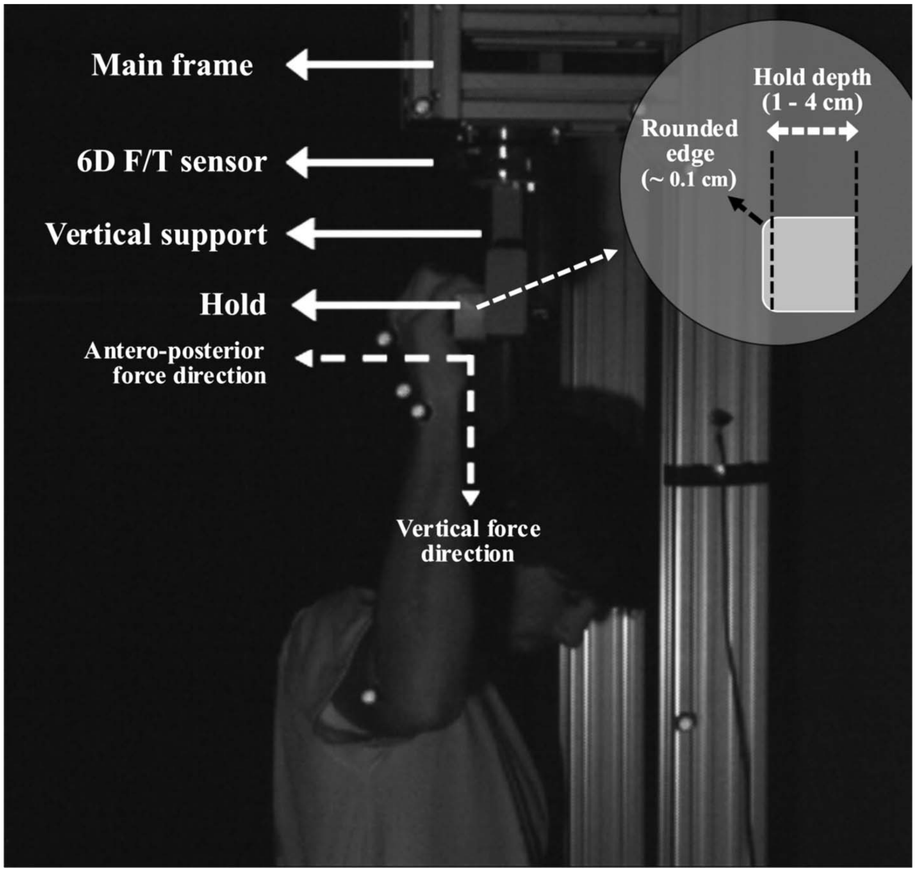

Figure 2. Force measurement system and experiment setup. The hold was mounted on a vertical support fixed on the force sensor. The hand and fingers on this drawing are placed in the half crimp grip technique.

the test setup and holds. After a rest, participants were asked to perform maximal voluntary force on the vertical axis; once participants attained their maximal values (around 3–4 seconds contraction) they were requested to progressively change the force direction from vertical to antero-posterior (Figure 3). During this period, participants were asked to maximise the antero-posterior force intentionally and they were allowed to increase the forearm angle without changing the lower body and trunk positioning. Trials were stopped at around seven seconds when participants were unable to apply any more force in the antero-posterior direction or when the hand slipped from the hold. All participants performed two maximal contractions per conditions (4 hold depths × 3 finger grip techniques) separated by 3 minute resting periods to avoid any fatigue effect. Participants were instructed to place the fingertips in contact with the backside of the hold for each condition. Fingertip position and the imposed grip techniques were controlled visually. If participants changed the grip technique or the finger position during a trial, it was stopped and performed again. Before each session, holds and participants' hands were cleaned with alcohol. Chalk was used by participants as a natural practice in climbing and holds were cleaned with a brush after each session. Conditions were randomised to avoid any learning or fatiguing effect. All experimental sessions were performed in room climatic conditions which were stable during all experimental sessions.

Data analysis

Force sensor data was filtered with a zero-lag low pass Butterworth digital filter (fourth order, 10Hz). Every trial was analysed for each condition and the highest one of the two trials was identified as maximal voluntary force values for both vertical and antero-posterior direction. A fitting of the results was used to express the force data according to hold depth for each grip technique. Quartic polynomials were fitted directly to the maximal force results of all participants for each grip technique according to hold depth. A fourth order polynomial was chosen as it gave better performance (r^2) than the lower orders (second and third) and polynomials with any higher order did not improve performance. Zero force values were added to the maximal force data for zero hold depth before the fitting process. Kinematic data of the markers were smoothed with an averaged moving window (25 points). At the instant of the maximal antero-posterior force, wrist angle was determined as the angle formed by the hand and

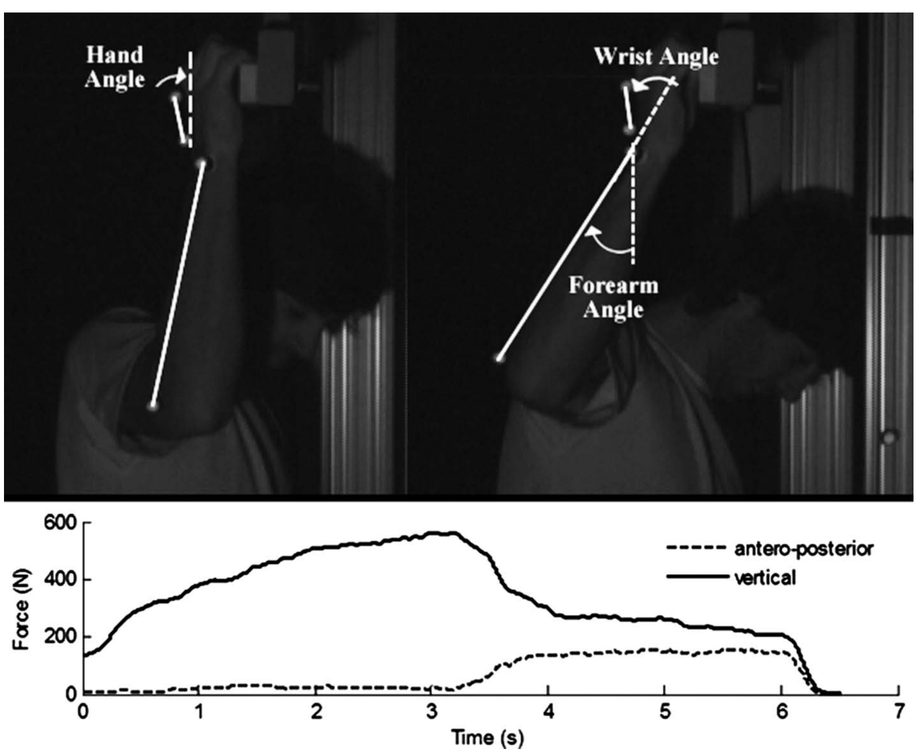

Figure 3. Upper pictures: experimental setup and illustration of the analysed angles. Hand and forearm angles were computed from the positions of corresponding markers with respect to the vertical axis (left picture). Wrist angle was determined as the angle formed by the hand and the forearm markers (right picture). During the test, participants were asked to perform a maximal vertical force and progressively change the force direction to antero-posterior. The second figure illustrates this behaviour by showing the forces along the vertical and antero-posterior directions during one typical trial.

the forearm in the sagittal plane. (Neutral position was defined as the position in which hand and forearm are aligned. This position corresponded to 0° wrist angle value). Meanwhile, hand and forearm angles in the sagittal plane were computed with respect to the vertical axis. Also, the angle between exerted force and vertical axis was computed at the point of the maximal antero-posterior force values. Angle values at the instant of the maximal vertical force were not analysed since the segments were nearly aligned in all conditions. All computation and fitting procedures were performed using MATLAB (The Math Works, Inc., USA).

Statistics

All measured values were reported as means and standard deviations (±). Normality of collected data was verified. Repeated measure Analyses of Variance (ANOVAs) were used to analyse the effect of "hold depth" and "grip techniques" on maximal vertical forces and maximal antero-posterior forces. A Tukey post-hoc was used to identify differences when ANOVA showed a significant effect (P value < 0.05). Statistical analysis was performed in Statistica (StatSoft, Inc. 1984-2005).

Results

Figure 4 presents the maximal resultant vertical forces applied with different grip techniques according to the hold depths. Mean maximal resultant vertical forces ranged from 350.8 ± 56.0 N to 575.7 ± 54.4 N according to the hold depth and the grip technique. Statistical analysis showed that the maximal vertical forces differed significantly according to the hold depth and the grip technique ($F_{3,\,27} = 151.5$, $F_{2,\,18} = 15.9$, $P < 0.05$). Moreover, a significant interaction was shown ($F_{6,\,54} = 10.6$, $P < 0.05$) which means that the effect of the hold depth was different according to the grip technique used. For the half and full crimp grips, the maximum forces were measured on Hold 3 (531.1 ± 40.4 N and 552.3 ± 46.6 N) while with the slope grip the participants performed maximum force on Hold 4 (575.7 ± 54.4 N). For the half crimp grip, the maximal forces increased from 350.8 ± 56.0 N to 490.1 ± 37.4 N and 531.1 ± 40.4 N between Hold 1, Hold 2 and Hold 3 respectively. No differences were found between Hold 3 and Hold 4. For the full crimp grip, resultant forces significantly increased between Hold 1 and Hold 2 and did not change between Hold 2, Hold 3 and Hold 4. For the slope grip the maximal force increased progressively with increasing hold depth. The obtained curves of the polynomial regression (Figure 5) fit well (all r^2 are superior to 0.70) to the experiment data for slope, half crimp and full crimp grip techniques ($r^2 = 0.87$, $r^2 = 0.84$, $r^2 = 0.75$ respectively). Figure 5 presents these curves and their equations compared to the mean experiment results.

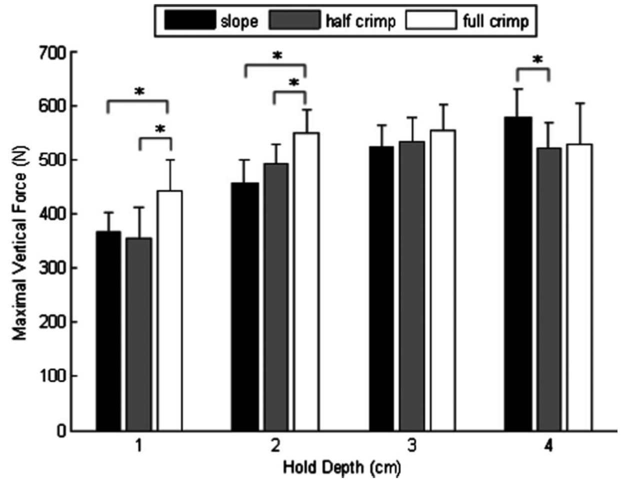

Figure 4. Mean maximal vertical forces (N) with standard deviations according to the hold depth. Significant differences between grip techniques were shown (* $P < 0.05$) for each hold depth.

For Hold 1, participants performed significantly better with the full crimp grip (439.6 ± 55.5 N) than with the half crimp (360.8 ± 34.6 N) and the slope grip (350.8 ± 56.0 N). For Hold 2, resultant mean forces amounted to 435.7 ± 41.59 N, 490.1 ± 37.4 N, 546.2 ± 40.9 N for slope, half crimp and full crimp grip respectively. These forces were significantly different only for slope-full crimp and half crimp-full crimp grips. For Hold 3, the differences in performance for each grip did not achieve significance level. Conversely, the maximal forces were significantly lower for the half crimp (517.11 ± 50.1 N) than the slope grip (575.7 ± 54.4 N) on Hold 4.

The maximal resultant antero-posterior forces applied during slope, half crimp and full crimp grips are presented in Figure 6. Mean maximal forces varied between 69.8 ± 20.0 N and 138.0 ± 43.1 N. Statistical analysis showed that the maximal antero-posterior forces differed significantly according to the hold depth ($F_{3,\,27} = 14.7$, $P < 0.05$). There was no significant effect of grip technique ($F_{2,\,18} = 1.7$, $P = 0.21$) but a significant interaction was noted between hold depth and grip technique ($F_{6,\,54} = 4.3$, $P < 0.05$). The maximum antero-posterior forces were observed on Hold 3 (127.2 ± 35.7 N) for the half crimp, Hold 2 (138.0 ± 43.1 N) for the full crimp and Hold 4 (125.4 ± 37.4 N) for the slope grip. Maximal forces significantly increased between Hold 1 and Hold 2 for all grip techniques. Unlike vertical forces, antero-posterior forces were similar for Hold 2, Hold 3 and Hold 4 for slope grip. For half and full crimp, forces decreased after Hold 3 and Hold 2

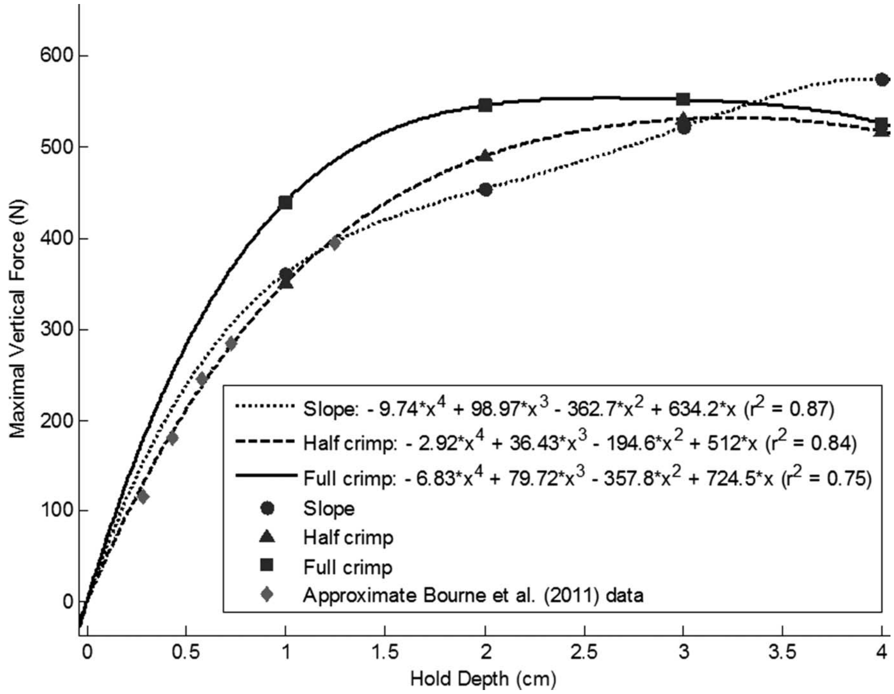

Figure 5. Mean maximal vertical forces (N) and fitted polynomials. The approximate mean maximal force results of Bourne et al. (2011) for half crimp technique are presented according to their graph.

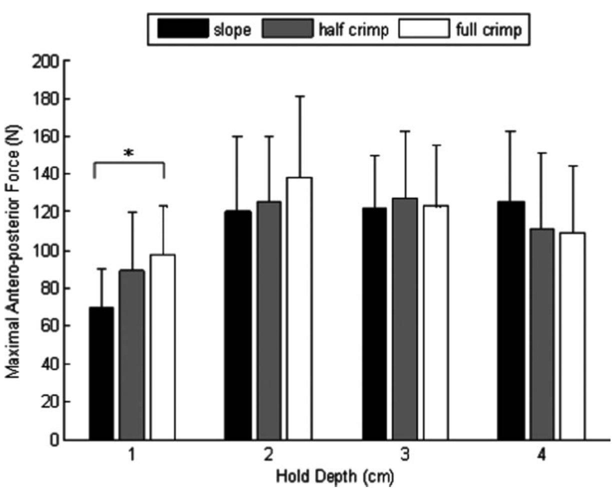

Figure 6. Mean maximal antero-posterior forces (N) with standard deviations according to the hold depth. Significant differences between grip techniques were shown (* $P < 0.05$) for each hold depth.

individually but these decreases were not significant. For Hold 1, participants showed significantly better antero-posterior performance in the full crimp (97.76 $\pm$ 24.98 N) than the slope grip (69.85 $\pm$ 20.0 N). For Hold 2, 3 and 4, there were slight differences between grips but they were not significant.

Kinematic results

Mean segment and joint angles of each grip and hold depths at the maximal antero-posterior force point are presented in Table II. Wrist angle varied between 51.6° $\pm$ 7.8° and 19.1° $\pm$ 14.6° extension. Statistical analysis showed that wrist angle differed significantly according to the hold depth and grip type ($F_{3,\ 24} = 4.3$ and $F_{2,\ 16} = 37.7$, $P < 0.05$). Post-hoc tests showed that for Hold 1 and Hold 2 wrist angles were significantly different between slope and both crimp grip techniques ($P < 0.05$). On the other hand, significant difference was only noted between slope and full crimp grips for Hold 3. Similar to the wrist angle, hand angle differed significantly according to the hold depth and grip type ($F_{3,\ 24} = 4.3$ and $F_{2,\ 16} = 45.5$, $P < 0.05$). Also a significant interaction was noted between hold depth and grip technique ($F_{6,\ 48} = 2.5$, $P < 0.05$). On the other hand, although mean forearm angles were a little bit higher in crimp grip they didn't reach the significant level.

Discussion

This study investigated the relationship between the different grip techniques, hold depths and maximal voluntary contraction values exerted in both vertical and antero-posterior directions. In most published finger force studies, maximal vertical resultant forces were reported between 400 N and 450 N on 1 cm holds for the slope and half crimp grip techniques (Grant, Hynes, Whittaker, & Aitchison, 1996; Quaine & Vigouroux, 2004; Quaine, Vigouroux, & Martin, 2003b; Vigouroux & Quaine, 2006) and 495 N for full crimp technique (Quaine et al., 2011). Although some of the participants performed similar

Table II. Hand, forearm and wrist angles (degrees) at the maximal antero-posterior force point (mean ± *s*).

	Hold 1			Hold 2			Hold 3			Hold 4		
	Slope	Half crimp	Full crimp	Slope	Half crimp	Full crimp	Slope	Half crimp	Full crimp	Slope	Half crimp	Full crimp
Forearm	47.1 ± 10.8	50.5 ± 10.0	50.4 ± 6.6	46.9 ± 9.0	50.5 ± 13.3	50.9 ± 9.9	44.7 ± 9.7	46.6 ± 12.3	48.9 ± 6.6	47.8 ± 7.5	50.5 ± 13.8	50.3 ± 10.2
Hand	21.8 ± 7.2	6.6 ± 7.8	−1.2 ± 5.6	27.9 ± 9.1	10.7 ± 6.4	4.0 ± 11.4	23.3 ± 11.7	15.7 ± 11.0	5.8 ± 11.6	25.6 ± 3.7	15.9 ± 7.9	15.0 ± 13.2
Wrist	25.3 ± 8.1	43.9 ± 11.3	51.6 ± 7.8	19.1 ± 14.6	39.9 ± 8.2	46.9 ± 10.2	21.4 ± 11.9	31.0 ± 19.2	43.2 ± 11.8	22.3 ± 7.0	34.6 ± 14.1	35.3 ± 14.0

values during our experiments, mean results are lower than these previous studies. Possibly different experimental and instrument designs and/or differences between levels of the climbers would cause different maximal forces.

The main results of the current study showed that the maximal vertical forces differ according to the hold depth and the grip technique. Maximal vertical forces increased significantly between 1 cm and 2 cm holds for all grip techniques. This result is in accordance with Grant et al. (1996) who also reported an increase in maximal vertical forces between small and big holds with the half crimp technique.

Although some participants performed better with the half crimp grip than the slope grip technique, we didn't observe any significant difference between these two grip techniques with Hold 1. These results confirm previous studies (Quaine et al., 2003a; Quaine & Vigouroux, 2004; Schöffl et al., 2009) which demonstrated that no biomechanical factors (joint angles, muscle moment arms, external force moment, muscle length...) lead to a better performance between slope and crimp grip techniques. Nonetheless, our results complete these previous observations for larger hold depths. We noticed that for the slope grip, the maximal resultant vertical force increased significantly with increasing hold depth. On the other hand for the half crimp grip, maximal resultant vertical force only increased from 1 cm to 3 cm holds before reaching a plateau. This result is in line with the results of Schweizer and Hudek (2011), who performed *in vitro* experiments on cadaver fingers. These authors observed a maximal force increase according to the position of force application from midnail (~0.8 cm hold depth) to DIP followed by a plateau for a second phalange position (in between DIP and proximal interphalangeal (PIP)) during the half crimp grip. We observed a similar form for the full crimp grip but the plateau was noted near the 2 cm hold. These different forms and plateau points were probably related to the difficulty of making a crimp grip on the larger holds. Hyper-extension of the distal interphalangeal joint in a half crimp grip indeed limits the use of finger phalanxes on the hold. Because of the hyper-extension, the proximal ends of the second phalanxes go higher and second phalanxes don't contact with the hold surface completely. In addition, when climbers put their thumb on the other fingers for full crimp technique they need to make their fingers a little bit steeper. So only the first phalanxes can be used and the plateau point gets smaller for this grip. On the other hand, using the thumb increased the maximal vertical finger strength by nearly 20% on small holds (1 cm and 2 cm). This result agrees with the results of Quaine et al. (2011). No plateau was observed for the open grip but we believe that such a plateau would obviously appear for bigger holds where the lengths of the fingers are inferior to the hold depth (>4 cm depth). To summarize, our results showed that the finger-hold interaction parameters enhanced the performance of one or other technique according to the hold depth. It thus seems that choosing one or other techniques is not primarily due to internal biomechanical factors (muscle length, moment arms, joint angle...) but more in order to optimise the finger-hold contact/interaction. However, this hypothesis should be further verified *in situ* with an experiment in which finger grip techniques are not imposed on climbers.

Concerning the antero-posterior maximal forces, we also showed a significant increase from the 1 cm to 2 cm hold for all grip techniques followed by a plateau or a decrease on force values. In addition, a difference between grip techniques was considered for Hold 1 and 2 but not for Hold 3 and 4. Consequently, one or other technique is not predisposed to better manage the antero-posterior forces which are fundamental for body posture equilibrium. However, the joint and segment angles at the point of maximal antero-posterior force indicated that participants have different hand-forearm posture strategies for slope and crimp grip techniques. Especially considering that participants used nearly vertical hand positioning and a larger wrist extension (caused by the increased forearm angle) with the crimp grip; whereas both the hand and forearm were more inclined (which lead to a smaller wrist extension) with the slope grip. These results indicate that with crimp grip technique wrist angle can be modified and this is used as a strategy to keep the fingers in place and maximise the contact between the fingers and the hold. In contrast, with the slope grip technique wrist angle is more stable and the entire arm has to be inclined. This would be an advantage for the crimp grip as climbers have more liberty to adjust body posture with the fixed hand. Moreover, the position of the wrist directly affects the length of the finger flexor muscles and maximal finger force capacity (Li, 2002). When climbers extend their wrists, the finger flexors lengthen and come into the passive/elastic phase which is more efficient. This would be used by climbers as a strategy to compensate the more flexed positions of the finger joint in a crimp grip. In this study, we only experimented on flat surface holds; there may be different effects of grip techniques on antero-posterior forces when the holds are incut. Further analysis is required to clarify this issue.

In addition, a polynomial regression was used to model the relationship between hold depth, grip techniques and maximal force capacity. From a general point of view the regression models had good quality and could be used to predict the mean maximal force based on hold depth and grip technique. In a very recent study, Bourne, Halaki, Vanwanseele, and Clarke (2011) reported a maximal vertical force increase between four different sizes of holds which ranged from 2.8 mm to 12.5 mm for the half crimp technique. Moreover, they reported that there is no correlation between maximum lifting forces on big holds and really small holds. Based on this, they pointed out that the lifting force generated on the small edges (<5 mm) could not be predicted by the lifting force on big holds. Conversely, using our polynomial regression model and extrapolating maximal force data for the little holds used in their study, we noticed that results of our model correspond with their maximal force data on the small edges. Based on their graph, differences between our estimations and their mean data are less than 10 N (Figure 5). It thus seems that it is possible to make an estimation model for maximal force capacity according to hold depth. Although our models were investigated for only a limited expertise level, these models can be used as a global index to predict the change of maximal forces according to hold depth. Nevertheless, it should be considered that different levels of expertise (beginners, intermediate, advanced and elite), different anatomical individual characteristics and climber skill also change the maximal force capacities. In this study, the effect of the thumb to make a pinch grip wasn't considered. But, as indicated in the literature, grip width also affects the maximum handgrip forces (Hoozemans & Dieën, 2005). The effect of the hold size on maximal force capacity for the pinch grip may be further analysed with more climbing specific devices and this relationship can be modelled. Such models for different grip techniques may be further improved and used by hold designers to make better classifications of difficulty levels of the holds, by trainers to arrange the intensity of training plans more precisely and by clinicians in order to discriminate the most appropriate hold for each grip technique used.

Conclusion

To conclude, this study pointed out that differences in performance between grip techniques are more due to hold/finger interaction than biomechanical factors. Thus, the slope grip allows the climber to increase the force progressively with hold depth while the crimp technique is better adapted for small hold depths and reaches a limit for larger holds. The effect of grip technique on antero-posterior forces is not different to the effect on vertical forces which suggests that the requirement of body posture equilibrium doesn't influence the choice of grip technique. However, when exerting antero-posterior forces the strategy used to optimise contact with the hold differs between the crimp and slope grip techniques and this could have an impact on the positioning of the body. Nonetheless, further examination is necessary to identify these interactions with varying friction characteristics and incut shape of holds.

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