Four Weeks of Finger Grip Training Increases the Rate of Force Development and the Maximal Force in Elite and Top World-Ranking Climbers

Article *in* The Journal of Strength and Conditioning Research · August 2017

DOI: 10.1519/JSC.0000000000002230

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Four Weeks of Finger Grip Training Increases the Rate of Force Development and the Maximal Force in Elite and Top World-Ranking Climbers

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Abstract

Levernier, G and Laffaye, G. Four weeks of finger grip training increases the rate of force development and the maximal force in elite and top world-ranking climbers. *J Strength Cond Res* XX(X): 000–000, 2017—The goal of this study was to assess the impact of a specific 4-week training program on finger grip in climbers; specifically, on the maximal force and the rate of force development (RFD) of finger muscles in isometric contraction. The participants were 14 French male rock climbers who took part in national and international bouldering competitions (at world-ranking and elite levels). They were divided into 2 samples. The experimental group performed a specific 4-week training program that included such exercises as suspensions on small holds at the rate of 3 times a week. The control group performed climbing exercises only. The maximal force and the RFD were recorded using a specific dynamometer in 3 different holding conditions (slope crimp, half crimp, and full crimp). Results reveal a significant gain of force for the slope crimp (+8%) and a high increase of the RFD in the first 200 ms of the force-time slope (between 27.5 and 32% for averaged conditions), suggesting a neural gain rather than a change in muscle-tendon structure. These results reveal that a 4-week training program is enough to improve the level of maximum force and the RFD in elite climbers. Bearing in mind that climbing will make its appearance in a future Olympic Games in the form of a combined competition, i.e., bouldering, speed climbing, and lead climbing, it will be crucial for each athlete to develop both a high level of force and RFD to be competitive.

AU4 **Key Words** field testing, training and, testing, bouldering, flexor digitorum profundus, flexor digitorum superficialis

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Journal of Strength and Conditioning Research

Introduction

Climbing is a performance sport that includes sub-disciplines, such as lead climbing, bouldering, and speed climbing. Bouldering is performed without the use of ropes or harnesses and is characterized by a succession of short complex movements on a climbing structure not exceeding 5 m in height. The movements necessitate a high level of coordination and physical ability. Climbing was recently approved to be included in the 2020 Olympic Games in Tokyo. The results of the 3 aforementioned sub-disciplines will be combined. In such a context, the motivation for improving performance factors is clear, especially for bouldering, which is one of the 3 events in the future Olympic Games. In recent decades, several studies have demonstrated that climbing performance is a combination of psychological factors (26), neuromuscular factors (15,28,37), tactical and technique factors (25), and anthropometric variables (23,28).

When focusing on bouldering, literature shows the importance of finger grip strength for elite boulderers. Averaged values range from 278 ± 18 to 459 ± 23 N according to various studies that have dealt with this topic (20,23,27) revealing the major role of flexor digitorum profondus (FDP) and flexor digitorum superficialis (FDS) in AU5 bouldering. Indeed, a recent study (20) revealed that elite climbers have a 20% higher value of finger grip strength than skilled ones and one that is 62% higher than for novices. Indeed, although there is a difference in strength in the flexor muscles of climbers' and nonclimbers' fingers (20,23), the force of the hand flexor muscles during an isometric effort between elites and novices (450 ± 122 N for the novices vs. 567 ± 121 N for the elite) does not diverge. The typical time for a bouldering attempt is about 30 seconds with an effective static phase of 7.5 seconds and a dynamic phase of 22.5 seconds (39). The dynamic phase is made up of explosive movements that require the grip to hold as strong and as fast as possible.

Moreover, the maximal force depends both on the level of expertise (16,38) and on the kind of hold used (i.e., slope, half crimp, or full crimp) (2). Climbers are able to deliver a higher

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level of force with a full crimp compared with a half crimp (439.6 ± 55.5 vs. 360.8 ± 34.6 N), whereas no difference has been found between the slope crimp and the half crimp (350.8 ± 56.0 N) (2).

Furthermore, the way the force is produced seems crucial. The change in force over time, namely the rate of force development (RFD in $N \cdot s^{-1}$), is highly dependent on the slope of the force until the maximal value or a percentage of this value. This variable is highly critical in several sports, such as sprinting or jumping (22), but has rarely been investigated in climbing. Indeed, several sports feature athletic movements that are shorter than the time necessary to achieve the maximum force (5). Typically, for lower limbs, the peak force occurs within around 250 ms (18), whereas athletic movements are of a lower duration; for example, in sprinting ≈100 ms (7), long jumping ≈160 ms (22), or high jumping ≈200 ms (11). Up to now, little is known on the way the force is produced during bouldering, except on the maximal and mean force (12). Only 1 study (14) reveals the crucial role of RFD to discriminate boulderers from lead climbers of comparable level of expertise during an isometric test of flexor finger, with a +36.7% higher value observed in boulderers. The authors conclude that "the RFD may reflect the specific requirements of bouldering and seem to be more appropriate than pure maximal strength for investigating muscle function in rock climbers." This higher value of RFD could be explained by the several situations requiring a high level of force to be used in a short time, such as the "dyno," which consists in jumping with arms in an aerial phase, during which time the climber is no longer in contact with the wall. If complementary studies should be done for a better understanding of the different movements in bouldering and their specific constraints of force and time, it seems obvious, based on the literature, that increasing the level of finger flexor strength and the RFD with training seems crucial for improvements in performance.

To the best of our knowledge, only 1 study has investigated the gain obtained with training. Medernach et al. (27) divided a sample of skilled climbers into 2 groups. The first group followed a specific training program, whereas the second one climbed freely without any special instruction. The training cycle lasted 4 weeks with 3 workouts per week. The sessions were performed on a fingerboard and the exercises lasted between 5 and 10 seconds. They solicited isometric and concentric muscular actions by grasping the grip in different positions. Results show that the "trained" group was able to hold the different grips for longer (12.5 ± 2.5 seconds vs. 8.6 ± 2.0 seconds for the full crimp and 11.4 ± 2.7 seconds vs. 9.2 ± 2.4 seconds for the slope crimp). If this study gives interesting information on the impact of a fingerboard training on the ability of holding a crimp as long as possible, little is known about the impact on maximal finger force. Nevertheless, to date, no study has dealt with the impact of training on the flexor muscles of the fingers for a sample of elite climbers in terms of the strength and RFD.

Based on this theoretical background, we hypothesize that a specific 4-week training program focusing on finger grip in world top-ranking climbers increases the maximal force and the RFD.

Methods

Experimental Approach of the Problem

The experiment took place between November 2016 and January 2017, so as not to clash with any competitive event. The subjects were elite and top world-ranking climbers, with a mean training frequency of 6 times a week. Recruitment was supported by the French national team's coaches and was based on the criteria of a minimal skill level and participation in national or international competitions. The goal of the study was to test the impact of a 4-week training program on finger grip force and the RFD. For this purpose, the 14 climbers participating were randomly divided into either the control group (7 climbers) or the experimental group (7 climbers). One week before the training cycle began, they visited the laboratory on 2 occasions to have force and anthropometric measurements taken. They returned 1 week after the cycle. The training program was designed in conjunction with the French national team's coaches and was repeated 3 times a week for 4 weeks. The other 3 training sessions involved regular exercises. Finally, the protocol did not change the frequency of training for both groups (6 regular climbing training sessions for the control group vs. 3 regular and 3 designed training sessions for the experimental group).

Subjects

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Fourteen French male rock climbers who take part in national and international bouldering world-ranking competitions participated in this study. The criteria to be included in the sample were as follows: a level higher than 8b Fb and YDS: 5.13d (Fb corresponds to Fontainebleau, a rating scale used in bouldering and YDS for Yosemite decimal system), minimum training experience of 5 years and no injury to the hands or the upper limb for the past year. All the climbers were ranked among the 20 top climbers in France for the 2015–2016 season; of these, 6 of them were in the top 20 world-ranking climbers. They were fully informed about the protocol before participating in this study and they signed an informed consent form. This research protocol was conducted according to the principles of the Declaration of Helsinki on human research.

Procedures

Each climber observed a 2-day resting period before each test to avoid the effect of fatigue caused by earlier climbing sessions. The test took place in the Karma Room at the French climbing center (Route Militaire, 77,300 Fontainebleau). Athletes received the same 10-minute warm-up followed by a period of 30 minutes of exercise during which they climbed on the same structure, starting at low intensity and ending with high-intensity movements. They performed

AU15 **Figure 1.** Slope (A), half crimp (B), and full crimp grip (C). The slope crimp is characterized by a flexion of the distal interphalangeal (IPD) and a little flexion of the proximal interphalangeal (IPP). For the half crimp, the angle of the IPP is 90° with an extension for the IPD. For the full crimp, the thumb closes the other fingers with a hyperextension for the IPD and an angle for 90° for the IPP.

the test at the same time of the day (10 AM) and in the same place to eliminate any influence of circadian variation or changes in ambient conditions (20 ± 0.5° C). Finally, they had 10 minutes to familiarize themselves with the material of the experiment (i.e., the dynamometer on the climbing wall). Subjects stood with 1 hand on the dynamometer. The angle between the arm and the chest was 20° in the sagittal plane and the angle between the arm and the forearm was set to 90°. During the test, the subjects were advised not to move. The other arm stayed still along the body. Three different holds were selected (i.e., the slope crimp, half crimp, and full
F1 crimp, Figure 1). These brought into play the flexor digitorum profundus (FDP) muscle and the flexor digitorum superficialis (FDS) muscle as the main muscles (2).

Climbers in the first group climbed regularly but did not follow a specific training program during the experiment. Subjects in the experimental group performed a specific training program 3 times a week for 4 weeks, which involved exercises with suspensions on small holds. The exercises were designed in conjunction with the French team's coach
T1 and consisted of a series of isometric-type exercises (Table 1 for details). The climbers were in a standing position, hanging from a personalized small hold (slats ranging from 25 mm to 6 mm off the mark 180°) (rue des dolmens, 46,220 Prayssac) and HRT (Mladost 4, 1715 Sofia, Bulgaria) with 1 hand. They had to hold on as long as possible without AU8 making contact between the foot and the ground, before falling with a 120° angle between the arm and the forearm (Figure 2). The other hand did not touch down. F2

The size and the grip of the hold were chosen individually in such a way that athletes could not stay in 1 hold for more than 6 seconds. To limit the risk of injury, climbers warmed up their upper limbs with suspensions that used a large degree of prehension (easier than those used in training).

TABLE 1. Training plan for the experimental group.*

No. of series: 2	
No. of exercises/series: 6	
Time of recovery between each exercise: 3 min	
Slope crimp	Time of effort: 4–6 s
Half crimp	Time of effort: 4–6 s
Half crimp	Time of effort: 4–6 s
Slope crimp	Time of effort: 4–6 s
Half crimp	Time of effort: 4–6 s
Half crimp	Time of effort: 4–6 s

*This training is performed 3 times a week during 4 weeks.

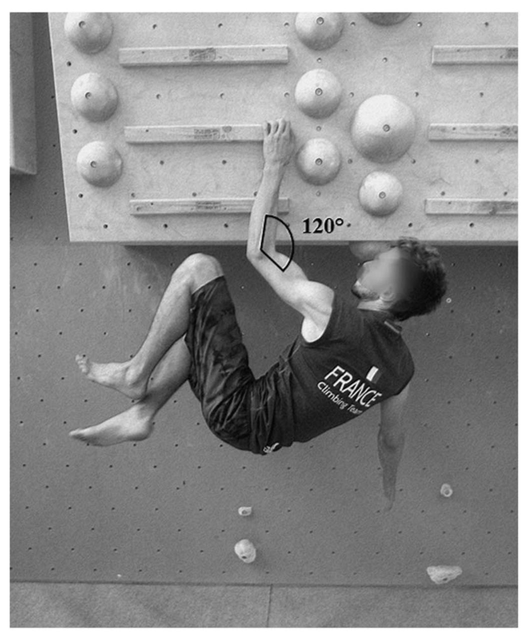

Figure 2. Training exercise for half crimp in no foot. The crimp is individually chosen to be held between 4 and 6 s with an elbow angle about 120°.

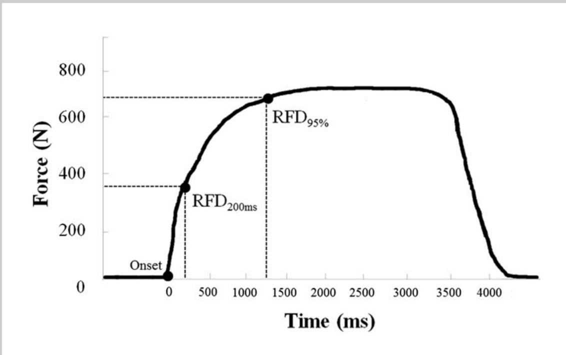

Figure 3. Typical force-time curve during an isometric contraction of finger during a slope crimp. The rate of force development (RFD) is defined as the mean value of the slope between the onset and 200 ms of the maximal force ($RFD_{200\ ms}$) and between onset and 95% of the peak of force ($RFD_{95\%}$).

In addition, if pain occurred during the exercise, they immediately had to stop. This exercise was repeated for both hands in both conditions (slope and half crimps), with the training plane detailed in Table 1. The training session lasted about 45 minutes.

Anthropometric Variables. The following variables were measured: height (in meters); percentage of fat (%); "Arm span," defined as the size of the arm; and the "APE index," defined as the ratio between the arm span and the height. Anthropometrical data were recorded using an anthropometer with 0.1 cm accuracy and with an impendency balance, "InnerScan," Tanita BC 545n (TANITA, Amsterdam, the Netherlands). This allowed us to measure variables such as body mass (BM), and body fat (BF %), with 0.1% accuracy.

Force and Rate of Force Development. Maximal force and RFD were assessed using a dynamometer "power grip manipulandum," PGM (SENSIX, biopôle, 4 rue Carol Heitz- 86,000 Poitiers), with dimensions of 120 × 45 × 25 mm, weight of 320 g, and sensitivity of 0.166%, calibrated at a frequency of 100 Hz. This dynamometer is powered by 5v and is connected to the computer with an acquisition card. The data can be processed by specific software and are stored in the computer for further analysis.

With regard to the type of grip, the slope crimp is characterized by a flexion of the distal interphalangeal (IPD) and a small flexion of the proximal interphalangeal (IPP). For the half crimp, the angle of the IPP is 90° and 0° for the IPD, with an extension for the IPD. Finally, for the full crimp, the thumb closes the other fingers with a hyperextension of the IPD and an angle of 90° for the IPP.

The instructions were to "hold the device as strongly as you can and as fast as possible" to optimize both variables (24): maximal force and RFD. Data were recorded using PGM software and then exported to Excel 2010 for further calculation of the biomechanical variables, i.e., maximal force and RFD. We used the systematic method detailed in a study by Tillin et al. (34) to determine the contraction onset of the unfiltered force-time curve recorded manually; in other words, the instant at which the force increased at a threshold of 4 N to obtain a robust onset of force. This method has been shown to be reliable and time efficient (3). Considering the importance of being able to accurately detect the onset and high variation of RFD, the force signal was not filtered or smoothed to maintain baseline noise and to prevent time shifts, as proposed by Maffiuletti et al. (24). The RFD was then measured in 2 ways, in line with the definition put forward by Aagaard et al. (1). First, we measured the explosive muscle strength as "the rise in the contractile force at the onset of contraction, i.e., the RFD exerted within the early phase of rising muscle force, within the initial 100–200 ms of contraction." The RFD was also measured from the onset to 200 ms ($RFD_{200\ ms}$) to assess what is called the "explosive muscle strength." Last, we calculated the absolute RFD, i.e., the time between the onset and the value of force obtained during the plateau of force, corresponding to the total contractile impulse than can be produced until the maximal force is achieved (24). Considering that the typical curve during the isometric contraction shows a maximal value of force that plateau over a long period, at either the beginning, middle, or end of the plateau, we chose a value of 95% of maximal force to calculate the total rate of force between the

Table 2. Anthropometric characteristics of the experimental (training) and control groups.*†

	Age (y)	Height (cm)	BMI (kg·m^{-2})	Arm spam	APE index	Weight (before training) (Kg)	Weight (after training) (Kg)	% Of body fat (before training)	% Of body fat (after training)
Control	26.1 ± 1.2	173 ± 5	21.7 ± 1.9	178.1 ± 8	1.02 ± 0.1	64.5 ± 3.3	64.0 ± 3.5	9.2 ± 1.4	9.3 ± 1.4
Training	26.1 ± 3	175.9 ± 6	20.9 ± 2.1	180.6 ± 9	1.02 ± 0.1	63.9 ± 3.6	64.2 ± 3.2	8.7 ± 3	9.0 ± 2.5

*BMI = body mass index; APE index, ratio of arm span to height.
AU16 †No statistical difference was found for any variable and no difference between before training.

onset and the final slope and not during the plateau when force is maintained. This parameter was also called $RFD_{95\%}$ F3 (Figure 3).

Statistical Analyses

Descriptive statistics were used to verify that the basic assumption of normality for all the studied variables was correct. Statistical tests were processed using STATISTICA software (version 10, StatSoft, Inc.). For each grip condition (slope crimp, half crimp, and full crimp), 3 trials were performed in a random order to avoid order effect.

To check the reliability of our method, the intraclass correlation (ICC) and the coefficient of variation (CV) were calculated. For the 3 conditions, the ICC ranged between 0.833 and 0.979 and the CV between 4 and 6%. According to Atkinson and Nevill (4), an ICC >0.8 and a CV <10% are guarantees of excellent reliability. The maximal force F_{max} was studied in terms of absolute and normalized values by dividing it by the weight of the climber. Indeed, the strongest climber would be the one who would be able to develop the most force with the smallest mass possible (23).

An analysis of variance (ANOVA) was performed with repeated measurements of the time (before and after training), with the group as an inter-subject factor and training as an intra-subject factor to compare the differences of gain between the 2 groups. When the ANOVA was significant, a Fischer's post hoc test and power (1-β) were performed. For all statistical analyses, significance was set at AU9 $p \le 0.05$ and effect size (η^2) was defined as small for $\eta^2 > 0.01$; medium $\eta^2 > 0.09$; and large for $\eta^2 > 0.25$ (10).

Results

T2 The anthropometric data are summarized in Table 2; no differences between groups were observed. Furthermore, no difference was found before and after training for the mass of the climbers (less than 1%).

Maximal Force

There were no significant differences between the experimental group and the control group when variables were expressed in absolute values. Nevertheless, the normalized values did reveal a significant effect for the right slope crimp ($F_{(1.12)} = 7.56$; $p = 0.02$, $\eta^2 = 038$ and $\beta = 0.71$). The post hoc Fisher's test revealed an effect of training for the experimental group ($p = 0.03$) and in the posttest between both groups AU10 T3 ($p = 0.02$) (Table 3).

Rate of Force Development

For the experimental group, the mean values for $RFD_{95\%}$ were 379.66 ± 182.75 $N\cdot s^{-1}$ before training and 398.87 ± 161.92 $N\cdot s^{-1}$ after training, for the full crimp; 342.12 ± 150.15 $N\cdot s^{-1}$ and 423.41 ± 195.93 $N\cdot s^{-1}$ for the slope crimp; and 343.92 ± 150.30 $N\cdot s^{-1}$ and 414.74 ± 138.86 $N\cdot s^{-1}$ for the half crimp. For the control group, the mean value was 295.4 ± 162.45 $N\cdot s^{-1}$ before training and 322.89 ± 182.60 $N\cdot s^{-1}$ after training, for the full crimp; 367.04 ±

Table 3. Normalized (force divided by body weight Fn) and absolute finger grip force (F) for the 3 hold conditions.*

	Control group			Training group			
Crimp	Pretest	Posttest	Difference (%)	Pretest	Posttest	Difference (%)	ANOVA
Fn slope L	0.72 ± 0.05	0.75 ± 0.06	4	0.83 ± 0.05	0.91 ± 0.06	8.8	NS
F slope L	459.51 ± 62.68	468.70 ± 59.65	2.0	521.55 ± 36.15	566.54 ± 64.44	7.9	NS
Fn slope R	0.75 ± 0.05	0.71 ± 0.07	−5.6	0.82 ± 0.05	0.88 ± 0.07	6.9†	$F_{(1,12)} = 7.56$ $p = 0.02$
F slope R	476.55 ± 74.38	448.57 ± 84.62	−6.3	509.79 ± 51.28	548.11 ± 69.15	7	NS
Fn half L	0.74 ± 0.05	0.75 ± 0.06	1.4	0.83 ± 0.05	0.88 ± 0.06	5.7	NS
F half L	468.74 ± 61.89	472.42 ± 70.22	0.8	517.98 ± 51.23	548.13 ± 55.38	5.6	NS
Fn half R	0.76 ± 0.05	0.75 ± 0.05	61.3	0.83 ± 0.06	0.89 ± 0.06	6.8	NS
F half R	484.84 ± 66.64	467.74 ± 46.69	−3.7	517.23 ± 64.88	551.04 ± 52.48	6.2	NS
Fn full L	0.65 ± 0.07	0.66 ± 0.08	1.6	0.82 ± 0.07	0.87 ± 0.08	5.7	NS
F full L	415.65 ± 84.44	411.94 ± 91.26	−0.9	505.68 ± 40.86	535.89 ± 33.72	5.7	NS
Fn full R	0.71 ± 0.08	0.69 ± 0.08	−2.7	0.82 ± 0.09	0.87 ± 0.08	5.8	NS
F full R	448.84 ± 75.74	434.51 ± 105	−3.3	508.13 ± 43.84	535.29 ± 38.22	5.1	NS

*ANOVA = analysis of variance; L = left hand; R = right hand.
†When statistical difference at $p < 0.01$.

AU17

240.60 $N \cdot s^{-1}$ and 377.44 $\pm$ 240.65 $N \cdot s^{-1}$ for the slope crimp; and 357.70 $\pm$ 142.27 $N \cdot s^{-1}$ and 305.89 $\pm$ 125.66 $N \cdot s^{-1}$ for the half crimp. There is no significant difference in $RFD_{95\%}$ between the experimental and control groups.

Concerning the $RFD_{200\ ms,}$ difference was found for any
F4 condition (Figure 4). For the right slope crimp, a significant effect was found ($F_{(1,12)} = 9.62$; $p = 0.009$, $\eta^2 = 0.44$ and $\beta = 0.812$) between the experimental and control groups. The post hoc Fisher's test reveals an effect of training for the experimental group ($p \leq 0.05$). For the left slope crimp, a significant effect was found ($F_{(1,12)} = 10.13$; $p = 0.008$, $\eta^2 = 0.46$ and $\beta = 0.83$) between the experimental and control groups. The post hoc Fisher's test reveals an effect of training for the experimental group ($p \leq 0.05$). For the half crimp, a significant effect was found with ($F_{(1,12)} = 11.18$; $p = 0.006$, $\eta^2 = 0.48$ and $\beta = 0.86$) for the right hand and ($F_{(1,12)} = 10.18$; $p = 0.006$, $\eta^2 = 0.47$ and $\beta = 0.85$) for the left between the experimental and control groups. The post hoc Fisher's

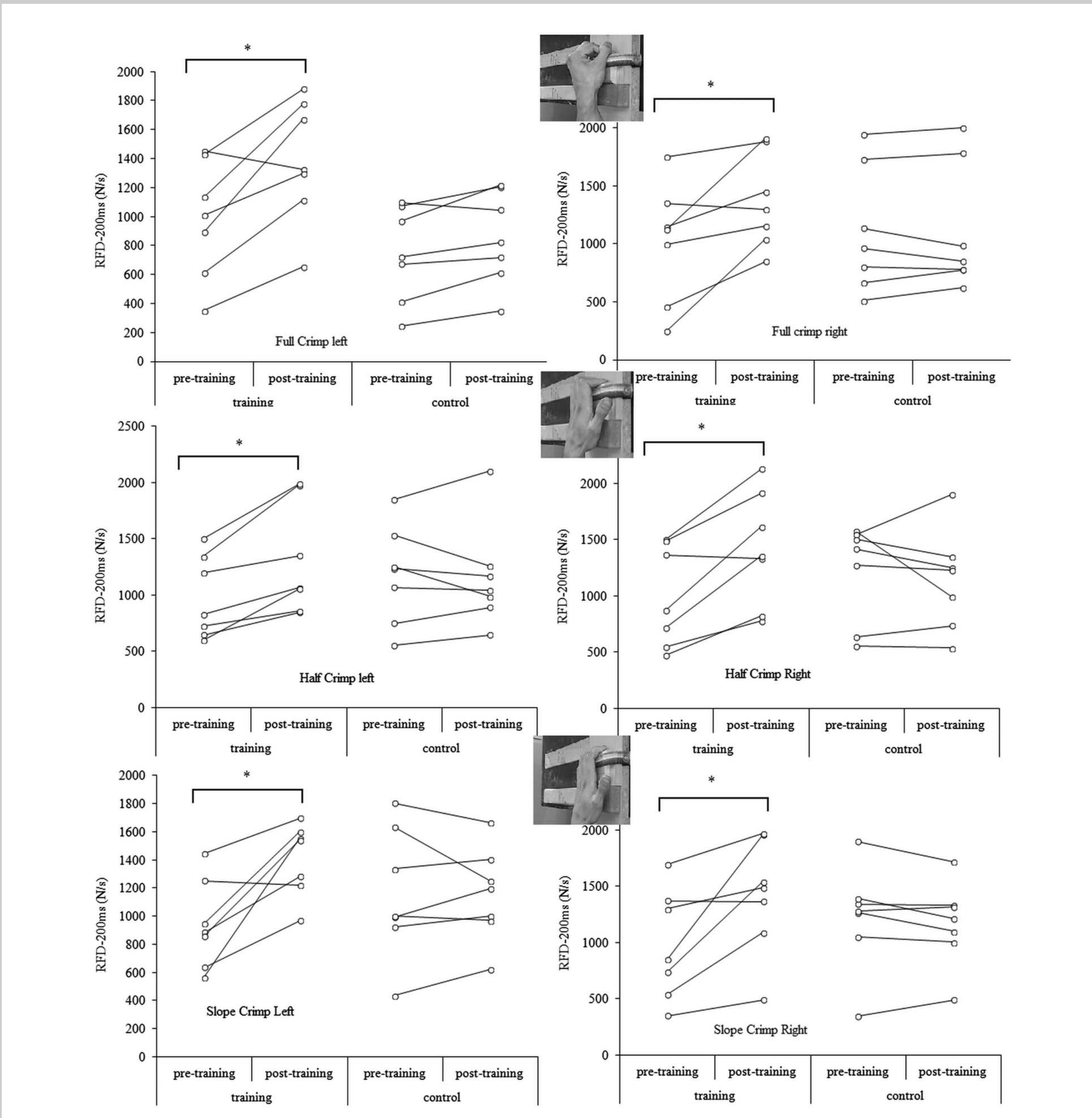

Figure 4. Individual changes of the rate of force development (RFD) at 200 ms before and after protocol for training group (left) and control group (right) for the full, half, and slope crimp. *Significant changes at $p \leq 0.05$.

TABLE 4. Result for $RFD_{200\ ms}$ ($N \cdot s^{-1}$) before and after training for the experimental and control groups.*

	Training group			Control group		
Crimp	Pretest	Posttest	Difference (%)	Pretest	Posttest	Difference (%)
Slope L	942.00 ± 314.68	1,407.50 ± 259.23	33.1†	1,161.29 ± 464.49	1,157.29 ± 334.57	<1
Slope R	978.29 ± 488.06	1,412.86 ± 513.52	30.9†	1,225.14 ± 465.21	1,168.29 ± 374.15	−4.2
Half L	978.86 ± 363.97	1,304.71 ± 491.46	25.0†	1,177.14 ± 441.62	1,158.29 ± 460.41	<1
Half R	995.50 ± 446.02	1,418.79 ± 510.75	29.9†	1,215.00 ± 436.17	1,142.79 ± 445.43	−6.3
Full L	983.86 ± 405.88	1,386.79 ± 428.86	30.1†	742.00 ± 328.16	851.43 ± 323.01	13.1
Full R	1,011.79 ± 513.74	1,366.86 ± 407.07	26.0†	1,106.79 ± 540.15	1,112.86 ± 545.34	<1

*L = left hand; R = right hand.
†When statistical difference at $p \leq 0.05$.

test reveals an effect of training for the experimental group ($p \leq 0.05$) for the left and right half crimps. Last, for the full crimp, a significant effect was found ($F_{(1,12)} = 7.36$; $p = 0.02$, $\eta^2 = 0.38$, with $\beta = 0.70$) for the right hand ($F_{(1,12)} = 6.39$; $p = 0.026$, $\eta^2 = 0.35$, with $\beta = 0.641$) and for the left hand between the experimental and control groups. The post hoc Fisher's test reveals an effect of training for the experimental group ($p \leq 0.05$) for the left and right full crimps. No difference was found for the control group between pretest and posttest. All averaged values are summarized in Table 4. T4

DISCUSSION

AU11 The anthropometric characteristics of both samples are similar to those of elite climbers in the literature. Indeed, top-ranking and elite climbers in our study were thin (BM: 64.2 ± 3.5 kg) and lean (BF = 8.9 ± 2.2%), with a body mass index of 21.3 ± 2.0 $kg \cdot m^{-2}$, and an ape index of 1.02 ± 0.1. AU12 These values are close to those found in the literature for climbing, with averaged BM values of between 60 and 70 kg (36), BF percentage of between 5.1 and 9.2% (25,36), and an ape index of about 1.02 (20), showing that climbers have a longer arm span relative to their body size. This characteristic is very advantageous in climbing competition (19,25) allowing to take the holds more far and easily.

No significant difference between training and control groups (<1%) was found for any of the anthropometric variables. Moreover, pretest and posttest intra-subject differences were negligible (<1%). Thus, this lack of difference legitimizes the normalized measurement of maximal force. Indeed, the ratio of strength-to-body weight has been shown to be a determining factor of climbing ability (20,28).

The results for the experimental group before training show a mean value of 515 ± 43.5 N for the slope crimp, 517 ± 57.5 N for the half crimp and 507 ± 41.5 N for the full crimp. This is in line with previous studies of elite climbers, which recorded a mean value of 552 ± 42 N for the slope crimp (14), 532 ± 23 N for the half crimp (16) and 494 ± 64 N for the full crimp (23). These slight disparities with the literature (about 5%) can be explained by small variations in the initial position of the body. In our study, the arm was in the sagittal plane, with an angle of 20° with the body and an elbow angle of 90°. This probably allowed a small amount of force from the lattisimus dorsi to be made from a small contribution of the shoulder adduction during the isometric contraction. In the Fanchini study, the athlete was seated, with the arm and forearm stretched out (14), thus allowing for a higher contribution of scapulae muscles. Moreover, in the Laffaye study, the climbers were seated, with their arms resting on a table (20), thus reducing the contribution made by the lattisimus dorsi.

Our results show slight (less than 5%) and insignificant differences in the force developed as a function of grip conditions. To the best of our knowledge, only Amca's study with experienced climbers compared the values between these 3 grip techniques, revealing that climbers develop more force (+11%) in the full crimp (546.2 ± 40.9 N) compared with the half crimp (490.1 ± 37.4 N) and the slope crimp (+21%); (435.7 ± 41.6 N) (2). Moreover, a recent study (30) has shown that using the thumb during a hold produces an increase in the force of finger flexor of 12% (442 ± 42.9 N without thumb vs. 494 ± 68.8 N with thumb) during the full crimp. In our study, the results for the experimental group, before training, showed a maximal force for the half crimp of 517 ± 57.5 N, as opposed to 507 ± 41.5 N for the full crimp. These close and insignificant differences between the 2 crimps is contrary to the literature and can perhaps be explained by the fact that many of the French team's climbers prefer the half crimp and slope crimp for fear of injury when using the full crimp (17,29,31). Indeed, in the full crimp, the A2 and A4 pulleys (rings that hold the FSP and the FPF) are subjected to maximum pressure with the thumb closed (17,31), and in the event of overloading, can even break. Amca et al. (2) recorded during the full crimp a tension of 254.8 N on the A2 pulley, whereas the A4 pulley received 220.9 N, for an external force of 95.6 N. On the contrary, in the slope crimp the tension was much lower (57.4 N for the A4 and 8.1 N for the A2 for the same external force) (35). According to Schweizer (32) in the full crimp position, at 25% of maximum strength, the A2 pulley received 3 times as much force applied on the fingers. Both these studies highlight a linear relationship between external force and tension for the A2 and A4 pulleys (35). These data suggest that for 505 N, which was developed by the climber of our study in the finger grip, the pressure of pulleys A2 and A4 received an overload that could damage this passive anatomic structure. Thus, it seems more reasonable to use the half crimp and the slope crimp in training rather than the full crimp to avoid injury.

With regard to the normalized values, there was a training-related increase for the right slope grip of 8% (0.82 $\pm$ 0.05 $N \cdot kg^{-1}$ before training vs. 0.88 $\pm$ 0.07 $N \cdot kg^{-1}$ after training). During the training modalities, the climbers had to make suspensions with a slope crimp grip, which may explain why the gain was obtained in the same conditions. This result is comparable to Maurizio's study of skilled climbers, which was based on a 4-week training program and gave results of a 5% increase in the half crimp. It also revealed that a 4-week training plan based on finger flexor muscular conditioning was sufficient to increase strength in elite climbers (14). The other conditions did not reveal any significant difference between the pretest and the posttest conditions for the experimental group, despite a slight increase of the maximal force for the full crimp and the half crimp (5.3 and 7.5% difference between the pretest and posttest for the full crimp and the half crimp). If insignificant, this reveals a possible transfer of force between the 3 conditions.

To the best of our knowledge, only 1 study has investigated the evolution of RFD for finger flexor with isometric contractions (14) in rock climbing. In this study, the authors showed normalized values of about 48 $\pm$ 18 $N \cdot s^{-1} \cdot kg^{-1}$ for the full crimp. By standardizing these values to our units, boulderers can be seen to produce about 3,300 $\pm$ 1,200 $N \cdot s^{-1}$ in the full crimp. But in this study, the RFD was measured as the maximal value during the slope grip. Consequently, these values are not comparable with ours, which ranged for $RFD_{95\%}$ from 398.87 to 423.41 $N \cdot s^{-1}$ and from 742 to 1,418.79 $N \cdot s^{-1}$ for $RFD_{200\ ms}$ after a 4-week training. Methodological studies have suggested that focusing only on the RFD peak is not a relevant method because it only takes into account a part of the curve, which is highly sensitive to variability and sudden changes (6,8). Thus, its use is not recommended in functional actions, such as climbing. Rather, it is more accurate to investigate the evolution of force as a function of a given time (8) as we have done, by cutting the slope into 2 parts (at early phase at 200 ms and up to the plateau at 95% of the maximal force) for a better and a more accurate interpretation.

Although few studies on RFD and climbing exist, several studies have focused on this variable by characterizing the way in which the force is produced. For instance, Fanchini and White (14) showed that boulderers are able to develop more strength at a faster rate than lead climbers. This could be explained by the temporal characteristics of the event. Indeed, the duration of the effort was shorter in bouldering (30 seconds rather than 2–7 minutes lead climbing) with 7.5 seconds of static phase and 22.5 seconds of dynamic phase, with a long resting time (114.5 $\pm$ 30.7 s) between the 2 attempts (39). In bouldering, movements are more explosive and dynamic and thus necessitate taking small crimps; this implies that boulderers are able to develop a high level of force in a shorter time so as to be able to stabilize the body (14,39). Furthermore, Laffaye et al. (19) revealed that arm jumps feature an explosive movement over a shorter time. Thus, boulderers demonstrate a better index of efficiency than climbers of the same skill level. All these studies highlight the importance of producing a high level of force for the finger flexor in a small amount of time, i.e., a high value of RFD. Thus, the RFD is a key variable in efficient bouldering. Nonetheless, it has not been investigated in climbing, as is the case for other explosive sports such as sprinting (7) and jumping (11,22).

Our results show a significant increase in $RFD_{200\ ms}$ for the training group for the 3 conditions of crimps (half, slope, and full). A 32% gain for the slope crimp, a 27.5% gain for the half crimp, and a 28% for the full crimp was recorded, whereas no change was recorded for the control group, with changes of–3% for the half crimp and +6% for the full crimp.

According to the literature on RFD changes with training, a gain in the early part of the force-time curve is due to changes in the neural control of muscular contraction. Indeed, the activation of the muscle during a rapid and explosive contraction is mainly determined by the discharge of motor units, i.e., the neural factor (1). This discharge occurs at the start of the contraction and is decisive in the first 100–200 ms (34). The time for the experimental group to reach the maximal force in our study before training was 2.62 $\pm$ 0.36 seconds. As the typical time needed during a bouldering event will always be shorter than the time needed to achieve the maximal force, increasing the RFD is, therefore, a crucial way to increase performance.

The change of $RFD_{200\ ms}$ is due to an increase in the motor unit discharge and the contractile impulse, as suggested by Aagaard et al. (1). A gain later in the force-time curve, i.e., in the second part of the RFD, is linked closely to changes in the tendon-muscle coupling and to the contractile properties of the muscle, which increase later in the RFD curve (34). The RFD is a factor which is primarily affected by training (9,13), before the maximal force is achieved. These indications are confirmed by Tillin et al. (33), who explained that isometric-type exercises would improve muscle activation. Based on this idea, we can hypothesize that the specific training performed by climbers is primarily impacted by the neural factor and by a probable increase in the discharge of the motor units. Therefore, a 4-week training program is sufficient to increase the force and RFD for the finger flexor for both elite and top world-ranking boulderers.

On the other hand, the training did not have an effect on the absolute $RFD_{95\%}$. The literature of RFD gain with training highlights that a gain on absolute RFD of the force-time curve is a combination of changes in the neural factor in the early phase and changes in the musculo-tendinous structure. The contractile properties and the architecture of the muscle (the number of type II and I fibers) are also involved in the increase in RFD (34). The fact that there is no effect on the $RFD_{95\%}$ tells us that a 4-week training had probably no impact on the structural factors (i.e., the muscle architecture, cross-sectional area, and type fibers II) (3), but had an important impact on the neural factor, more particularly on the increase of the discharges of the motor units, as suggested by the gain obtained during the first 200 ms. It would be interesting to confirm this conjecture in future studies by measuring how muscular-tendon architecture evolves with training.

Last, the training workouts were based on the slope and half crimps, and the gain of $RFD_{200\ ms}$ was significant for all conditions. This transfer could be explained by the muscles involved during the 3 conditions. Indeed, the half crimp necessitates the activation of the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) using an angle of the IPP of about 90° and a 0° angle of the IPD. The full crimp necessitates an angle of 90° of the IPP and an hyperextension of the IPD because of the action of the thumb on the dorsal side of the other fingers. This action involves both muscles, FDP and FDS, but with a dangerous pressure of the A2 and A4 pulleys. In other terms, using the half crimp grip allows the climbers to increase the RFD on the full crimp without increasing the risk of injuries on the pulley.

This study is the first to investigate RFD changes with training in elite and top world-ranking climbers. The first row of data offers some interesting information about the way the force was improved. We made the choice to investigate the slope of the force production in the first 200 ms and until the plateau of force is reached to gain a better understanding of the internal processes. To gain a more in-depth and accurate comprehension of this phenomena, a data recording at 1,000 Hz would be useful in giving us an understanding of what happens in the first 50 or 100 ms, which is known to be a signature of the peak of the RFD. We could then compare this peak with an RFD value over a given time (24). Moreover, it would be interesting to know how long this gain of force and RFD can last. This was difficult to measure with top world-ranking climbers because the scientific protocol requires them to change their training schedule during the experiment. It would be difficult to ask climbers who are preparing for international competition to miss specific training so as to have a control group.

Furthermore, considering the few studies that have investigated the link between RFD and the climbing performance, we encourage future research to characterize the constraints of force and time during bouldering and lead climbing for a better understanding of the way the force is produced in both sub-disciplines. More accurately, it could be useful to investigate the threshold of normalized force sufficient to gain and maintain the control of a hold and the time necessary to reach this force. The literature of RFD may be more important in climbing and having more information on this topic, such as typical values in different levels of expertise seem important to monitor climbers' performance.

Practical Applications

The goal of this study was to show the impact of a 4-week training program on finger flexor force and the RFD in elite and top world-ranking boulderers.

Results reveal a gain of force and RFD in the early phase of the slope (200 ms) of finger flexor for all hold conditions. Concerning the finger flexor force, there was a significant gain for the right slope crimp (with an 8% difference between the group control and the experimental group). In addition, there was an evolution of the force exerted during the other holds (5.3 and 7.5% difference between pretest and posttest for the full crimp and the half crimp). Thus, 4 weeks were seen to be enough to improve the level of maximum force in elite climbers. Increasing the maximal force of the finger flexor is also of importance for climbers of difficulty and bouldering (20,21), and such a training plan could be useful for both sub-disciplines.

The gain of RFD in the first 200 ms of the slope of the force is very high (between 27.5 and 32% for averaged conditions), revealing a gain in the neural factor rather than a change in the muscle-tendon structure. Reaching a high level of force in a small amount of time is highly important because the constraints of international bouldering competitions necessitate dynamic movements with a high level of holding force (39) in a short amount of time. Considering the fact that climbing makes its appearance in the 2020 Olympic Games in Tokyo in the form of a combined competition, i.e., bouldering, speed climbing, and lead climbing, it will be crucial for each athlete to be able to develop a high level of force and of RFD in especially 2 events. Like bouldering, lead climbing requires a high level of finger flexors (14,20).

Furthermore, our study reveals that there was an increase of the $RFD_{200\ ms}$ for all the condition crimps, whereas the training plan was based on isometric contractions in the slope and half crimp grips, suggesting a possible transfer of force between the crimps. This result could help trainers to manage the gain of force and the prevention of injury. Indeed, the full crimp overloads the A2 pulley at maximum pressure, which could be broken when overused. Our study suggests that it is not necessary to work specifically on the full crimp grip to increase the force in this position; rather, working with the half crimp or the slope crimp grip can result in an increase in finger flexor force and rate of force for all grips.

Acknowledgments

The authors thank the head coaches of the national climbing federation, Mr Januel Nicolas and Mr Remi Samyn, for the design of the training plane, their valuable advices, and the members of the French climbing team. The authors have no conflicts of interest to disclose.

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