Article

# The Effects of Plyometric Training on Neuromuscular Performance in Advanced Boulder Climbers

Guillermo Cortés-Roco * , Verónica Low-Barría , Rodrigo Yáñez-Sepúlveda , Jorge Pérez-Contreras , Yeny Concha-Cisternas , Juan Hurtado-Almonacid , Exal Garcia-Carrillo

Posted Date: 18 May 2026

doi: 10.20944/preprints202605.1106.v1

Keywords: plyometric training; bouldering; upper-body power; isometric strength; neuromuscular adaptations

doi:10.20944/preprints202605.1106.v1

*Article*

# The Effects of Plyometric Training on Neuromuscular Performance in Advanced Boulder Climbers

**Guillermo Cortés-Roco [1,*], Verónica Low-Barría [1], Rodrigo Yáñez-Sepúlveda [2], Jorge Pérez-Contreras [3], Yeny Concha-Cisternas [4,5], Juan Hurtado-Almonacid [6] and Exal García-Carrillo [7,8]**

[1] Facultad de Ciencias de la Vida, Magíster en Evaluación y Planificación del Entrenamiento Deportivo, Universidad Viña del Mar, Viña del Mar 2520000, Chile
[2] Faculty Education and Social Sciences, Universidad Andrés Bello, 2520000, Viña del Mar, Chile
[3] Escuela de Ciencias del Deporte, Facultad de Salud, Universidad Santo Tomás, Santiago 8370003, Chile
[4] Vicerrectoría de Investigación e Innovación, Universidad Arturo Prat, Iquique 1100000, Chile
[5] Escuela de Pedagogía en Educación Física, Facultad de Educación, Universidad Autónoma de Chile, Talca 3460000, Chile
[6] Escuela de Educación Física, Pontificia Universidad Católica de Valparaíso, Valparaíso 2340000, Chile
[7] Department of Physical Activity Sciences, Faculty of Education Sciences, Universidad Católica del Maule, Talca 3480112, Chile
[8] Department of Physical Activity Sciences, Universidad de Los Lagos, Osorno 5290000, Chile
* Correspondence: guillermo.cortes@uvm.cl

## Abstract

**Background:** Plyometric training has been proposed as an effective strategy for improving neuromuscular performance in climbing. However, its specific effects on upper-body explosive capacity and rate of force development (RFD) in advanced boulder climbers remain unclear. The objective was to determine the effect of a 10-week plyometric training program on neuromuscular performance in advanced boulder climbers. **Methods:** Eighteen male climbers participated, divided into a plyometric training group (n = 9; 31.33 ± 5.63 years) and a control group (n = 9; 29.67 ± 4.50 years). Maximal strength and rate of force development (RFD) of the finger flexor muscles were assessed, and RFD was analyzed in time intervals from 0 to 200 ms and in a relative range of 20–80% of maximal strength. Maximal pulling strength (isometric pull-ups) was assessed using a load cell in a standardized pull-up position. Lower-body power was assessed using the counter-movement jump (CMJ) test, and upper-body specific power using the Power Slap test on a campus board. The plyometric training program was conducted over ten weeks (two sessions of 45 to 60 minutes each). **Results:** Significant differences were observed between groups in pull-ups (Δ difference = +3.89 repetitions; 95% CI:-7.48,0,30, $p=0.036$; $\eta^2p=0.248$), push-up power (Δ difference = +174.5 W; 95% CI: 5.05,–343. 46, $p=0.044$; $\eta^2p=0.128$) and isometric pull-up RFD at 200 ms (Δ difference = +107.85 kg/s; 95% CI: 27.54, -188.16; $p=0.012$; $\eta^2p=0.336$), and in the 20–80% range (Δ difference = +261.78 kg/s; 95% CI: 23.09–500.47; $p=0.034$; $\eta^2p=0.194$). No differences were observed between groups in Power Slap ($p=0.409$) or in CMJ height ($p=0.122$). **Conclusion:** A 10-week plyometric training program produced specific neuromuscular adaptations in advanced boulder climbers, improving pull-up performance, upper body explosive power, and isometric pull-up RFD. The absence of transfer to finger strength, Power Slap, and CMJ confirms the high specify of neuromuscular adaptations to the trainer movement pattern.

**Keywords:** plyometric training; bouldering; upper-body power; isometric strength; neuromuscular adaptations

doi:10.20944/preprints202605.1106.v1

## 1. Introduction

Bouldering is characterized by solving motor problems on low walls that demand high intensity, technical precision, and intermuscular coordination, involving short bursts of effort and high neuromuscular demands [1,2]. Unlike lead climbing, where endurance plays a predominant role, bouldering requires the application of effective force within very short time intervals, frequently less than 200 milliseconds, making explosive force production a key determinant of performance [1,3]. In advanced stages of development, when climbers already possess a solid technical foundation and high levels of relative strength, progression depends less on increasing maximum strength and more on the efficiency with which it is produced within short intervals [4–6]. This approach aligns with the evolution of modern bouldering, characterized by problems that integrate dynamic, reactive, and time-limited actions for applying force. Various studies have indicated that, in advanced climbers, finger flexor muscles have higher oxidative capacity, relative strength (strength-to-weight ratio), and overall strength levels compared to non-climbers [7].

Performance differences are not explained solely by the magnitude of maximum force, but also by the way in which this is expressed over short time intervals [8]. In this context, rate of force development (RFD) is defined as the slope of the force-time curve during the initial phase of contraction and constitutes a sensitive indicator of neuromuscular function in explosive actions [1]. RFD is particularly critical in the short-duration actions characteristic of bouldering, such as dynamic movements, reactive blocks, and campus board sequences, where the time available to apply force is typically less than 200 ms [2]. Long dynamic movements, coordinated throws, reactive blocks on small holds, and sequences on the campus board involve brief contacts and rapid changes in the direction of the centre of mass. These actions are typically performed within narrow time windows for force application, making RFD a determining factor in competitive performance [9].

In disciplines where body weight constitutes the primary resistance to be overcome, mechanical efficiency and the optimization of the centre of mass play a decisive role[10]. Vereide et al. [9] have shown that elite climbers not only exhibit higher relative strength values but also greater efficiency in the application of that force, reducing the energy cost per movement. This efficiency is linked to more coordinated muscle activation patterns and better synchronization between the upper and lower limbs [11]. In this context, improving RFD could not only influence the ability to perform explosive movements, but also the temporal precision with which these movements are integrated into complex technical sequences [1,2,9]. Furthermore, the lower body also plays a crucial role in modern bouldering. Although historical climbing was associated primarily with upper-body strength, current literature recognizes the importance of generating momentum from the lower limbs to optimize the transfer of the centre of mass and reduce the load on the finger flexors[12,13]. Li et al. [14] observed that jump power is related to efficiency in large-range dynamic movements, whilst Vigouroux & Quaine [15] noted that coordination between leg propulsion and arm pull allows for maximizing mechanical efficiency in explosive sequences, reducing energy expenditure, and improving body stability.

Plyometric training has emerged as a promising strategy for developing RFD and explosive power in sports requiring rapid force production [16,17]. Based on the stretch-shortening cycle, plyometric exercise involves a rapid transition between eccentric loading and concentric contraction, generating adaptations in neuromuscular efficiency, motor unit recruitment, and muscular stiffness [16,18,19]. Meta-analytical evidence supports plyometrics training improves vertical jump performance and explosive force production across multiple sports contexts [17]. In upper-body dominant sports, plyometrics protocols incorporating ballistic push-ups, reactive pull-ups, and campus board- based exercises have been shown to increase peak power and RFD in pulling and pushing actions [20–22]. Despite this evidence, the application of plyometric training remains largely unexplored. To date, only a limited number of studies have examined explosive training intervention in climbers [22,23], and none have specifically investigated the effects of a structured plyometric program targeting both upper and lower body explosive capacity of RFD in advanced boulder climbers. Given that bouldering performance depends critically on the ability to generate force rapidly in pulling actions and dynamic sequences, there is a clear rationale for examining the efficacy of plyometrics training as a targeted approach to neuromuscular intervention in this population.

Therefore, this study aims to determine the effect of a plyometric training programme on muscle strength in advanced boulderers. Given this background, improving the ability to generate force rapidly could be a key factor in performance in advanced bouldering. Therefore, this study aims to determine the effect of a plyometric training programme on muscle strength in advanced boulderers.

## 2. Materials and Methods

### *Design*

The study employed a randomized experimental design with two parallel groups and repeated measures (group × time) over ten weeks.

### *Sample*

Eighteen advanced climbers were assigned to an experimental group (n=9) that undertook a plyometric training programme at a frequency of two sessions per week for 10 weeks, and a control group (n=9), which maintained their usual training without the systematic incorporation of additional plyometric stimuli. Random allocation was performed using a simple randomization procedure with a computer-generated random number generator. The athletes had a minimum bouldering level of ≥ V5, at least two years of continuous experience in sport climbing, and a regular training frequency of three or more sessions per week. No priori sample size calculation was performed. The sample size was determined by the availability of advanced climbers who met the predefined inclusion criteria during the recruitment period. Given the difficulty of accessing a homogeneous sample of trained Boulder climbers with similar performance levels and training backgrounds, the present study should be interpreted as a controlled exploration trial.

### *Inclusion Criteria*

Male climbers aged between 20 and 40 years were considered eligible if they had a minimum bouldering performance level of ≥ V5, at least two years of continuous sport climbing experience, and a regular training frequency of three or more sessions per week over the previous six months.

### *Exclusion Criteria*

The absence of active musculoskeletal injuries at the time of the initial assessment was required, with the aim of ensuring comparable baseline conditions and reducing the risk of adverse events during the plyometric programme. Participants with medical conditions or ailments contraindicating reactive or ballistic training were excluded, as were those who sustained injuries during the intervention period that prevented continuation of the protocol. In addition, subjects with an adherence rate of less than 80% of the scheduled sessions were excluded.

Baseline characteristics included age, body mass, and body composition. Body composition was assessed by electrical bioimpedance using an InBody 270S® multi-frequency analyzer (InBody Co., Seoul, Korea). Measurements were taken under standardized conditions, including prior fasting, abstention from vigorous exercise in the preceding 24 hours, and control of hydration (Table 1)

**Table 1.** Sample characteristics of the intervention and control groups.

| Variable | Intervention Group (n = 9) | Control Group (n = 9) |
|---|---|---|
| Age (years) | 29.67 ± 4.50 | 31.33 ± 5.63 |
| Height (cm) | 173.33 ± 2.69 | 171.22 ± 7.89 |
| Body mass (kg) | 71.70 ± 9.40 | 67.12 ± 12.18 |
| Muscle mass (kg) | 34.80 ± 3.47 | 32.80 ± 6.58 |

| | | |
|---|---|---|
| Body fat % | 14.47 ± 5.15 | 13.89 ± 5.65 |

*Instruments*

Finger Strength on a 20 mm Hold:

A Tindeq Progressor® load cell attached to a standard 20 mm hold was used to assess maximum finger strength and RFD. This device has demonstrated adequate validity and reliability for isometric strength measurements in climbing [24]. The protocol consisted of maximum isometric contractions with a standardized posture, recording the complete force-time curve for subsequent analysis. Signals were acquired at 80 Hz and filtered using a fourth-order Butterworth filter (low-pass, 10 Hz). The onset of contraction was defined as the point at which the force exceeded 5% of the maximum force above the baseline level. From the processed signal, Fmax, RFD0-200 ms, and RFD 20-80% were calculated, including their normalization relative to Fmax and body mass.

Maximum Pull Force (Pull-Up)

Maximum pull force (isometric pull-up) was assessed using the Tindeq Progressor® system. The force-time curve was recorded in a standardised position, following methodological recommendations for the analysis of force-time variables [25]. Signal processing, definition of the onset, and calculation of variables (Fmax, RFD 0–200 ms, and RFD 20–80%) followed the same criteria described for the assessment of finger strength, including the normalisation of values.

Lower-Body Power

Lower limb power was assessed using the Countermovement Jump (CMJ) test on a Chronojump® contact platform (Boscosystem, Barcelona, Spain). Jump height (cm) was recorded based on flight time, and estimated power (W) was calculated. Participants performed the test with their hands on their hips to minimize the contribution of arm swing

Specific Power of the Upper Limbs

Upper limb power was assessed using the plyometric push-up test performed on a Chronojump® contact platform (Boscosystem, Barcelona, Spain), recording flight time to estimate variables such as height (cm) and power (W), as suggested by previous studies [20,21]. In the starting position, each athlete was asked to place both hands on the contact platform in a prone plank position, shoulder-width apart, with elbows extended, the trunk aligned, and feet flat on the ground. From the starting position, the athlete performs a controlled elbow flexion (90°). They immediately perform an explosive arm extension, lifting their hands off the platform. During the aerial phase, the athlete must keep their body aligned (avoiding hip flexion). Flight time is recorded from the moment contact with the platform is lost until it is regained. Three attempts were made, with 1-2 minutes of recovery between each. The best value was recorded for analysis. An attempt was considered valid when there was a clear lift-off of both hands and no compensatory movements (hip flexion or arm asynchrony).

Upper-body specific power was assessed using the Powerslap test on a campus board, recording the distance achieved in centimeters, a procedure described previously [1,26]. The athletes started from a static hanging position on a standardized bar, with both hands in a prone grip, shoulder-width apart, elbows extended, and without support from the lower limbs. From this position, they were asked to perform a maximum explosive pull, reaching as high as possible with one hand, without allowing any prior momentum or body sway. The recorded variable was the distance reached (cm) between the starting bar and the highest point touched. Two to three attempts were made on the dominant arm only, with 3-5 minutes between each, and the best valid attempt was recorded. Only attempts performed from a static position and with clear contact on the target bar were considered valid.

*Procedures*

The study was conducted in three stages. In the first stage, the initial assessment (pre-test) was carried out, which included standardized measurements of body composition, maximum grip strength, maximum strength, RFD of the fingers on a 20 mm hold, isometric pull strength, and power of the upper and lower limbs. Three attempts were made per test, with the best value recorded for analysis. For the Power Slap test, attempts were performed on the dominant arm only. Pre- and post-intervention assessments were carried out at a climbing centre at the same time of day (±1 hour), under similar environmental conditions and using the same equipment and standardized protocols. To minimize external variability, participants were instructed to refrain from intense training during the 48 hours before each assessment, to maintain their usual sleep pattern (minimum 7 hours the night before), and not to alter their regular diet during the week before the measurements. No specific dietary intervention was implemented; however, participants were asked to maintain consistent nutritional habits during the assessment period to reduce potential confounding effects.

To control training volume, the plyometric load was quantified by the number of reactive contacts per session, considering both lower limb (LL) and upper limb (UL) explosive actions. Reactive contact was defined as any landing or explosive support in lower limb (LL) plyometric exercises, as well as any brief, reactive contact in upper limb (UL) explosive pulls exercises (campus board, plyometric pull-ups, and plyometric TRX). The volume per session was expressed as a range of contacts, as the effective load could vary slightly depending on the level of technical execution, individual selection of progressions, and the neuromuscular tolerance of each participant.

The second stage corresponded to the 10-week intervention (Table 2). During the adaptation phase (weeks 1–4), the volume ranged from 90 to 288 reactive contacts per session, at low to moderate intensities, prioritizing landing control, technical quality, and the progressive preparation of the musculotendinous structures. This initial progression was based on recommendations for the safe implementation of plyometric training in trained populations, where a prior adaptation phase is suggested before increasing intensity to optimize neuromuscular adaptations and reduce the risk of injury [16,17]. In the bouldering-specific plyometric phase (weeks 5–6 and 8–10), the volume progressed to approximately 168–384 reactive contacts per session, at moderate to very high intensities, incorporating greater heights, increased eccentric demand, reduced contact time, and exercises highly transferable to bouldering technique. The seventh week was a deload week, aimed at reducing both volume and intensity, promoting neuromuscular recovery and consolidating previous adaptations [18,27], preserving the quality of the stimulus and reducing the risk of musculotendinous overload [16]. In the third stage, the final assessment (post-test) was conducted, replicating the initial protocols to ensure methodological consistency and control of experimental variability.

**Table 2.** Periodized plyometric training program across the 10-week intervention.

| **Week** | **Phase** | **Lower Body** | **Upper Body** | **Sets x reps** | **Rest** | **Intensity** | **Reactive contacts per session** |
|---|---|---|---|---|---|---|---|
| **1** | **Adaptation** | Depth Jumps, Lateral Bounds, Pogo Jumps. | Supported Campus, Plyometric Pull-ups, Plyometric TRX Rows | 3x5 | 60–90 | Low | 90–180 |
| **2** | **Adaptation** | Depth Jumps, Lateral Bounds, Squat Jump | Supported Campus, Plyometric Pull-ups, Plyometric TRX Row | 3x6 | 60-90 | Low | 108–216 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | **Adaptation** | Depth Jumps, Lateral Bounds, Squat Jump | Single-leg step-ups, Plyometric pull-ups, TRX plyometric row | 3x6 | 75 | Medium | 108–216 |
| 4 | **Adaptation** | Depth Jumps, Lateral Bounds, Squat Jump Upper Body | Single-leg step-ups, Plyometric pull-ups, TRX plyometric row | 4x6 | 75 | Average | 144–288 |
| 5 | **Specify** | Depth Jumps, Lateral Bounds, Squat Jump | Wall bars without support 1-5-7, Plyometric pull-ups, TRX plyometric row | 4x7 | 90 | High | 168-336 |
| 6 | **Specify** | Depth Jumps, Lateral Bounds, Squat Jump | Unsupported Wall Bars 1-4-5-5, Plyometric Pull-ups, TRX Plyometric Row | 4x8 | 90 | High | 192-384 |
| 7 | **Download** | Depth Jumps, Lateral Bounds, Squat Jump Middle School | One-arm pull-ups, Plyometric pull-ups, TRX plyometric row | 3x5 | 75 | Low | 90-180 |
| 8 | **Specify** | Depth Jumps, Lateral Bounds, Squat Jump | Double Campus Dynos 4-6-5-7-6, Pull-up Plyo, TRX Plyo Row | 4x7 | 90 | High | 168-336 |
| 9 | **Specify** | Depth Jumps, Lateral Bounds, Squat Jump | Unsupported parallel bars double dynos 1-4-4-3-5-4, Plyometric pull-ups, TRX plyometric row | 4x8 | 90 | Very High | 192-384 |
| 10 | **Specify** | Depth Jumps, Lateral Bounds, Squat Jump | Unassisted Campus 1-5-3-1, Plyometric Pull-up, TRX Plyometric Row | 4x8 | 90 | Very High | 192-384 |

Rest: inter-set recovery in seconds. Reactive contact per session includes all explosive ground contact (lower body) and reactive pull contacts (upper body). Campus sequences are expressed as run numbers. Intensity was defined as follows: Low=controlled landings, submaximal efforts; Moderate=increased eccentric demand, near-maximal effort; High = maximum reactive effort, reduced contact time; Very High: maximum intensity, complex sequences with minimal ground contact. ↓ Week 7 corresponds to a deload week aimed at reducing accumulated fatigue and consolidating prior adaptations. .

### *Ethical Considerations*

The study was conducted in accordance with the regulations governing research involving human subjects and was reviewed and approved by the Scientific Ethics Committee of the University of Viña del Mar ( CEC-UVM 32-25; date of approval: 24 June 2025). Furthermore, the ethical principles established in the Declaration of Helsinki for medical research involving human subjects [28] were observed. All participants signed an informed consent form detailing the procedures, potential risks and benefits, ensuring the confidentiality of the information and the right to withdraw voluntarily at any stage without consequences for their training programme.

### *Statistical Analysis*

doi:10.20944/preprints202605.1106.v1

Data processing and statistical analysis were performed using Jamovi software (version 2.4.11). In the first stage, we verified that the variables met the assumptions of normality using the Shapiro-Wilk test, given its adequate sensitivity for small samples in applied research contexts. Likewise, the homogeneity of variances was assessed using Levene's test to confirm the equality of variances across groups, a particularly important consideration in small samples, where the presence of outliers can influence the results. Once the parametric nature of the data and the equality of variances were confirmed, a 2×2 mixed-design analysis of variance (group × time) was applied to examine the main effect of time, the main effect of group, and the group × time interaction, which allowed for the identification of differential changes attributable to the plyometric intervention. Since the time factor had only two levels (pre and post), it was not necessary to assess the assumption of sphericity. To estimate the practical magnitude of the observed changes, effect sizes were calculated using the partial eta-squared statistic ($\eta^2p$). Effect sizes estimated using $\eta^2p$ were interpreted according to Cohen's [26] guidelines: small ($\eta^2p = 0.01$), moderate ($\eta^2p = 0.06$), and large ($\eta^2p = 0.14$). (Δ%) was calculated as [Post − Pre) / Pre] × 100 as a descriptive indicator of performance development. To complement the inferential analysis and facilitate practical interpretation, mean changes (Δ = Post − Pre) were calculated for each variable, and between-group differences in change (Δ Difference = IG − GC) were compared using independent-samples Student's t-tests with 95% confidence intervals (95% CI). A 95% CI for Δ Difference that did not include zero was interpreted as evidence of a statistically significant between-group difference. The level of statistical significance was set at $p < 0.05$ for all analyses.

## 3. Results

Table 3 shows that the intervention group demonstrated consistent improvements in most variables related to upper-body performance and force production. Increases were observed in pull-up performance (+6.93%), CMJ height (+9.17%), push-up power (+8.93%), and power-slap (+7.50%). Likewise, finger strength variables showed moderate increases, including maximum grip strength (+7.20%) and maximum strength of the right-hand fingers (+4.40%). The highest relative changes in the intervention group were observed in rate of force development (RFD) variables, particularly in isometric push-ups with increases of +477.9% (RFD 200 ms) and +233.7% (RFD 20–80), suggesting significant improvements in the ability to generate force rapidly. In contrast, the control group showed changes of lesser magnitude and variability.

**Table 3.** Descriptive results before and after the intervention and percentage changes (Δ%) in neuromuscular performance variables in the intervention group (IG) and control group (CG).

| | **Intervention group (IG)** | | | **Control Group (CG** | | |
|---|---|---|---|---|---|---|
| **Variable** | **Pre** | **Post** | **Δ%** | **Pre** | **Post** | **Δ%** |
| **Pull-up** | 17.11±3.33 | 23.11±6.25 | +6.93% | 17.33±6.54 | 19.44±7.47 | +5.98% |
| **Push-up Height (cm)** | 10.16±4.13 | 10.46±1.96 | +2.96% | 11.20±4.65 | 9.30±3.00 | -16.96% |
| **Push-up Power (W)** | 915.83±225.62 | 997.45±144.18 | +8.93% | 963.71±301.37 | 871.08±177.41 | -9.59% |
| **Power Slap (cm)** | 81.11±8.72 | 87.22±5.12 | +7.50% | 76.11±15.89 | 79.50±18.14 | +4.40% |
| **CMJ Height (cm)** | 34.13±5.75 | 37.74±4.02 | +10.56% | 32.71±5.39 | 34.18±5.42 | +4.49% |
| **CMJ Power (W)** | 869.36±138.35 | 948.94±107.42 | +9.17% | 822.36±131.05 | 839.97±122.08 | +2.15% |
| **Maximum grip strength, right hand, 20 mm (kg)** | 56.13±6.41 | 60.18±6.21 | +7.20% | 52.85±12.34 | 54.41±11.35 | +2.90% |
| **Maximum grip strength, right hand, 20 mm (kg)** | 55.51±6.74 | 57.95±7.06 | +4.40% | 51.27±10.97 | 53.23±11.34 | +3.80% |
| **RFD 200ms Right Fingers (kg/s)** | 154.93±92.16 | 126.17±96.89 | +134.4% | 143.88±126.84 | 92.13±72.11 | +205.8% |
| **RFD 200ms Left Fingers (kg/s)** | 77.16±97.63 | 151.56±120.67 | +96.4% | 17.97±30.68 | 67.50±67.29 | +275.6% |
| **RFD 20-80** | 154.33±92.17 | 215.40±61.42 | +39.6% | 143.88±126.84 | 133.05±77.51 | -7.5% |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Right Fingers (kg/s)** | | | | | | |
| **RFD 20-80 Left Fingers (kg/s)** | 168.97±111.18 | 221.46±75.21 | +31.1% | 105.89±118.66 | 99.10±71.70 | -6.4% |
| **RFD 200ms Isometric Pull-up (kg)** | 24.41±58.21 | 141.02±115.09 | +477.9% | 5.99±11.46 | 14.74±15.58 | +146.0% |
| **RFD 20-80 Isometric Pull-up (kg/s)** | 107.29±120.10 | 357.92±233.28 | +233.7% | 81.78±90.03 | 70.64±159.75 | -13.6% |

Values are presented as mean ± standard deviation (SD); Δ%: percentage change calculated as [(Post-Pre) / Pre × 100]; IG: Intervention group; CG: Control group; CMJ: Countermovement jump; RFD: Rate of force development.

Table 4 shows significant interactions in pull-up performance (F=526; p=0.036; $\eta^2p$=0.248), with a moderate effect size. In the power-slap test (F=477; p=0.44; $\eta^2p$=0.23) with a moderate effect, and in the RFD (200 ms) isometric pull-up (F=8.10; p=0.012; $\eta^2p$=0.336), with a large effect, and in the RFD 20-80% of isometric pull-up (F=5.41; p=0.034; $\eta^2p$=0.253)with a moderate-to-large effect demonstrating a specific effect of the plyometric training program on rapid force production capacity and upper limb pulling performance.

**Table 4.** Results of the repeated-measures analysis of variance (two-way ANOVA: group × time) for the neuromuscular performance variables.

| | Group | | | Time | | | Group x Time | | |
|---|---|---|---|---|---|---|---|---|---|
| **Variable** | **F** | **p** | **$\eta^2p$** | **F** | **p** | **$\eta^2p$** | **F** | **p** | **$\eta^2p$** |
| Pull-up | 0.39 | 0.540 | 0.024 | 22.90 | <.001 | 0.589 | 5.26 | 0.036 | 0.248 |
| Push-up Height (cm) | <0.01 | 0.969 | 0.000 | 0.78 | 0.391 | 0.046 | 1.47 | 0.243 | 0.084 |
| Push-up power (W) | 0.47 | 0.503 | 0.029 | 14.64 | 0.001 | 0.478 | 2.35 | 0.145 | 0.128 |
| Power Slap (cm) | 0.17 | 0.688 | 0.010 | 0.02 | 0.892 | 0.001 | 4.77 | 0.409 | 0.230 |
| CMJ Height (cm) | 1.12 | 0.307 | 0.065 | 14.94 | 0.001 | 0.483 | 2.66 | 0.122 | 0.143 |
| CMJ Power (W) | 1.93 | 0.184 | 0.107 | 7.20 | 0.016 | 0.310 | 2.93 | 0.106 | 0.155 |
| Maximum grip strength, right hand, 20 mm (kg) | 10.17 | 0.006 | 0.389 | 0.06 | 0.803 | 0.004 | 1.52 | 0.235 | 0.087 |
| Maximum grip strength, left hand, 20 mm (kg) | 1.08 | 0.315 | 0.063 | 9.92 | 0.006 | 0.383 | 0.12 | 0.733 | 0.007 |
| RFD 200ms Right Fingers (kg/s) | 1.14 | 0.301 | 0.067 | 8.77 | 0.009 | 0.354 | 0.72 | 0.409 | 0.043 |
| RFD 200ms Left Fingers (kg/s) | 0.61 | 0.446 | - | 5.11 | 0.038 | - | 1.53 | 0.234 | - |
| RFD 20–80 Right Fingers (kg/s) | 1.95 | 0.181 | 0.109 | 5.14 | 0.038 | 0.243 | 0.42 | 0.525 | 0.026 |
| RFD 20–80 Left Fingers (kg/s) | 1.78 | 0.201 | 0.100 | 0.32 | 0.578 | 0.020 | 1.96 | 0.180 | 0.109 |
| RFD 200ms Isometric Pull-up (kg) | 8.93 | 0.009 | 0.358 | 10.95 | 0.004 | 0.406 | 8.10 | 0.012 | 0.336 |
| RFD 20–80% Isometric Pull-up (kg/s) | 3.51 | 0.007 | 0.180 | 7.88 | 0.013 | 0.330 | 5.41 | 0.034 | 0.253 |

The results are presented as F-statistics, p-values, and effect sizes ($\eta^2p$) from the repeated-measures analysis of variance (two-factor ANOVA: group × time). IG: intervention group; CG: control group; CMJ: countermovement jump; RFD: rate of force development.

Table 5 shows that the intervention group demonstrated consistent improvements in specific upper-body variables, notably push-up performance (Δ=+6.00; 95% CI: 2.52, -9.48), power slap in the dominant arm (Δ=+6.11; 95% CI: 0.08, -12.14), and push-up power (Δ=+81.62; 95% CI: -38.00, -201.24). Likewise, significant increases in pull-up RFD were observed at both 200 ms (Δ=+116.60; 95% CI:

30.95, -202.26) and 2080 ms (Δ=+250.63; 95% CI: 44.24, -457.03). Furthermore, regarding CMJ height, the intervention group showed a moderate increase (Δ=+3.61; 95% CI: 1.73, -5.48), while the control group exhibited a smaller change with greater variability.

**Table 5.** Pre- and post-intervention results, percentage changes (Δ%), and mean changes with 95% confidence intervals (95% CI) for neuromuscular performance variables in the intervention group (IG) and control group (CG).

| Variable | Group | Pre (Mean ± SD) | Post (Mean ± SD) | Δ% | Δ (IC95%) |
|---|---|---|---|---|---|
| **Pull-up (reps)** | GI | 17.11 ± 3.33 | 23.11 ± 6.25 | +6.93% | +6.00 (2.52, 9.48) |
| | GC | 17.33 ± 6.54 | 19.44 ± 7.47 | +5.98% | +2.11 (0.33, 3.89) |
| **Power Slap Dominant arm (cm)** | GI | 81.11 ± 8.72 | 87.22 ± 5.12 | +7.50% | +6.11 (-12.14, 0.08) |
| | GC | 76.11 ± 15.89 | 79.50 ± 18.14 | +4.40% | +3.39 (-0.89, -7.67) |
| **CMJ Height (cm)** | GI | 34.13 ± 5.75 | 37.74 ± 4.02 | +10.56% | +3.61 (1.73, -5.48) |
| | GC | 32.71 ± 5.39 | 34.18 ± 5.42 | +4.49% | +1.47 (-0.91, -3.84) |
| **Push-up Power (W)** | GI | 915.83 ± 225.62 | 997.45 ± 144.18 | +8.93% | +81.62 (-38.00, 201.24) |
| | GC | 963.71 ± 301.37 | 871.08 ± 177.41 | −9.59% | −92.63 (-232.52, -47.26) |
| **RFD 200 ms Pull-up (kg/s)** | GI | 24.41 ± 58.21 | 141.02 ± 115.09 | +477.9% | +116.60 (30.95, 202.26) |
| | GC | 5.99 ± 11.46 | 14.74 ± 15.58 | +146.0% | +8.76 (-8.41, -25.92) |
| **RFD 20–80% Pull-up (kg/s)** | GI | 107.29 ± 120.10 | 357.92 ± 233.28 | +233.7% | +250.63 (44.24, 457.03) |
| | GC | 81.78 ± 90.03 | 70.64 ± 159.75 | −13.6% | −11.15 (-168.68, -146.39) |

Values are presented as mean ± standard deviation (SD); Δ: mean change (post-Pre); (Δ%): Percentage changes [(Post-Pre) / Pre] × 100. IG: intervention group; CG: control group; CMJ: countermovement jump; RFD: rate of force development. A confidence interval for Δ that does not include zero indicates a statistically significant within-group change.

Table 6 shows significant differences between groups in pull-up performance (Δ Difference = +3.89; 95% CI: 0.30, -7.48; p = 0.036; $\eta^2p$ = 0.248) and push-up power (Δ Difference = +174.25 W; 95% CI: 5.05, -343.46; p = 0.044; $\eta^2p$ = 0.128), and in isometric pull-up RFD at 200 ms (Δ Difference = +107.85 kg/s; 95% CI: 27.54, -188.16; p= 0.012; $\eta^2p$=0.336), and in the 20–80% range (Δ Difference = +261.78 kg/s; 95% CI: (23.09, -500.47; p= 0.034; $\eta^2p$=0.253). In contrast, no significant differences were observed between groups in Power Slap (Δ Difference = +2.72 cm; 95% CI: -4.08, 9.52; p= 0.409), nor in CMJ height (Δ Difference = +2.14 cm; 95% CI:-0.64,-4.92; p= 0.122), indicating that changes in these variables were similar across groups. Taken together, these results confirm that the effects of plyometric training were evident in specific upper-limb variables related to rapid force production, whereas more general or coordinative variables did not show consistent differences between groups.

**Table 6.** Comparison of changes (Δ) in neuromuscular performance variables, including Δ for the difference (EG–CG), 95% confidence intervals (95% CI), p-values, and effect sizes ($\eta^2p$).

| Variable | Δ GI (95% CI) | Δ GC (95% CI) | Δ Difference (95% CI) | p | $\eta^2p$ |
|---|---|---|---|---|---|
| **Pull-up (reps)** | +6.00<br>(2.52, 7.48) | +2.11<br>(0.33, 3.89) | +3.89<br>(-7.48, -0.29) | 0.036 | 0.248 |
| **Power Slap (cm)** | +6.11<br>(-12.14, 0.08) | +3.39<br>(-0.89,-7.67) | -2.72<br>(-9.522, +4.078) | 0.409 | - |
| **CMJ Height (cm)** | +3.61<br>(1.73, -5.48) | +1.47<br>(-0.91, 3.84) | -2.14<br>(-0.64, +4.92) | 0.122 | - |
| **Push-up Power (W)** | +81.62<br>(+5.05,+343.46) | -92.63<br>(-232.52,-47.26) | 174.25<br>(-343.46, -5.05) | 0.044 | 0.128 |
| **RFD 200 ms Pull-up (kg/s)** | +116.60<br>(27.54, 188.16) | +8.76<br>(-8.41,-25.92) | -107.85<br>(-188.16, -27.53) | 0.012 | 0.334 |
| **RFD 20–80 Pull-up (kg/s)** | +250.63<br>(+23.19, 500.47) | −11.15<br>(-168.68,-146.39) | -261.78<br>(-500.47, -23.08) | 0.034 | 0.194 |

Mean changes (Δ) with 95% confidence intervals (95% CI) for the intervention group (IG) and control group (CG), and between-group differences in change (Δ difference), along with p-values and effect sizes ($\eta^2p$). A p-value of <0.05 was considered statistically significant. For the Δ Difference column, a confidence interval that does not include the value zero indicates a statistically significant difference in changes between groups.

## 4. Discussion

The main findings indicate that the intervention produced greater improvements than the control group in pull-up performance, plyometric push-up power, and isometric pull-up RFD, both in the early phase (0-200 ms) and in the 20-80% range of maximal force. In contrast, no significant differences were observed between groups in the Power Slap or CMJ height, suggesting a highly specific adaptation to the applied stimulus. The improvements observed in pull-ups and upper limb power are consistent with the literature, which indicates that specific strength and power in the upper extremities are key determinants of climbing performance. Faggian et al. [4], in a recent systematic review, concluded that specific neuromuscular capabilities likely reflect neuromuscular adaptations that optimize force production in pulling actions, which are fundamental in bouldering.

The significant improvement in isometric pull-up RFD, both in the early phase (0-200 ms; Δ difference = +107.85 Kg/ms; p=0.012; $\eta^2p$ = 0.336) and in the 20–80% range (Δ difference = +261.78 Kg/ms; p=0.034; $\eta^2p$ = 0.253), supports the hypothesis that plyometric training improves the ability to generate force within short time intervals as it requires the application of maximum force over a brief period, pre-dominantly targeting fast-twitch muscle fibers [22], which is a determining factor in bouldering performance. Both effect sizes were moderate-to-large, reinforcing the practical relevance of the adaptations of bouldering performance. From a physiological perspective, Maffiuletti et al. [25] note that RFD depends primarily on early neural activation (50–75 ms), in particular on the firing rate of motor units and neuromuscular synchronization. Furthermore, research on climbing has shown that RFD, especially in intervals of <200 ms, is associated with performance in dynamic movements [30], and the literature has established that RFD can be improved through explosive and ballistic stimuli, supporting the use of plyometrics as an effective strategy for optimizing this quality, particularly in upper-body strength and conditioning [22,31]. The significant increase in RFD intervals is consistent with studies showing that explosive and plyometric training improves the enhancement of force production in the early phases of muscle contraction [19,25]. However, unlike studies reporting generalized improvements in RFD across multiple muscle groups following explosive strength training, in this study, the improvements were limited to the pull-up pattern, with no changes in finger RFD. This suggests that, in advanced climbers, the transfer of RFD is highly specific to the trained motor pattern, which is consistent with evidence indicating that adaptations in RFD depend on the type of contraction and the applied force vector [27]. The pull-up, specifically in the context of bouldering, is a closed-chain, multi-joint upper-body strength exercise that, whilst requiring dynamic concentric strength from the arm and shoulder muscles to perform the elbow flexion and shoulder extension necessary for climbing walls [32,33], in the context of bouldering, represents a closed-chain, multi-joint pulling pattern involving the upper body and a complex interplay of factors.

In contrast, no significant differences were observed between groups in the Power Slap, based on the independent-sample t-test comparing the Δ value (p=0.409). However, this important to note that the repeated measures ANOVA did detect a significant group x time interaction for this variable (F=4.77; p=0.044; $\eta^2p$ = 0.230). This discrepancy may reflect differences in statistical sensitivity between the two approaches and underscores the importance of treating the ANOVA interaction as the primary inferential criterion, as pre-specified in the statistical analysis plan. Regardless of the analytic approach, the between-group difference in Power Slap was modest (+2.72 cm) and may lack practical relevance in the context of the bouldering performance. This result partially contrasts with studies that have used explosive upper body strength tests as indicators of climbing performance, including batteries such as the IRCRA [26]. However, our results suggest that the Power Slap may capture only a partial dimension of performance, primarily explosiveness, without adequately

doi:10.20944/preprints202605.1106.v1

integrating technical, coordinative, and centre-of-mass control components, which are decisive in bouldering [4]. This is consistent with evidence indicating that climbing performance is better explained by highly specific tests than by general or less specific assessments [4].

A notable finding is the absence of significant changes in maximum finger strength and RFD. This contrasts with studies that have reported improvements in grip strength following specific interventions in climbers [34]. The absence of significant changes may be explained by the interaction between the nature of the applied stimulus and the climbers' level of specialization. In this regard, Vigouroux et al. [33] demonstrated that smaller climbing holds impair strength and power, as well as the number of pull-ups to failure among elite climbers. The absence of significant changes in maximum finger strength and RFD can be explained, firstly, by the fact that the programmer implemented was based on plyometric exercises focused on whole-body pull-ups, which differ from the specific isometric stimuli typically used to develop strength on small holds [23,30].

In this regard, the literature has shown that adaptations in the finger flexor muscles are highly dependent on the specificity of the stimulus [35,36], requiring direct and sustained loads on small grips to induce significant improvements [3,15]. Furthermore, advanced climbers exhibit a high level of structural and neural adaptation in these muscles, which limits the scope for improvement in response to non-specific stimuli [37]. In this regard, Francinni et al. [1] previously demonstrated that boulder climbers were able to develop finger flexor strength at a higher rate than lead climbers and that the maximum RFD of the finger flexors was a crucial factor in distinguishing between the two disciplines. Furthermore, the programmer's focus on dynamic pulling actions may have favored adaptations in the proximal segments (shoulder-elbow) without generating sufficient overload at the distal level [38,39]. Arm training studies conducted to date have incorporated exercises that also involve the fingers [23,40], making it difficult to distinguish between the impact on the fingers and the arms [39]. Taken together, these factors suggest that the absence of changes in finger strength should not be interpreted as a limitation of the programmer, but rather as a manifestation of the principle of specificity, which is well documented in climbing, where neuromuscular adaptations are highly dependent on the type of grip, the mode of contraction, and the distribution of mechanical load [39].

### *Practical Implications*

From an applied perspective, the results suggest that incorporating pull-oriented plyometric training is an effective strategy for improving upper-body explosive capacity and isometric pull-up RFD in advanced boulder climbers. However, the development of finger flexor muscles requires specific stimuli, such as fingerboard or hangboard training. Likewise, if the aim is to improve lower-body explosive power, exercises with greater mechanical similarity to vertical jump should be included, as the present program did not produce significant CMJ improvements relative to controls. Climbing training planning should therefore integrate specific stimuli for each performance component, avoiding assumption of generalized transfers across different neuromuscular domains. From an applied perspective, the results also allow us to suggest that plyometrics is an effective tool for optimizing the time dimension of strength in advanced climbers, but it does not replace specific maximum strength training, nor does it guarantee universal improvements across all assessed performance measures. The strategic combination of maximum strength phases and reactive power interventions appears conceptually sound, provided that dosage and load progression are carefully controlled.

### *Limitations*

Firstly, the small sample size may limit the statistical power and generalizability of the findings. Secondly, the exclusive inclusion of male athletes restricts the extrapolation to female populations. Furthermore, the control group's external training was not strictly controlled, which may have influenced the results. Baseline differences in isometric pull-up RFD between groups, despite random allocation, represent a potential source of confounding. In addition, it should also be noted that the

Power Slap test was performed on the dominant arm only, which limits the assessment of the bilateral explosive capacity and potential asymmetries between the limbs. Finally, specific performance in an ecological context (track or competition) was not assessed, which limits the direct interpretation of the functional transfer of the observed adaptations.

### *Future Directions*

Regarding recommendations for future studies, it is suggested to explore the strategic combination of maximum strength phases and power phases, progressively integrating higher volumes of specific reactive work on the campus board, always in accordance with the criteria of progression and individualized control. Likewise, it would be pertinent to incorporate specific maximum grip load protocols to analyze possible synergistic effects between maximum finger strength and rapid force development in pulling. Another relevant line of development involves evaluating the direct transfer of improvements in RFD to indicators of competitive performance, such as block resolution within a time limit, number of attempts, or execution efficiency in dynamic problems.

From a methodological perspective, future research could increase sample sizes and consider longer intervention periods, with the aim of analyzing structural adaptations of greater magnitude. It would also be advisable to explore differences by gender, competitive level, or age, as well as to integrate biomechanical and electromyographic variables that allow for a deeper understanding of the neural mechanisms underlying the observed improvements. The incorporation of multicenter designs across different regional contexts would strengthen the evidence base in Latin America, helping to bridge the existing gap between international research and local practice.

## 5. Conclusions

Plyometric training carried out twice a week for 10 weeks produced specificity neuromuscular adaptations in advanced boulder climbers. Significant differences between groups were observed in pull-up performance, plyometric push-up power, and isometric pull-up rate of force development (RFD), both in the early contractions phase (0-200 ms) and in the 20-80% range of maximal force. These adaptations reflect improvements in the capacity to produce force rapidly in pulling specific movement patterns, which are directly relevant to the demands of bouldering.

**Author Contributions:** The following statements should be used: Conceptualization, G.C. and V.L.; methodology, G.C.; software, R.Y.; validation, V.L., G.C., and J.P.; formal analysis, G.C., J.P.; investigation, V.L.; data curation, R.Y.; writing—original draft preparation, G.C.; writing—review and editing, J.P., J.H., E.G; visualization, Y.C., E.G; supervision, G.C.; project administration, V.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** Please add: This research received no external funding.

**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki and approved by the Scientific Ethics Committee of Universidad Viña del Mar (CEC-UVM) (protocol code 32-25, date of approval: June 24, 2025).

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions related to the participants' personal information.

**Acknowledgments:** The authors wish to thank the climbers of Centro de Escalada Tornamesa (Valparaíso, Chile) for their voluntary participation and commitment throughout the study, and to the center's management for providing the facilities and logistical support necessary for the intervention.

**Conflicts of Interest:** The authors declare no conflicts of interest.”.

## Abbreviations

doi:10.20944/preprints202605.1106.v1

The following abbreviations are used in this manuscript:

| Abbreviation | Definition |
|---|---|
| ANOVA | Analysis of variance |
| CG | Control group |
| CI | Confidence interval |
| CMJ | Countermovement jump |
| ICC | Intraclass correlation coefficient |
| IG | Intervention group |
| IRCRA | International Rock Climbing Research Association |
| RFD | Rate of force development |
| SD | Standard deviation |
| $\eta^2p$ | Partial eta-squared |

## References

1. Fanchini, M., Violette, F., Impellizzeri, F. M., & Maffiuletti, N. A. (2013). Differences in climbing-specific strength between boulder and lead rock climbers. Journal of strength and conditioning research, 27(2), 310–314. Doi:10.1519/JSC.0b013e3182577026
2. Laffaye, G., Levernier, G., & Collin, J. M. (2016). Determinant factors in climbing ability: Influence of strength, anthropometry, and neuromuscular fatigue. Scandinavian journal of medicine & science in sports, 26(10), 1151–1159. Doi:10.1111/sms.12558
3. Baláš J, Gajdošík J, Giles D, Fryer S, Krupková D, Brtník T, Feldmann A. Isolated finger flexor vs. exhaustive whole-body climbing tests? How to assess endurance in sport climbers? Eur J Appl Physiol. 2021 May;121(5):1337-1348. doi: 10.1007/s00421-021-04595-7.
4. Faggian, S., Borasio, N., Vecchiato, M., Gatterer, H., Burtscher, M., Battista, F., Brunner, H., Quinto, G., Duregon, F., Ermolao, A., & Neunhaeuserer, D. (2025). Sport climbing performance determinants and functional testing methods: A systematic review. Journal of sport and health science, 14, 100974. doi.org/10.1016/j.jshs.2024.100974
5. Langer K, Simon C and Wiemeyer J (2023) Physical performance testing in climbing—A systematic review. Front. Sports Act. Living 5:1130812. doi: 10.3389/fspor.2023.1130812
6. Michailov, M. L., & Baláš, J. (2023). Reliability and validity of various force-time indicators for the assessment of finger and shoulder girdle strength in climbing. Journal of Applied Sports Sciences, 7(1), 3-14. Doi:10.37393/JASS.2023.01.1
7. Assmann, M., Steinmetz, G., Schilling, A. F., & Saul, D. (2020). Comparison of Grip Strength in Recreational Climbers and Non-Climbing Athletes-A Cross-Sectional Study. International journal of environmental research and public health, 18(1), 129. Doi:10.3390/ijerph18010129
8. Saeterbakken, A. H., Bratland, E., Andersen, V., & Stien, N. (2024). Five weeks of dynamic finger flexor strength training on bouldering performance and climbing-specific strength tests. A randomized controlled trial. Frontiers in physiology, 15, 1461820. doi.org:10.3389/fphys.2024.1461820
9. Vereide V, Andersen V, Hermans E, Kalland J, Saeterbakken AH and Stien N (2022) Differences in Upper-Body Peak Force and Rate of Force Development in Male Intermediate, Advanced, and Elite Sport Climbers. Front. Sports Act. Living 4:888061. doi: 10.3389/fspor.2022.888061
10. Rong, W., Soh, K. G., Samsudin, S., Zhao, Y., Wang, X., Zhang, X., & Cao, L. (2025). Effect of resistance training on kinetic and kinematic indicators in jump athletes: a systematic review. BMC sports science, medicine & rehabilitation, 17(1), 210. Doi:10.1186/s13102-025-01249-5
11. Hugues, X., Oudar, S., Cahouet, V., & Quaine, F. (2025). Coordination of upper and lower limbs in climbing dyno movement. Multidisciplinary Biomechanics Journal, 49th congress of the Société de Biomécanique. Doi:10.46298/mbj.14571 (hal-04738064v2)

12. García-Heras, F., Diez-Martín, M., González-Martín, D., Gutiérrez-Arroyo, J., Molinero, O., & Salguero, A. (2025). Analysis of Lower Limb Performance Determinants in Sport Climbing. Applied Sciences, 15(16), 8797. Doi:10.3390/app15168797
13. Ginszt, M., Saito, M., Zięba, E., Majcher, P., & Kikuchi, N. (2023). Body Composition, Anthropometric Parameters, and Strength-Endurance Characteristics of Sport Climbers: A Systematic Review. Journal of strength and conditioning research, 37(6), 1339–1348. Doi:10.1519/JSC.0000000000004464
14. Li, M., Zhu, Y., & Peng, Y. (2026). The Relationship Between Lower-Limb Explosive Strength and Climbing Speed in Elite Speed Climbers: A Comprehensive Analysis Based on Muscle Morphology and Electromyography. International journal of sports physiology and performance, 21(3), 456–462. Doi:10.1123/ijspp.2025-0329
15. Devise, M., Quaine, F., & Vigouroux, L. (2023). Assessing climbers' pull-up capabilities by differentiating the parameters involved in power production. PeerJ, 11, e15886. Doi:10.7717/peerj.15886
16. Ramirez-Campillo, R., Perez-Castilla, A., Thapa, R. K., Afonso, J., Clemente, F. M., Colado, J. C., de Villarreal, E. S., & Chaabene, H. (2022). Effects of Plyometric Jump Training on Measures of Physical Fitness and Sport-Specific Performance of Water Sports Athletes: A Systematic Review with Meta-analysis. Sports medicine - open, 8(1), 108. Doi:10.1186/s40798-022-00502-2
17. Markovic G. (2007). Does plyometric training improve vertical jump height? A meta-analytical review. British journal of sports medicine, 41(6), 349–355. Doi:10.1136/bjsm.2007.035113
18. Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. Sports medicine (Auckland, N.Z.), 41(2), 125–146. Doi:10.2165/11538500-000000000-00000
19. Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. Sports medicine (Auckland, N.Z.), 41(1), 17–38. Doi:10.2165/11537690-000000000-00000
20. Wang, R., Hoffman, J. R., Sadres, E., Bartolomei, S., Muddle, T. W. D., Fukuda, D. H., & Stout, J. R. (2017). Evaluating Upper-Body Strength and Power From a Single Test: The Ballistic Push-up. Journal of strength and conditioning research, 31(5), 1338–1345. Doi:10.1519/JSC.0000000000001832
21. Dhahbi, W., Chaouachi, A., Dhahbi, A. B., Cochrane, J., Chèze, L., Burnett, A., & Chamari, K. (2017). The Effect of Variation of Plyometric Push-Ups on Force-Application Kinetics and Perception of Intensity. International journal of sports physiology and performance, 12(2), 190–197. Doi:10.1123/ijspp.2016-0063
22. Shih, W.-L., Yeh, M.-L., Chuang, M.-H., & Wu, C.-E. (2024). Dynamic Analysis of Upper- and Lower-Extremity Performance During Take-Offs and Landings in High-Wall Climbing: Effects of a Plyometric and Strength Training Intervention. Applied Sciences, 14(22), 10137. Doi:10.3390/app142210137
23. Stien, N., Pedersen, H., Vereide, V. A., Saeterbakken, A. H., Hermans, E., Kalland, J., Schoenfeld, B. J., & Andersen, V. (2021). Effects of Two vs. Four Weekly Campus Board Training Sessions on Bouldering Performance and Climbing-Specific Tests in Advanced and Elite Climbers. Journal of sports science & medicine, 20(3), 438–447. doi.org/10.52082/jssm.2021.438
24. Labott, B. K., Held, S., Wiedenmann, T., Rappelt, L., Wicker, P., & Donath, L. (2022). Validity and Reliability of a Commercial Force Sensor for the Measurement of Upper Body Strength in Sport Climbing. Frontiers in sports and active living, 4, 838358. Doi:10.3389/fspor.2022.838358
25. Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. European journal of applied physiology, 116(6), 1091–1116. Doi:10.1007/s00421-016-3346-6
26. Draper, N., Dickson, T., Blackwell, G., Priestley, S., Fryer, S., Marshall, H., Shearman, J., Hamlin, M., Winter, D., & Ellis, G. (2011). Sport-specific power assessment for rock climbing. The Journal of sports medicine and physical fitness, 51(3), 417–425.
27. Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular Strength in Athletic Performance. Sports medicine (Auckland, N.Z.), 46(10), 1419–1449.doi:10.1007/s40279-016-0486-0
28. World Medical Association. World Medical Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects. JAMA. 2013;310(20):2191–2194. doi:10.1001/jama.2013.281053

29. Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers.
30. Levernier, G., & Laffaye, G. (2019). Four Weeks of Finger Grip Training Increases the Rate of Force Development and the Maximal Force in Elite and Top World-Ranking Climbers. Journal of strength and conditioning research, 33(9), 2471–2480. Doi:10.1519/JSC.0000000000002230
31. Dickie JA, Faulkner JA, Barnes MJ, Lark SD. Electromyographic analysis of muscle activation during pull-up variations. J Electromyogr Kinesiol. 2017 Feb;32:30-36. doi: 10.1016/j.jelekin.2016.11.004.
32. Garavaglia, L., Romanò, J., Lazzari, F., & Pittaccio, S. (2024). Biomechanical characterisation of the pull-up exercise. Sport Sciences for Health, 20(1), 221-234. doi.org/10.1007/s11332-023-01097-1
33. Vigouroux, L., Devise, M., Cartier, T., Aubert, C., & Berton, E. (2019). Performing pull-ups with small climbing holds influences grip and biomechanical arm action. Journal of sports sciences, 37(8), 886–894. Doi:10.1080/02640414.2018.1532546
34. Baláš, J., Pecha, O., Martin, A.J. and Cochrane, D. (2012), Hand–arm strength and endurance as predictors of climbing performance. European Journal of Sport Science, 12: 16-25. Doi:10.1080/17461391.2010.546431
35. Dankel, S. J., Counts, B. R., Barnett, B. E., Buckner, S. L., Abe, T., & Loenneke, J. P. (2017). Muscle adaptations following 21 consecutive days of strength test familiarization compared with traditional training. Muscle & nerve, 56(2), 307–314. doi.org/10.1002/mus.25488
36. Mattocks, K. T., Buckner, S. L., Jessee, M. B., Dankel, S. J., Mouser, J. G., & Loenneke, J. P. (2017). Practicing the Test Produces Strength Equivalent to Higher Volume Training. Medicine and science in sports and exercise, 49(9), 1945–1954. doi.org/10.1249/MSS.0000000000001300
37. Saeterbakken, A. H., Stien, N., Pedersen, H., Langer, K., Scott, S., Michailov, M. L., Gronhaug, G., Baláš, J., Solstad, T. E. J., & Andersen, V. (2024). The Connection Between Resistance Training, Climbing Performance, and Injury Prevention. Sports medicine - open, 10(1), 10. doi.org/10.1186/s40798-024-00677-w
38. Antinori, F., Felici, F., Figura, F., Marchetti, M., & Ricci, B. (1988). Joint moments and work in pull-ups. The Journal of sports medicine and physical fitness, 28(2), 132–137.
39. Vigouroux, L., & Devise, M. (2024). Pull-Up Performance Is Affected Differently by the Muscle Contraction Regimens Practiced during Training among Climbers. Bioengineering (Basel, Switzerland), 11(1), 85. doi.org/10.3390/bioengineering11010085.
40. Philippe, M., Filzwieser, I., Leichtfried, V., Blank, C., Haslinger, S., Fleckenstein, J., & Schobersberger, W. (2019). The effects of 8 weeks of two different training methods on on-sight lead climbing performance. The Journal of sports medicine and physical fitness, 59(4), 561–568. Doi:10.23736/S0022-4707.18.08399-8