Assessment and training for climbing-related performance

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Doctor Philosophiae
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2. List of original articles

The present thesis is based on the following papers:

I. Stien, Nicolay; Riiser, Amund; Shaw, Matthew Peter; Saeterbakken, Atle Hole; Andersen, Vidar. Effects of climbing- and resistance-training on climbing-specific performance: A systematic review and meta-analysis. Submitted March 3rd, 2021 to Biology of Sport.

II. Stien, Nicolay; Vereide, Vegard Albert; Saeterbakken, Atle Hole; Hermans, Espen; Shaw, Matthew Peter; Andersen, Vidar. (2021). Rate of force development discriminates performance levels in sport climbing. PLoS ONE, 16(3): e0249353.


IV. Stien, Nicolay; Frøysaker, Tor Frithjof; Hermans, Espen; Vereide, Vegard Albert; Andersen, Vidar; Saeterbakken, Atle Hole. (2021). The effects of prioritizing lead or boulder climbing among intermediate climbers. Frontiers in Sports and Active Living, 3:661167.

V. Stien, Nicolay; Pedersen, Helene; Vereide, Vegard Albert; Saeterbakken, Atle Hole; Hermans, Espen; Kalland, Jarle; Schoenfeld, Brad J; Andersen, Vidar. (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 and Medicine, 20, 438-447.
### 3. Abbreviations

<table>
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<th>Description</th>
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<tr>
<td>ANCOVA</td>
<td>Analysis of covariance</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<tr>
<td>CI</td>
<td>Confidence interval</td>
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<td>CV</td>
<td>Coefficient of variation</td>
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<td>EMG</td>
<td>Electromyography</td>
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<td>ES</td>
<td>Effect size</td>
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<td>ICC</td>
<td>Intra-class correlation</td>
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<td>IRCRA</td>
<td>International Rock Climbing Research Association</td>
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<td>MVIC</td>
<td>Maximal voluntary isometric contraction</td>
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<td>RFD</td>
<td>Rate of force development</td>
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<td>SD</td>
<td>Standard deviation</td>
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<td>SMD</td>
<td>Standardized mean difference</td>
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4. Summary

Climbing-specific resistance-training (RT) and systematic climbing training can be performed to improve climbing performance and/or performance in climbing-specific tests. While myriad experience-based training techniques exist, very few approaches for improving climbing-related strength and endurance are supported by scientific evidence. Currently, no consensus exists among researchers regarding methods for assessing performance factors and the physiological mechanisms associated with these factors among climbers. Additionally, climbing tests and testing procedures vary considerably between studies. The present thesis aimed to explore some of the novel methods for assessing and improving climbing-related performance factors.

Paper I was a systematic review and meta-analysis that examined the effects of climbing training and RT on climbing performance and climbing-specific tests. The systematic search was limited to randomized-controlled trials that included active climbers. The included studies had to examine the effects of training on climbing performance or climbing-specific strength- and/or endurance measurements. The meta-analysis showed that forearm endurance and finger strength were improved by RT of the finger flexors, whereas the systematic review revealed that climbing performance can be improved following climbing-specific RT or interval-style bouldering training. The available literature suggests that RT, or a combination of climbing- and RT could be more effective than climbing training alone for improving performance measures (e.g., finger strength or forearm endurance) among active climbers. Moreover, females are underrepresented in the climbing literature, the available longitudinal research consists mainly of short-duration interventional studies, and most papers fail to provide a detailed description of their study samples. Finally, a scarcity of scientific evidence was identified in the field of training for climbing performance, and future research is required to confirm the findings of this systematic review and meta-analysis.

Paper II assessed and compared maximal strength and RFD among climbers performing on an intermediate, advanced, and elite level. The measurements were collected during an isometric pull-up performed using a 23 mm deep rung, and RFD was calculated using several absolute (milliseconds from the onset of contraction) and relative (% of time to reach peak force) time-periods to examine which measure was the most reliable and discriminatory between performance levels. The elite climbers produced a significantly higher RFD than the
other groups using all relative time periods, whereas between-groups differences were detected at the 50 ms, 100 ms, and 150 ms of absolute time periods. No differences were found at any time-period between the intermediate and advanced groups. Moreover, using relative time periods of the force curve to calculate RFD produced more reliable and discriminatory measurements. The results indicate that maximal strength and RFD during an isometric pull-up can be used to discriminate between performance levels in climbing. Using 100% of the force curve to calculate RFD appears to be the most discriminatory and reliable measure in this test.

Paper III compared climbing-specific endurance, as well as maximal and explosive strength between lead- and boulder climbers. The strength measures were collected during isometric and dynamic pull-ups using one small and one large hold, thereby including, and excluding the finger strength demands, respectively. We were, therefore, able to examine whether finger strength (the weakest link in the pulling-apparatus when using shallow holds) limited performance differently between the two groups. In addition, forearm endurance was assessed during an intermittent test (7 seconds work and 3 seconds rest) until failure using a shallow rung. The results revealed that explosive strength was the most discriminatory factor between the groups. Boulder climbers demonstrated significantly greater rate of force development (RFD) and pull-up velocity than the lead climbers. Moreover, maximal isometric strength was also greater among the boulder climbers, but the two groups were similarly limited by finger strength when performing the pull-up using a shallow hold. Conversely, forearm endurance was not significantly different between disciplines. The results could reflect the specific physiological requirements of the two disciplines, suggesting that the more powerful style of bouldering promotes maximal and explosive strength more than lead climbing does. However, the differences could also be the result of individuals selecting their preferred discipline based on their underlying physiological characteristics.

Paper IV examined the effects of prioritizing either lead climbing or bouldering for five weeks. Prioritizing one discipline included conducting two weekly moderate-to-high intensity sessions of that discipline while only performing one low-intensity session of the other discipline. Participants were tested for lead climbing and bouldering performance, as well as maximal strength, RFD, and forearm endurance. Following five weeks, no changes in lead- or boulder climbing had occurred in either group, nor were any significant differences detected between the groups for any of the tested variables. However, only the lead climbing group

improved forearm endurance, while the bouldering group improved isolated, maximal finger strength. Moreover, both groups improved maximal, isometric pull-up strength. The results indicate that either discipline can be prioritized in a five-week block without a risk of reduced performance in the other discipline. Individuals aiming to improve maximal finger flexor strength may benefit from prioritizing bouldering for a five-week block period, whereas lead climbing training may be beneficial for climbing-specific forearm endurance. Both approaches appear to improve maximal, isometric pull-up strength among intermediate climbers.

Paper V examined the effects of five weeks of campus board training among advanced and elite climbers, as well as an active control condition (i.e., climbing training as usual). The total training volume was equated between groups but divided over two or four weekly sessions. The participants were tested in bouldering performance, RFD, maximal strength, forearm circumference, campus board moves to failure, and maximal reach on the campus board. Following the five weeks of training, no significant differences were detected between the training groups. However, four weekly campus board training sessions improved RFD and maximal isometric pull-up strength more than the control condition. The group that performed two weekly sessions achieved greater improvements in bouldering performance and number of moves to failure on the campus board when compared to the control group. Moreover, when merging the training groups and comparing them to the control condition, campus board training improved maximal strength using a shallow rung, bouldering performance, and maximal reach and moves to failure on the campus board. In conclusion, a five-week campus board training block can improve performance in several climbing-specific tasks, regardless of training frequency. However, greater improvements in RFD may be achieved by dividing the volume over four shorter sessions, whereas two weekly sessions may be beneficial for improving bouldering performance.
5. Introduction

As the first scientific work examining performance factors in rock climbing was published in 1993 [1] and the first intervention study was not conducted until 2012 [2], the field of research investigating performance factors in climbing is still in its infancy. In the last decade, the sport has received a growing interest from researchers as well as professional and recreational athletes and will, for the first time, be included in the upcoming Tokyo Olympics [3]. Although athletes continue to advance the limit of what is considered possible in rock climbing (Figure 1)[4], the anecdotal evidence for effective training prescription far outweighs the scientific knowledge, and researchers have yet to agree on standardized practices for testing and monitoring climbers. The aim of this thesis was to expand on the scientific knowledge about experimental assessment and training for climbing-specific performance factors. The following section will provide a rationale for the research that forms this thesis.

![Figure 1: Peak recorded sport climbing performance throughout the past decades. Adapted from Michailov et al. [4] with permission.](image-url)

Outside of competition settings, climbing performance is usually quantified using various scales that indicate the difficulty of accomplished ascents. Several scales exist (e.g., the French numerical and Yosemite decimal systems for sport climbing routes, or the
Fontainebleau and Vermin systems for boulder problems) and are usually selected based on the respective discipline or the geographical location of the route or boulder problem. To assist the description of difficulty across disciplines and locations, a standardized, numerical system (1 – 32) proposed by the International Rock Climbing Research Association (IRCRA) is usually implemented in research [5]. For research purposes, the system can be used to divide climbers into lower-grade, intermediate, advanced, elite, and higher elite performance levels with different cut-off values for males and females, as well as for lead- and boulder climbers.

Competitive climbing is divided into the three subdisciplines speed climbing, bouldering, and sport climbing. Speed climbing involves scaling a 15 meter tall, slightly overhanging wall with big, standardized hand- and footholds as quickly as possible (typically between five and ten seconds for elite athletes) while wearing an auto-belay device for safety. In sport climbing, the climbers attempt to ascend an approximately 10 – 20 meter tall wall while using a rope to secure themselves. In contrast to speed climbing, a sport climbing attempt can take up to seven minutes to complete and the difficulty, hold size and placement, and gradient of the wall vary between routes [6]. Bouldering is performed on 4 – 5 meter tall walls and typically include fewer but more difficult and athletic moves [7]. In contrast to lead- and speed climbing where the protection is used to avoid falling to the ground, a soft pad allows the boulderer to safely fall off a boulder problem with a minimal risk of injury. Finally, lead- and speed climbing competitions allow one attempt per route, whereas athletes are permitted to attempt a boulder problem several times within four minutes. Of the three disciplines, bouldering and sport climbing are the two most practiced and researched disciplines [3, 7], and only these two disciplines will be discussed in the present thesis.

Due to the distinctly different characteristics of sport climbing and bouldering, researchers early hypothesized that the physiological attributes could vary between athletes specializing in either discipline [7]. Indeed, different performance in climbing-specific tests between athletes specializing in lead- or boulder climbing has since been identified [8-10]. Of the parameters that have been examined, RFD, maximum voluntary isometric contraction (MVIC) and power output of the fingers and upper body have been identified as discriminatory factors, whereas no clear difference in forearm endurance has yet been detected [8-10].
Researchers have further attempted to identify how the climbing performance level is affected by factors such as technical skills [11], oxygen consumption [12], forearm endurance [13-15], muscle activity [16], anthropometry [17], upper-limb power [18], and RFD and maximal strength of the pulling apparatus [19-21]. Albeit reports of all these parameters being determining factors for the performance level of climbers [13, 17, 19, 20, 22], and discriminating between climbers and non-climbers have been published [17, 19, 23-26], comparisons across several performance levels are scarce [18, 27]. Moreover, the studies vary greatly in measuring techniques and study sample characteristics, making generalization based on the results problematic.

A limited amount of scientific research has been dedicated to examining the effects of different training strategies for improving climbing performance [28-30]. Contrarily, most of the available literature has described the effect of RT on performance in climbing-related strength- and endurance tests rather than actual climbing performance [2, 31-34]. Hence, the current available literature describing effective methods for improving climbing performance consists mainly of anecdotal evidence from athletes and coaches.

Albeit the amount of research examining performance assessment and training modalities for climbing is increasing, the sport is still tremendously underrepresented in the scientific literature (i.e., < 10 available records for intervention studies) compared to other Olympic sports. The available literature is further limited by vast variations in the approach to training, rendering most suggested training methods unverified by reproduction as most training- or measuring methods have only been investigated once [35]. Common limitations in interventional climbing research includes small (n < 20) sample sizes [2, 31, 33], lack of a control group [2, 29-32, 34], varying performance levels, and short (i.e., < 5 weeks) intervention durations [33, 34]. Moreover, intervention studies including elite and higher-elite climbers are rare [33, 34]. Regarding acute studies, researchers have yet to agree upon standardized measuring techniques (e.g., test selection, body positioning, and hold type) for assessing climbing-related performance and the current knowledge is, therefore, characterized by several fragments and not one continuous advancement.

On the basis of the aforementioned studies and limitations of the current knowledge, this thesis aimed to explore the following research questions: 1) How does performance in climbing-specific tests differ between lead- and boulder-climbers (Paper III), and between
performance levels (Paper II)? 2) how campus board training frequency affects bouldering performance and climbing-specific physical tests (Paper V)?; and 3) how can climbing performance and performance in climbing-specific tests be improved by prioritizing one discipline (Paper IV), or by various RT methods (Paper I)?
6. Review of the literature

This section will provide an overview of the current knowledge about 1) performance factors dictating climbing performance, 2) available testing procedures for assessing different attributes among climbers, and 3) training methods for improving such attributes. In this thesis, RT is defined as the act of performing non-climbing RT exercises with the aim of improving performance in specific tasks or increasing strength in specific muscles or muscle groups. Since climbing is usually performed using mainly small hand- and foot holds to remain in contact with the wall and progress upwards, finger strength and forearm endurance are generally recognized as a crucial factor for climbing performance [15, 17, 36-38], and have been among the main outcomes in several training studies [2, 32-34], as well as in cross-sectional investigations.

6.1 Acute investigations of climbing-related performance factors

6.1.1 Performance factors in climbing

Studies describing factors that predict lead- and boulder climbing performance have reported highly developed strength and endurance of the trunk and upper extremities, low body fat, excellent technical skills, and high hip mobility as key characteristics of climbers performing on high levels [3, 13, 37, 39-41]. For example, did Deyhle et al. [38] identify strength of the digit- and elbow flexors as especially important for climbing performance. Conversely, MacKenzie et al. [37] suggested that shoulder girdle strength may be more important, whereas the authors identified strength of the trunk, fingers, and arms as secondary determinants for climbing performance. Moreover, Baláš and colleagues [41] examined the relationship between climbing performance and hand-arm strength and endurance among 205 sport climbers with self-reported red-point grades ranging from 5 – 29 on the IRCRA scale. The authors concluded that climbing-specific tests (grip strength, bent-arm hang, and finger hang) as well as anthropometric factors and bioelectric impedance analysis explained 97% of the variance in climbing performance. In addition to these trainable and measurable factors, other researchers have identified self-efficacy, mental balance, route previewing skills, and risk management as influential factors for climbing performance [42-44]. However, only physical performance factors will be discussed in this thesis.
6.1.2 Explosive- and maximal strength tests

Several studies have examined parameters such as maximal strength, RFD, and power among climbers [8, 9, 17-19, 23, 39, 45-47]. Generally, three types of test set-ups have been implemented in the available research: 1) handheld dynamometers, 2) wall- or table-mounted dynamometer tests isolating the forearm muscles while excluding the thumb, elbow flexors, and shoulder extensors, and 3) unconstrained tests allowing force to be generated from the entire pulling apparatus (fingers, arms, shoulders, and back). See Table 1 and Figure 2 for examples of applied strength- and power tests. Albeit handheld dynamometers could be criticized for not providing a climbing-specific hold and body position, and not be associated with climbing performance, they may be a sensitive, simple, and low-cost alternative for assessing strength of the finger flexors [48]. The second type of test set-ups includes isolating the forearm muscles (typically by fixating the elbow in a 90° angle [39, 49]) to exclude any force generated by the arms- and back muscles, and only registering the actual finger flexion force. Finally, some investigations have used unconstrained tests in which participants are able to utilize the entire pulling apparatus [18, 19], possibly providing the most climbing-related task of the three, but at the risk of higher variability due to the inclusion of several joints.

Table 1: Examples of applied climbing-related strength-and power testing protocols.

<table>
<thead>
<tr>
<th>Author</th>
<th>Test set-up</th>
<th>Measurements</th>
</tr>
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<tbody>
<tr>
<td>Baláš, et al. [41]</td>
<td>Dynamometer</td>
<td>MVC</td>
</tr>
<tr>
<td>Ozimek, et al. [48]</td>
<td>Dynamometer</td>
<td>MVC and RFD</td>
</tr>
<tr>
<td>Grant, et al. [50]</td>
<td>Constrained elbow</td>
<td>MVC using half crimp</td>
</tr>
<tr>
<td>MacLeod, et al. [15]</td>
<td>Constrained elbow</td>
<td>MVC using half crimp</td>
</tr>
<tr>
<td>Fanchini, et al. [8]</td>
<td>Constrained elbow</td>
<td>MVC and RFD in full- and open crimp</td>
</tr>
<tr>
<td>Levernier and Laffaye [19]</td>
<td>Unconstrained</td>
<td>MVC and RFD in unilateral open crimp</td>
</tr>
<tr>
<td>Laffaye, et al. [18]</td>
<td>Jug holds</td>
<td>Power and velocity in arm-jump</td>
</tr>
<tr>
<td>Levernier, et al. [10]</td>
<td>Pull-up bar</td>
<td>Power in pull-up with extra-load</td>
</tr>
<tr>
<td>Torr, et al. [51]</td>
<td>20mm rung</td>
<td>Unilateral dead-hang with de-load</td>
</tr>
<tr>
<td>López-Rivera and González-Badillo [2]</td>
<td>15mm rung</td>
<td>5s bilateral dead-hang with extra-load</td>
</tr>
</tbody>
</table>

s = seconds; MVC = maximal voluntary isometric contraction; RFD = rate of force development
Figure 2: Examples of (A) handheld dynamometer test [34], (B) constrained testing [52], and (C) an unconstrained test set-up [19]. Note that B and C includes shallow rungs, whereas A is not performed on a climbing-specific hold.

For many of studies implementing the aforementioned tests, the aim has been to either compare disciplines [8, 9, 18] or performance levels [1, 18, 19, 46]. For between-discipline comparisons, it is generally accepted that athletes specializing in boulder climbing are stronger and more explosive than lead-climbers [8, 9]. Comparing a diverse range of performance levels (ranging from lower-grade to elite), Draper and colleagues [27] reported that the power-slap test differentiated between the levels. Furthermore, Levernier and Laffaye [19] concluded that maximal strength and RFD measured on a climbing-specific hold while standing with an unconstrained elbow in a 90° angle discriminated between climbing levels (i.e., international-, skilled-, and non-climbers). Similarly, Grant et al. [17] showed that finger grip strength discriminated between female elite-, recreational, and non-climbers. The findings of Levernier and Laffaye [19] and Grant et al. [17] might not be surprising considering the considerable difference between performance levels (e.g., international climbers versus non-climbers). Of note, the researchers tested grip strength using a table-mounted dynamometer, which could lack specificity to climbing performance.
6.1.3 Forearm endurance tests

Many studies have reported on the forearm endurance characteristics of climbers [9, 13, 14, 17, 22, 28, 31, 53-58]. While some have tested forearm endurance via dead-hang duration on a fingerboard [28, 31] or sustained isometric force development at a given threshold to failure [48, 59], tests including intermittent contractions [9, 13, 22, 57] have been the most applied protocol (Table 2). The aim of these endurance tests are typically to mimic hold types [26] and contraction patterns observed in climbing [52]. It has been reported that a crimp grip is the most applied grip position in climbing [60], whereas the sport is characterized by bouts of force development during contact with holds (typically 5-10 s) separated by one-to-five seconds of rest while performing movements between holds [7]. For example, forearm endurance using intermittent tests with a work-to-rest ratio of 10:4 (seconds) at 40% of MVIC [13, 22], 8:2 ratio at 60% of MVIC [58], and 5:5 ratio at 80% of MVIC [25] have been examined.

<table>
<thead>
<tr>
<th>Author</th>
<th>Test set-up</th>
<th>%MVIC</th>
<th>Protocol</th>
<th>Work:rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozimek, et al. [48]</td>
<td>Dynamometer</td>
<td>50%</td>
<td>Sustained</td>
<td>•</td>
</tr>
<tr>
<td>Limonta, et al. [59]</td>
<td>Dynamometer</td>
<td>80%</td>
<td>Sustained</td>
<td>•</td>
</tr>
<tr>
<td>MacLeod, et al. [15]</td>
<td>Constrained elbow</td>
<td>40%</td>
<td>Intermittent</td>
<td>10:3</td>
</tr>
<tr>
<td>Fryer, et al. [22]</td>
<td>Constrained elbow</td>
<td>40%</td>
<td>Intermittent</td>
<td>10:3</td>
</tr>
<tr>
<td>Michailov, et al. [52]</td>
<td>Constrained elbow</td>
<td>60%</td>
<td>Intermittent</td>
<td>8:2</td>
</tr>
<tr>
<td>Staszkiewicz, et al. [61]</td>
<td>Constrained elbow</td>
<td>60%</td>
<td>Intermittent</td>
<td>7:3</td>
</tr>
<tr>
<td>Saeterbakken, et al. [61]</td>
<td>Constrained elbow</td>
<td>70%</td>
<td>Intermittent</td>
<td>7:3</td>
</tr>
<tr>
<td>Vigouroux and Quaine [26]</td>
<td>Constrained elbow</td>
<td>80%</td>
<td>Intermittent</td>
<td>5:5</td>
</tr>
<tr>
<td>Baláš, et al. [58]</td>
<td>Climb to failure</td>
<td>•</td>
<td>•</td>
<td></td>
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<tr>
<td>Medernach, et al. [34]</td>
<td>30mm fingerboard</td>
<td>•</td>
<td>Intermittent</td>
<td>8:4</td>
</tr>
<tr>
<td>López-Rivera and González-Badillo [62]</td>
<td>11mm fingerboard</td>
<td>•</td>
<td>Sustained</td>
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</table>

%MVIC = threshold expressed as percentage of maximal voluntary isometric contraction
Work:rest = ratio between seconds of work and rest.
Of the studies examining the training effects on climbing-related forearm endurance, López-Rivera and González-Badillo demonstrated that a sustained, isometric dead-hang to failure on a fingerboard rung was sufficiently sensitive for detecting changes following a training period [2, 32]. Regarding cross-sectional comparisons, Fryer et al. [22] reported a higher force-time-integral (FTI) among elite climbers compared to sub-elite- and non-climbers using a 10:3 work-to-rest ratio in a constrained test set-up. Fryer and colleagues reported in another study [13] that oxygen recovery in the finger flexors during a similar test set-up was also greater among the elite climbers. Moreover, Baláš et al. [58] showed that both sustained and intermittent contraction impulse (N×s) displayed significant differences between intermediate and advanced lead climbers. Despite proving a useful tool for demonstrating differences between performance levels and between climbers and non-climbers, forearm endurance has not yet successfully been used to discriminate between disciplines.

6.1.2 Reliability and validity of climbing-specific performance tests

Some research has been dedicated to examining the reliability and validity different performance assessment tests for climbers [19, 27, 39, 51]. For example, Michailov and colleagues [39] conducted a series of tests (e.g., finger grip RFD, maximal strength, and forearm endurance) with and without elbow flexion and concluded that 1) testing with elbow flexion provided more reliable results (ICC = 0.94 vs. 0.88), especially for maximal strength, but 2) testing without elbow flexion was slightly more related to self-reported red-point climbing ability (r² = 0.48 vs. r² = 0.42). In a later study, Levernier and Laffaye [19] examined the reliability of a similar test for measuring RFD and maximal strength of the finger flexors. The maximal strength measurements displayed an acceptable reliability (CV = 2.9% – 10.0%) and was proposed as a sensitive test able to detect differences between performance levels. The authors further concluded that RFD200 (calculated using the first 200ms from the onset of contraction) and RFD95% (calculated using the first 95% of the force curve) were reliable measures (CV = 7.8% – 28.3%), and that competitive climbers were able to produce more reliable results compared to skilled- and non-climbers. Importantly, the authors neglected testing other relative time periods (percentages from the onset). Moreover, the absolute time periods tested (50ms, 100ms, and 200ms) might only be useable in the specific task tested, as the time to reach peak force will likely vary between tasks.
6.2 Intervention studies

6.2.1 Climbing-specific resistance-training

Among competitive climbers, two of the most practiced finger strength training methods are campus board and fingerboard training [63]. Whereas campus board training includes a dynamic movement pattern that mimics climbing, fingerboard training aims to improve the ability to hang statically from small holds. In the available scientific literature, campus board training has received little attention [29], whereas fingerboard training has been among the more frequently examined training methods among climbers [2, 32-34]. Fingerboard training includes hanging statically from a shallow rung (usually 10mm to 23mm) with the goal of increasing the strength or endurance in the finger flexors. Fingerboard training can be performed using different hold types (e.g., flat rungs, slopers, or pockets) and grip positions (e.g., open hand, half-crimp, or full-crimp; Figure 3). Moreover, some protocols attempt to mimic the work to rest ratio [7] observed in climbing (e.g., ten seconds hangs with five seconds rest [32]), whereas others more closely resemble traditional strength training (e.g., three-to-six seconds maximal hangs and three minutes rest [33]).

![Figure 3: Illustrations of the A) open hand, B) half-crimp, and C) full-crimp grip positions.](image-url)
The studies describing the effects of fingerboard training have reported improvements in RFD [33], maximal strength [32-34], and endurance [32, 34] in the finger flexors among advanced-to-elite lead- and boulder climbers following four-to-eight weeks of training. Importantly, only Medernach et al. [34] and Levernier and Laffaye [33] included a control group in which the participants continued their normal climbing- and training-routines. According to their results, both bi- [34] and unilateral [33] fingerboard training without extra-weight was more effective than continuing the regular lead- or boulder climbing training. Of note, all the studies neglected assessment of the changes in actual lead- or boulder climbing performance [2, 32-34].

Furthermore, strength and endurance in the remaining muscle groups responsible for generating vertical propulsive force (e.g., elbow flexors and shoulder girdle) have been examined and classified as important factors for climbing performance [37, 38]. However, only one study [28] has explored the effect of training these muscles among climbers. Hermans et al. [28] reported that a ten-week period of upper-limb RT improved dead-hang endurance and pull-down strength in lower-grade and intermediate climbers, regardless of training method (high-repetitions-low-load or few-repetitions-high-load). However, no significant changes occurred in lead-climbing performance. It is possible that more climbing-specific training could be preferable for improving climbing-performance in a population performing on a lower level, whereas climbers already performing on a very high level might benefit more from upper-limb RT.

Finally, trunk muscle strength may be an important determinant for climbing performance [16, 37], and isometric trunk muscle training has been shown to improve performance in climbing-specific strength tests [31]. Saeterbakken et al. [31] reported that ten weeks of performing dynamic or isometric trunk muscle RT improved isometric trunk flexion strength and body-lift (number of repetitions) among elite climbers. However, the authors did not include a measure of climbing performance, and the effects of trunk muscle RT on actual climbing performance are, thus, still unknown.
6.2.2 Climbing training

Very little research has been dedicated to exploring the effects of climbing training on climbing performance (i.e., measured by route or boulder problem difficulty) and climbing-specific strength or endurance among active climbers. However, Medernach et al. [30] examined the changes in climbing time to exhaustion following four weeks of conventional bouldering and interval-style bouldering. The authors reported that interval-style bouldering was more effective than conventional bouldering training for improving climbing-time to exhaustion (assessed by repeated ascents of a four-meter high bouldering wall). In a more recent study, Philippe et al. [29] compared the effects of two different training methods (described as muscular hypertrophy and endurance training) on on-sight lead climbing performance among non-competitive climbers with an on-sight level of IRCRA 20.8 ± 2.0. The participants in the hypertrophy training group were assigned to prioritize hard bouldering training, campus board training and lead-climbing projecting, whereas the endurance group performed a combination of hard and easy lead-climbing sessions. Following eight weeks, both groups improved on-sight lead-climbing performance, but the improvement was not different between the groups.

In addition to these studies, the effects of undertaking climbing training among non-climbers have been explored [64-66]. A recent review and meta-analysis by Li et al. [66] suggested that college students could improve overall fitness following a period of climbing training. For example, Lopera and colleagues [64] reported that seven weeks of indoor lead-climbing increased handgrip strength, pinch strength, handgrip endurance, arm hang-time, and climbing performance. Albeit not applicable to active climbers, these results could reflect which physiological attributes that are mainly affected by climbing training. Importantly, as the authors acknowledge themselves, the early-phase improvement in climbing performance is likely the result of technical improvements rather than physical adaptations.
6.3 Limitations of the existing knowledge

Only a handful of intervention studies examining climbing-related performance have been conducted since the first climbing-related intervention was published in 1993 [1]. Hitherto, evidence-based training recommendations (e.g., volume, intensity, and frequency) are limited for climbing compared to other Olympic sports. Even though discovering evidence based methods for improving climbing ability could be considered the paramount goal of intervention studies, very few studies have included a measure of actual climbing performance [28, 29]. Rather, performance in climbing-related tasks has been measured to assess the potential changes [2, 31, 32, 34]. However, the specific strength- or endurance tests incorporated in different studies vary, rendering the reported effects incomparable. Moreover, many intervention studies have failed to include a control group [2, 29, 32], and the study populations have often been poorly described [5].

The body of cross-sectional investigations is considerably richer. However, different tests for measuring factors such as strength and endurance have been applied and the results may not be comparable. Although researchers have examined the validity and reliability of some climbing-specific performance tests [19, 48, 52], the findings may be limited to the specific test and procedure examined. Hence, validations of novel and existing tests are warranted. Finally, vast disparities in performance levels and disciplines of the study populations exist. Only a limited number of results can, therefore, be discussed across studies.
7. Aims and hypotheses

The purpose of this thesis is threefold: 1) to explore the role of muscle strength in the finger flexors and pulling apparatus for climbing performance/discipline, 2) to examine the effects of training (climbing or climbing-specific RT) on climbing performance and climbing-related tasks, and 3) to investigate methods for assessing climbers, with extra focus on their rapid force production capabilities.


In the last decade, a growing number of intervention studies have examined the effects of climbing-training or climbing-specific RT. However, the findings are often contradictory and methodological approaches vary greatly between studies. Moreover, although systematic [3] and narrative reviews [67-69] have described the physiological requirements of rock climbing and the characteristics of climbers performing on different levels, no systematic review and meta-analysis has yet been conducted on the effects of climbing-training or climbing-specific RT. Therefore, this study aimed to provide an overview of the current knowledge of training for climbing, as well as to meta-analyze the effects of climbing- and climbing-specific RT on climbing performance and performance in climbing-specific tasks.

Paper II: Rate of force development discriminates performance levels in sport climbing.

Performing on a high level in sport climbing includes being able to perform long and difficult moves and rapidly grip hold with progressively smaller size. Hence, RFD in the finger flexors has been proposed as a significant indicator for sport climbing performance [19]. However, no prior study has examined the differences in RFD in the entire pulling apparatus (finger flexors, elbow flexors and back muscles) between climbing levels. The aim of this study was, therefore, to compare the RFD of the entire pulling apparatus between intermediate, advanced, and elite climbers, as well as to identify the most reliable method for calculating RFD. It was hypothesized that the elite climbers would produce higher RFD than both the other groups, and that the advanced climbers would demonstrate higher RFD than the intermediate climbers. It was also expected that RFD calculated using longer time periods of the force curve would be a more reliable and discriminatory measure between performance levels than the shorter periods.
Paper III: Comparison of climbing-specific strength and endurance between lead and boulder climbers.

Indoor competitive lead climbing and bouldering differ in terms of strength and endurance requirements [7, 8]. Whereas leading a route may take between two to seven minutes on a 10-20 meter high wall, bouldering is characterized by shorter (~5 meters) and steeper walls and consists of around eight to ten explosive climbing moves [7]. Despite the distinctive differences between disciplines, little is known about the differing upper-body strength characteristics of athletes specializing in either lead climbing or bouldering. Furthermore, the effect of hold size on performance in climbing-specific tasks has not been sufficiently examined. The aims of the present study were 1) to examine maximal and explosive strength in dynamic and isometric pull-up, 2) to identify the utilization rate of force using a ledge hold compared to a jug hold, and 3) to compare forearm muscle endurance between lead and boulder climbers. It was hypothesized that boulder climbers would demonstrate greater maximal force, rate of force development and pull-up velocity, while lead climbers were expected to demonstrate greater climbing-specific forearm muscle endurance. Both groups were also expected to demonstrate reduced force output and RFD in the isometric pull-up when performing the tests on smaller holds with higher finger-strength requirements.

Paper IV: The Effects of Prioritizing Lead or Boulder Climbing Among Intermediate Climbers.

Lead- and boulder climbing vary in terms of duration and climbing style [7], and cross-sectional studies have identified distinctive differences between athletes specializing in lead- and boulder climbing [8, 9]. However, no study has yet investigated the effects of prioritizing either lead- or boulder climbing training. The aim of this study was to compare the changes in climbing performance, RFD, maximal strength in a climbing-specific task, and forearm endurance following five weeks of prioritizing either lead- or boulder climbing. It was hypothesized that both training groups would improve their prioritized discipline more than the non-prioritized discipline, and that each group would improve their respective discipline more than the other group. It was also hypothesized that prioritizing lead climbing would produce greater improvements in forearm endurance, whereas the bouldering group was expected to improve RFD and maximal strength more than the lead climbing group.
Paper V: Effects of two vs. four weekly campus board training sessions on bouldering performance and climbing-specific tests in advanced and elite climbers.

High levels of maximal and explosive strength of the fingers and forearms, elbow flexors, and shoulder- and back muscles (pulling apparatus) have been identified as significant attributes of highly accomplished climbers [3, 17, 18, 23, 38]. Whereas traditional upper-body RT [28] and isolated finger flexor training [2, 32, 33] have been examined previously, no study has thus far explored the effects of campus board training which engages the entire pulling apparatus in a highly climbing-specific task. Furthermore, due to the being a highly explosive and demanding exercise with a noteworthy risk of injury [63], dividing the training volume over several days may be beneficial during campus board training [70-72]. Therefore, the aim of this study was to assess the effects of campus board training, as well as to compare the effects of dividing the weekly training volume over two and four days. It was hypothesized that the training groups would improve maximal strength, RFD, bouldering performance, and maximal number of moves and maximal reach on the campus board more than the control group. Moreover, the group that trained four times per week was expected to improve bouldering performance, RFD, and maximal reach more than the other groups, whereas the group that trained two times per week was expected to achieve superior improvements in number of moves to failure on the campus board. Finally, maximal strength was expected to increase similarly between the training groups.
8. Materials and methods

All data collection for the papers within the present thesis was conducted between 2019 – 2020 at the Faculty of Education, Arts and Sports; Western Norway University of Applied Sciences, campus Sogndal. All the studies were approved by the Norwegian Centre for Research Data and conformed to the ethical guidelines of the university and the latest revision of the declaration of Helsinki. All participants in the original papers were informed verbally and in writing about the potential risks and benefits of participating in the studies before signing an informed consent form.

8.1 Participants

A total of 118 healthy and recreationally trained climbers were included in the original investigations (Papers II - V; Table 3). All of whom were over the age of 18 and none had any illnesses or injuries that could restrict performance in testing or training. The different papers had some additional inclusion criteria that had to be met. In Paper III, the minimal self-reported accomplished climbing grade had to be no less than 7a (IRCRA 17) for men and 6b (IRCRA 13) for women, whereas the cut-off was set at 6c (IRCRA 15) and 6b+ (IRCRA 14) in Paper IV. Paper III included 28 men and three women, whereas Paper IV comprised 11 men and three women. In Papers II and V, only men were included and the required performance level to be included was 7a+ (IRCRA 18). The average climbing experience ranged from six to eleven years across the studies.

Table 3: Overview of the participants included in the papers presented as means ± SD.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Study design</th>
<th>Participants (n)</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Body mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Meta-analysis</td>
<td>67</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>1</td>
<td>Systematic review</td>
<td>168</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>2</td>
<td>Acute</td>
<td>57</td>
<td>27.9 ± 6.2</td>
<td>180.8 ± 14.6</td>
<td>72.5 ± 7.5</td>
</tr>
<tr>
<td>3</td>
<td>Acute</td>
<td>31</td>
<td>26.9 ± 5.5</td>
<td>177.2 ± 7.5</td>
<td>70.5 ± 8.3</td>
</tr>
<tr>
<td>4</td>
<td>Intervention</td>
<td>14</td>
<td>27.5 ± 5.3</td>
<td>175.5 ± 4.1</td>
<td>68.0 ± 4.9</td>
</tr>
<tr>
<td>5</td>
<td>Intervention</td>
<td>16</td>
<td>30.3 ± 7.4</td>
<td>181.1 ± 6.6</td>
<td>74.5 ± 6.1</td>
</tr>
</tbody>
</table>

n = number, cm = centimeters, kg = kilograms
8.2 Experimental designs and approach

Paper I was a systematic review and meta-analysis implementing stratified analyses of forearm endurance and maximal finger strength. Paper II used a cross-sectional design to investigate if RFD could discriminate between performance levels in lead climbing. A between-subjects cross-sectional design was used in Paper III, with group as the independent variable. The two groups performed all tests in a standardized order during one laboratory session. Paper IV was a randomized within- and between-groups design with two groups performing different training programs prioritizing either lead- or boulder climbing. In Paper V, a randomized, controlled trial with a within- and between-groups design was conducted to assess and compare the effects of two different training frequencies with equated training volume.

8.3 Testing procedures

8.3.1 Preparation and warm-up

In Papers II - V, participants agreed to refrain from climbing and climbing-related training in the 48 hours before testing. The warm-up in Papers II - V consisted of at least 15 minutes of light-to-moderate bouldering. Please see the original papers for more detailed descriptions of the warm-up procedures.

8.3.2 Climbing performance level and experience

The participants were asked to report their climbing performance as the highest accomplished red-point difficulty grade using either the French or the Scandinavian grading system. Self-reporting grades have been proposed as highly reliable and acceptable for use in a scientific context [73]. The grades were then converted to a standard numerical (1-32) grading system suggested by the International Rock Climbing Research Association (IRCRA). Participants also self-reported their preferred climbing discipline (lead, bouldering, or speed), average weekly number of climbing sessions, and their climbing experience expressed as years of active climbing.
8.3.3 Anthropometrics

In Papers II - V, body composition (fat mass and fat-free mass) and body mass were measured using a bioelectrical impedance scale (Tanita MC780MA S, Tokyo, Japan) with the participants wearing light clothing and no shoes. In all papers, body composition was measured prior to the warm-up. The Tanita scale has been shown to provide accurate measurements of body composition that strongly correlates ($r = 0.852 - 0.976, P < 0.001$) to the measurements taken using Dual-Energy X-Ray Absorptiometry [74]. Body height was measured using a wall mounted measuring tape. In Paper V, forearm circumference was collected at 2/3rd of the distance between the ulnar styloid process and the coronoid process using a flexible measuring tape.

8.3.4 Maximum voluntary isometric contraction and rate of force development

In Papers II - V, the maximal voluntary isometric contraction (MVIC) and rate of force development (RFD) were collected during isometric pull-ups on either a 23mm deep wooden rung with rounded edges (Metolius Climbing, Bend, Oregon, USA) or on a deep jug hold (Beastmaker 1000 series, Beastmaker Limited, Leicester, United Kingdom) [49]. The participants wore a climbing harness anchored to the floor via a static rope, a force sensor, and an expansion bolt in the floor (Ergotest Innovation A/S, Porsgrunn, Norway) to remain in an isometric position (Figure 4). The length of the rope between the climbing harness and force sensor was adjusted to maintain a correct elbow angle of 90 degrees (measured using a goniometer). Briefly, a maximal effort, isometric pull-up was performed to collect the maximal force and RFD (Figure 4A). However, the exact methodology (e.g., number of attempts and standardization of the execution) varied slightly between papers. In all papers, the force output was recorded by the force sensor (200Hz) and analyzed with the MuscleLab software (v. 10.4.37.4073, Ergotest Innovation A/S, Porsgrunn, Norway). Please see Papers II - V for more extensive descriptions of the procedures.
The collected force curves were used to calculate the RFD at different absolute and relative time scales. For an attempt to be deemed acceptable and useable for extracting RFD, the following criteria had to be fulfilled: 1) very little deviations in baseline force before exerting maximal force, 2) a continuous rise in force without a plateau before peak force output, and 3) no excessive peak force created by a high momentum using hip flexion. Please see Figure 4 for illustrations of acceptable (B) and unacceptable force-curves (C and D).

In Paper IV, a measure of finger grip strength was also included, in which the arm-, shoulder- and back-muscles were excluded. This test was conducted using a wooden fingerboard (Climbro, Innovative Hangboards, Sofia, Bulgaria) with built-in force sensors. With the elbows constrained in a 90° angle to eliminate any force production by the pulling apparatus (Figure 5), the participants held on to the finger board with a half crimp grip. On
verbal command, they pulled as hard as possible with the fingers and maintained the force for three-to-five seconds. Due to the very low technical demands on this task, only one attempt was given, and the highest registered force output was used in the analyses.

![Figure 5](image_url)

**Figure 5**: Schematic illustration of the test set-up used for assessing isolated finger grip strength and forearm endurance, with (A) the fingerboard with the built-in force cell and (B) the constraining of the elbow. The distance between A and B was adjustable to allow identical conditions for all participants.

### 8.3.5 Forearm endurance test

In Papers III and IV, the forearm endurance was assessed using an intermittent forearm endurance test to failure. The threshold was set to 60% of MVIC with a 7:3 ratio between work and rest. The test was performed using the 23 mm rung of a wooden fingerboard (Climbro, Innovative Hangboards, Sofia, Bulgaria). The participants were seated (Paper III) or standing (Paper IV) in front of a table with the fingers holding on to the fingerboard using a half crimp grip and with the elbow constrained to eliminate any force development from the pulling apparatus (Figure 5B). In Paper IV, the built-in force sensors in the fingerboard were used to collect the force data, whereas in Paper III, the fingerboard was connected to a force cell that registered the force to a computer with the commercial software MuscleLab (v.10.4, Ergotest Innovation A/S, Porsgrunn, Norway). In both papers, the test was eliminated when the force fell below the threshold for one second [34].
8.3.6 Climbing performance

In Papers IV and V, the climbing performance was assessed using a competition-style format (rules available from https://tinyurl.com/bewfx8tn). The test included two (Paper V) or three (Paper IV) boulder problems, and the participants were allowed four minutes to execute as many attempts as they wished on each problem. The highest hold that they could reach and maintain in controlled contact with, was registered and the accumulated score after attempting all boulder problems was used in the analyses (maximal score = 25 in Paper IV and 15 in Paper V). In Paper IV, lead climbing performance was assessed on an 18 meters high wall. The participants were given one attempt and the last handhold they were in controlled contact with was registered. The performance score was then calculated as a percentage of the route ((hold number reached / total number of holds) * 100).

8.3.7 Pull-up velocity

In Paper III, a maximal-effort pull-up was performed on the jug hold of a Beastmaker wooden beam (Beastmaker 1000 series, Beastmaker Limited, Leicester, United Kingdom). One concentric pull-up was performed as fast as possible from a dead-hang position (elbows fully extended) until the eyes were above the hands. Counter-movement or kipping with the legs were not allowed. The peak and average velocity during the pull-up were measured via a linear encoder (Ergotest Innovation A/S) attached to the ground and to the belay loop of a climbing harness worn by the participants. The encoder has a resolution of 0.075 mm and counts the pulses with a 10 mm interval. The velocity was instantly registered using the commercial software MuscleLab (v.10.4., Ergotest Innovation A/S, Norway).

8.3.8 Campus board performance

In Paper V, maximal reach and number of moves to failure on a campus board were tested pre- and post-intervention. The rung size used in the testing was 20 mm deep and were placed at 13 cm intervals, and the board was slightly (15°) overhanging (Figure 6). For the maximal reach test, participants started with both hands on the lowest rung and had to hang motionless before the test began. On verbal command, the participants pulled themselves up and reached as far as they could with one hand. Four attempts were given with one-to-two minutes rest between each attempt. The self-selected hand was used in the test. The highest rung they could reach and hold on to in a controlled manner was registered as the maximal
reach. For the number of moves to failure, the participants started on rung one and moved upwards one rung at the time with alternating hands without matching each rung. If they reached the top, they continued to climb down and up again until failure. The number of completed moves before failure was registered and used in the analyses.

Figure 6: Illustration of the campus board used for the training and testing.

8.4 Training interventions

Papers IV and V were training studies that included five-weeks intervention periods. A brief overview of the training interventions will be provided here. Please see Papers IV and V for more details.

8.4.1 Paper IV – Discipline prioritization

In Paper IV, participants were randomized into two groups that prioritized either lead- or boulder climbing training for five weeks. The training program was designed in cooperation with highly experienced lead- and boulder climbers. The participants performed three weekly climbing sessions and were encouraged not to conduct any climbing-related training outside the intervention. Two of the weekly sessions included the prioritized discipline, whereas one
session was dedicated to the opposite discipline. The session of the non-prioritized discipline was performed with low intensity and acted as a maintenance session [75]. Of the two sessions of the prioritized discipline, one emphasized quality (i.e., long rests and maximal effort attempts) and one focused on quantity (i.e., short rests and high number of attempts). For the bouldering group, the quality session lasted 90-minutes and included projecting boulder problems near their individual limit. The lead climbing group trained for one hour and were instructed to complete six attempts on hard lead routes. The quantity sessions lasted 60-minutes for the bouldering group in which the participants performed five sets of four consecutive boulder problems. The lead climbing group climbed for 75-minutes and were instructed to complete as many routes as possible with <3-minutes of rest between attempts.

8.4.2 Paper V – Campus board training

The participants included in Paper V were randomized into three groups: 1) four weekly campus board sessions, 2) two weekly campus board sessions, or 3) an active control group that refrained from campus- and fingerboard training. All groups were instructed to continue their regular climbing training routines. The campus board training program consisted of the following four exercises that were designed in cooperation with highly accomplished climbers that were experienced with campus board training: 1) 1-4-7-10; 2) ladder; 3) 1-2-3; and 4) 10 repetitions maximum (RM). Self-selected intervals were used for the 10RM exercise depending on preferred move length and fatigue. Illustrations of exercises 1-3 are presented in Figure 7. Please refer to Paper V for a more extensive description of the exercises. The participants that trained twice per week completed all exercises within each session, whereas the group that trained four times per week alternated between performing exercises 1 and 2, and 3 and 4. Thus, the total training volume was identical between the two groups. Each exercise was performed four times with a rest period of two-to-three minutes between each set.
Figure 7: Examples of the (A) 1-4-7-10, (B) ladder, and (C) 1-2-3 exercises used in the training when leading with the right hand.

R = right hand
L = left hand

8.5 Statistical analyses

All statistical analyses were performed using SPSS statistical software (versions 23-25, SPSS Inc., Chicago, IL, USA). In Papers II - V, the data were controlled for normality visually (Q-Q plots) and using either Shapiro-Wilk (Papers III and V) or Kolmogorov-Smirnov tests (Papers I and IV). Statistical significance was accepted at $p < 0.05$ in all papers. Brief descriptions of the statistical analyses will be provided below. Please see Papers I - V for more extensive descriptions.
The meta-analyses in Paper I were performed in Comprehensive Meta-Analysis (CMA) version 3.0 (Biostat, Englewood, New Jersey, USA) using random effect models. Effect estimates were presented as standardized mean difference (SMD) with 95% confidence intervals (CI). Heterogeneity was presented as $I^2$ with P-values.

In Paper II, a one-way ANOVA with Bonferroni post-hoc test was used to assess the potential differences between the performance levels. The CV (%) of the different measurements were calculated as follows; standard deviation divided by the mean, multiplied by 100.

In Paper III, differences between the groups were identified using an independent student’s t-test. Average pull-up velocity deviated from normality and a Mann-Whitney U Test was used for the non-parametric variable.

Paper IV applied a mixed-model repeated measures analysis of variance (ANOVA) with Bonferroni post-hoc tests to identify potential differences between the groups and between pre- and post-test.

The results in Paper V were analyzed using an analysis of covariance (ANCOVA) with the pre-test results as the covariate. When significant interactions were found, Bonferroni post-hoc corrections were used to detect the differences. Between-groups differences in the non-parametric variables were analyzed using a Kruskal Wallis Test, followed by independent Mann-Whitney U-tests. Paired samples t-tests were used to identify differences between the pre- and post-test results for the parametric variables, while a Wilcoxon signed rank test was used for the non-parametric variables.

In Papers II – V, Cohen’s d effect sizes (ES) for the within- and between-groups differences were calculated as the mean difference divided by the pooled standard deviation (SD). In all papers, the ES were interpreted as follows: < 0.2 trivial, 0.2 – 0.5 small, 0.5 – 0.8 medium, and > 0.8 large [76].
9. Summary of the main findings

Only the main findings are presented in the following chapter. Please see the individual papers for more extensive presentations of the results.

9.1 Main finding of the systematic review and meta-analysis

Paper I

In Paper I, a systematic review and meta-analysis was performed to explore the current knowledge about the effects of resistance- and climbing-training on climbing-related performance. The study revealed that scientific research about methods for improving climbing-related performance is lacking as only eight studies could be included. Moreover, 1) female participants are underrepresented in the literature, 2) many studies fail to report a sufficient description (e.g., preferred discipline) of the participants, and 3) few studies have included a control group. However, some recommendations could be made based on the available literature. First, the studies included in the meta-analysis suggested that climbing-specific strength and endurance may be improved by specific resistance-training of the finger flexors. The studies included in the systematic review did not demonstrate the same effects but suggested that finger resistance-training is effective for improving RFD. Regarding climbing-training, interval-style bouldering may be more effective for improving climbing-specific endurance compared to conventional bouldering.

9.2 Main findings of the acute studies

Paper II

Paper II explored the ability of upper-body RFD and maximal strength to discriminate between climbers performing on an intermediate, advanced, or elite level. Different time periods from the onset of contraction were used to calculate RFD to address whether they differed in level of ability to discriminate between performance levels. In agreement with the primary hypothesis, elite climbers produced higher RFD than the advanced and intermediate climbers according to all relative measures (ES = 1.02 – 1.58, P < 0.001 – 0.002). Using the absolute time periods, only 50ms, 100ms, and 150ms displayed differences between the elite and sub-elite groups (ES = 0.72 – 0.84, P = 0.032 – 0.040). However, and in disagreement with
the hypothesis, no significant difference was found between the advanced and intermediate climbers (P = 0.942 – 1.000).

**Paper III**

Paper III examined the isometric and dynamic strength characteristics among lead and boulder climbers during a climbing-specific pull-up test, as well as the forearm endurance during an intermittent test to failure. The boulder climbers demonstrated 28.7 – 52.9% higher peak force, average force, and RFD using the 23 mm rung and the jug (P = 0.013 – 0.015). No significant difference between the groups was found for forearm muscle endurance (P = 0.088). Regarding the dynamic pull-up test, boulder climbers achieved a 26.2% higher average velocity than lead climbers (P = 0.014). When comparing the isometric results from the ledge and the jug holds within the groups, both groups demonstrated lower peak force, average force, and RFD in the ledge condition compared to the jug condition (ES = 1.79 – 2.02, p < 0.005). However, the utilization of force in the ledge condition relative to the jug condition (57 – 69%) was not different between the groups (P = 0.290 – 0.996).

**9.3 Main findings of the intervention studies**

**Paper IV**

In Paper IV, the effects of prioritizing lead- or boulder climbing in a five-week block among intermediate climbers were examined. After the intervention period, no significant differences were detected between the groups and no changes occurred in lead- or bouldering performance or RFD. However, the lead climbing group improved forearm intermittent endurance (ES = 0.55, P = 0.007), whereas the bouldering group improved maximal, isolated finger flexor strength (ES = 0.35, P = 0.015).

**Paper V**

Paper V compared the effects of dividing the campus board training volume over two and four weekly sessions and compared the training groups to an active control group. Although no significant differences between the training groups were found (P = 0.107 – 1.000), the training groups did improve certain attributes more than the control group. Only the group that trained four times per week improved maximal force in the jug condition and RFD.
more than the control group (ES = 0.40, P = 0.043 and ES = 2.92, P = 0.025), whereas only the group that trained twice per week improved bouldering performance and number of moves to failure on the campus board more than the control group (ES = 2.59, P = 0.016 and ES = 1.65, P = 0.008). As a secondary aim, the training groups were merged and compared the control group. This revealed that the five weeks of campus board training, regardless of training frequency, improved maximal strength in the rung condition (ES = 0.87, P = 0.002), bouldering performance (ES = 2.37, P = 0.006), maximal reach (ES = 1.66, P = 0.006) and moves to failure on the campus board (ES = 1.43, P = 0.040) more than the control group.
10. Discussion across papers

This section will provide a discussion of the main findings across the original papers. Please see the individual papers for more in-depth discussions.

10.1 Climbing performance

Although previous papers have examine changes in climbing performance following upper-body resistance-training [28, 29] or bouldering [30], Papers IV and V were the first to scientifically examine the effects on climbing performance following discipline prioritization and campus board training, respectively. Following the five-week training block in which one discipline was prioritized in Paper IV, no changes in lead- or boulder climbing performance were observed. Contrarily, five weeks of campus board training improved boulder climbing performance in Paper V. The findings could be considered surprising since the participants in Paper IV were intermediate climbers, whereas the study sample in Paper V comprised advanced and elite climbers. Still, the campus board training was likely a more effective training stimulus for factors that are paramount for climbing performance (e.g., RFD and maximal strength in the fingers and upper body [15, 17, 51]). Although it is reasonable to assume that campus board training is less climbing specific than actual climbing training, the structured campus board training program likely provided a higher intensity and novel training stimulus. For the participants in Paper IV, relatively small changes to their regular training-type and -volume can likely explain the lack of improvements in climbing performance.

In comparison, Philippe and colleagues [29] reported improvements in lead climbing performance following both muscular endurance (i.e., light and hard lead route climbing) and -hypertrophy training (i.e., bouldering, campus board training, and lead route projecting). However, the authors reported no different changes between the groups. Of note, the study implemented a combination of lead climbing, bouldering, and campus board training, rendering it impossible to attribute the reported changes to either training method. Still, one group prioritized lead climbing training more, whereas bouldering and campus board training constituted a greater portion of the volume for the other group [29]. The longer training period, more varied training stimulus, and larger study population in the study by Philippe and colleagues [29] can probably explain the different findings from Paper IV.
Medernach et al. [30] reported that interval bouldering was more effective than conventional bouldering for improving climbing-time to exhaustion. Interestingly, to standardize the training volume the interval bouldering was performed using rungs on an overhanging wall. Hence, the interval bouldering could be considered similar to the campus board training. Based on the findings of Papers IV and V, as well as those by Medernach et al. [30] and Philippe et al. [29], one could speculate that climbing-specific exercises that are easily standardized and quantified could be more effective than conventional climbing training for short-term improvements in climbing performance and climbing-specific tests. Moreover, such exercises could allow the stress applied to the fingers to be more easily modified and periodized. Since climbing training comprises a variety of body positions, movements, and hold types, the complexity of the training could make it less effective for improving specific attributes. Additionally, different technical execution (e.g., movement efficiency and foot placement) will likely cause the training volume of the fingers to vary between individuals during climbing training. However, as climbing is a complex sport, emphasizing variety and specificity in the training is likely paramount for long-term improvements.

10.2 Rate of force development

Of the parameters measured in Paper III, RFD was the strongest discriminator between lead- and boulder climbers. The findings of Paper III were in line with Paper II and previous reports [8] and suggest that RFD is a crucial performance factor for boulderers and should be emphasized in prospective studies comparing rock climbers of different levels and disciplines. The findings also highlight the importance of including RFD as a measure for coaches monitoring athletes. The higher RFD among boulder climbers is likely a result of specific adaptations to the physical demands of the two disciplines (e.g., ascent duration, number of moves, distance between holds and steepness of the route). In disagreement with the findings from Paper II, the five-week training intervention described in Paper IV produced no significant improvements in RFD for either group. Importantly, as previously speculated [8], climbers could have selected their preferred discipline based on their inherent physical attributes. Moreover, it is possible that the training volume was not large enough, or that the training intervention was too short to produce significant differences in RFD. Still, Levernier and Laffaye [33] showed that only a four-week training period was sufficient for improving
RFD among elite climbers. It should be noted, however, that Levernier and Laffaye [33] implemented fingerboard training, which could be more effective than climbing training, as well as more task-specific toward the test set-up used to assess RFD.

Another explanation for the findings in Paper IV could be the fact that Paper II revealed that the used method for measuring RFD is more suitable for assessing elite climbers, whereas the results for intermediate and advanced (i.e., sub-elite) climbers may be more varied. Hence, the test set-up for assessing RFD might not have been appropriate for the study sample in Paper IV. Indeed, since the elite climbers displayed higher RFD than the sub-elite climbers while no difference was observed between advanced and intermediate climbers (Paper II), RFD might not become a crucial factor of climbing performance until the more demanding grades are reached (> 24 IRCRA). The explanation for the large variability among the sub-elite climbers in Paper II is likely the fact that performing a maximal, isometric pull-up on a shallow rung while supporting the body mass is a very demanding test, and only the strongest climbers can utilize their maximal potential repeatedly in these conditions. Since several joints are involved in this task, one might further expect significant variations in the measurements across levels, rendering the test less reliable than isolated tasks. However, the observed CV-values for RFD in Paper II (10.0% – 31.3%) were comparable to those reported by Levernier and Laffaye [19] in a more constrained task (7.8% - 28.3%).

Finally, the lack of changes observed in Paper IV could be explained by the calculation of the RFD. The RFD in Paper IV was calculated using the first 200ms of the force curve, whereas Paper II revealed that RFD calculated using longer periods of the force curve generated lower CV values and larger between-groups ES. This might be because the maximal number of muscle fibers recruited while exerting maximal force is more reproducible than the time it takes to recruit the fibers, making the earlier phase of the force curve more susceptible to variation [19, 77, 78]. Using relative time periods (percent of the time to reach peak force) rather than absolute time periods (ms from the onset of force) proved more reliable. This is likely a result of large variations between individuals’ time to reach peak force.

In contrast to the findings from Paper IV, the campus board training in Paper V improved RFD more than the control condition (i.e., climbing training as usual). Importantly, Paper V included advanced-to-elite climbers and the RFD was calculated using the whole force curve, which was found in Paper II to be the most reliable calculation. Moreover, the lower
performance level of the climbers in Paper IV could indicate that a less demanding test should have been used. For example, a larger hold could allow for a more controlled execution of the test [79], and an isolated finger strength test would have excluded the need to support the body mass during testing [19]. Moreover, the campus board training implemented in Paper V could be considered a highly specific exercise for improving RFD since the training is performed with maximal effort in each repetition. Furthermore, the campus board training includes pull-up movements performed on rungs similar to that used in the testing. Hence, it is reasonable to assume that the task specificity of campus board training for the testing procedures is considerably higher than general climbing training which includes large varieties of holds, positions, and movements. This speculation is supported by previous findings suggesting that a short (4 weeks) fingerboard training period can improve RFD more than climbing training among highly accomplished climbers [33].

Regarding the between-levels comparisons in Paper II, the elite climbers have likely developed a higher RFD following several years of climbing difficult routes, performing long and difficult moves and having to quickly grip small or difficult holds. Since significantly higher RFD among the elite climbers was accompanied by greater maximal force output, one might speculate that the difference in RFD is merely the result of a higher maximal strength. Indeed, Paper II, as well as previous investigations [19, 20, 23] and unpublished data from our lab have shown that an association exists ($r = 0.59 – 0.69$, $p < 0.001$) between finger- and upper-body strength and climbing ability. However, the normalized RFD was still higher among the elite climbers compared to the other groups. Moreover, the intermediate climbers in Paper IV improved maximal strength, but not RFD following a five-week training period. Taken together, these findings suggest that the ability to exert the force rapidly 1) remains a key factor for discriminating between performance levels and 2) may be developed later than the maximal force factor.

10.3 Maximal strength

Due to the distinctive physiological demands of lead- and boulder climbing, the findings for the strength measures in Paper III were not surprising. Whereas lead climbing generally presents a longer climbing duration characterized by static and controlled movements, competitive bouldering contains short and intense routes and a higher frequency...
of moves performed with maximal effort [7]. Hence, the physiological demands of bouldering share more similarities with the recommendations for maximal strength training [80] and is likely a more appropriate training stimulus than lead climbing for improving maximal force output and explosive strength. Of note, Paper III demonstrated differences between the groups for maximal strength measured using a shallow rung hold as well as a deep jug hold. This novel finding showed that not only finger strength, but also isometric pull-up strength in a test with very little finger strength demands discriminates between disciplines. This should be considered by researchers as most of the current literature has examined climbing-specific strength in test set-ups neglecting the arm- and back muscles. Furthermore, maximal strength measured in the same test set-up also displayed a distinct difference between lead-climbers performing on elite and sub-elite levels in Paper II. These results are in line with previous findings following test set-ups excluding the back muscles, which are likely the strongest portion of the pulling apparatus [17, 19]. Hence, the results of Paper II expand on the current knowledge and confirm that maximal strength discriminates between performance levels using different portions of the pulling apparatus.

Regarding the relative force utilization ((rung force / jug force) × 100), no difference was observed between climbers specializing in the two disciplines in Paper III (P = 0.290 – 0.996). The lack of difference in relative force utilization observed between the ledge- and jug conditions suggests that specific finger flexor strength training may benefit advanced climbers of both disciplines. Since the fingers are the weakest link in the force development chain, increasing the utilization rate can allow for a greater portion of the strength of the pulling apparatus to be applied in climbing. This may explain why fingerboard training is among the most commonly applied training methods among climbers [34, 63], despite not providing a highly climbing-specific training stimulus (e.g., not including dynamic movements).

The bouldering training in Paper IV was associated with improved finger strength and, thereby, supports the findings from Paper III suggesting that boulder climbers can generate greater finger flexion force compared to lead climbers. As previously mentioned, this is likely the result of a more maximal strength-specific training stimulus following the bouldering training [80]. However, Paper IV revealed no improvements in isometric pull-up strength performed using a shallow rung. Although Paper II and 4 suggested that boulderers and more highly trained climbers can generate higher pull-up force, the training period in Paper IV could have been too short to produce detectable differences. Note that the intervention included a 2:1
ratio between prioritized and non-prioritized discipline. Despite providing a high ecological validity, ratios of 3:1 or 3:0 would likely have produced clearer between-groups differences. Moreover, the test set-up used in Paper IV could have been too demanding (i.e., shallow hold and including the full body-mass) for the intermediate-to-advanced study-population, rendering it difficult to detect potential pre-to-post changes or between-groups differences.

In Paper V, the improvement in maximal strength for the group that trained four times per week may be explained by the fact that this attribute requires maximal effort to be tested and trained properly [80]. Dividing the training volume over several shorter sessions could have allowed the group to execute the training with a higher effort and velocity, thereby resulting in only this group improving more than the control group. Indeed, it has been reported that higher training frequencies may be translated into greater strength improvements, but only when the volume is not equated (i.e., higher training frequency entailing greater volume) [81]. Conversely, the findings could be explained by 1) more frequent elevations in muscle protein synthesis [82], or 2) the shorter sessions producing less fatigue and allowing a higher intensity and effort in the training, which may be more beneficial and specific for high intensity tests such as maximal strength or RFD [72, 83].

10.4 Forearm endurance

In contrast to the strength and RFD measurements, the forearm endurance was not a discriminatory factor between climbers specializing in either discipline in Paper III. These findings could be somewhat surprising as a lower intensity maintained over a longer period during lead-climbing compared to bouldering (2-7 minutes vs. ~30 s [7, 68]) likely provides a more endurance-specific training stimulus. However, the findings agreed with previous studies [9, 15, 39, 53] and could be explained by the test’s low specificity to climbing. It is possible that technical and mental skills could be more important for allowing the climber to remain calm and climb using as little energy as possible in each move. Still, it should be noted that the higher MVIC of the boulder climbers resulted in a higher force that had to be maintained during the endurance test. Albeit providing identical relative conditions for the two groups, using identical absolute thresholds could have produced different results. Alternatively, other work-to-rest ratios (e.g., 10:3, 8:2, or 5:5 [13, 15, 26, 84]) or thresholds (e.g., 40% or 80% of MVIC [13, 15, 26, 84]) could have favored one group and displayed differences between disciplines.
Whereas Paper III was unable to detect different forearm endurance characteristics among climbers specializing in either discipline, the findings of Paper IV revealed that only lead climbing training was associated with improved intermittent forearm endurance. This could reflect the different demands of the two disciplines: whereas boulder problems may include between two and ten very difficult moves [7], lead competition routes can take up to seven minutes to complete and include up to ~50 moves. The longer duration maintaining a sub-maximal effort is likely a more suitable training stimulus for developing muscular endurance. Considering the discipline-specific improvements in forearm endurance that occurred after a five-week training period, it can be speculated that specializing in one discipline over longer periods could result in more distinct differences between the groups. Of note, Medernach et al. [85] reported that the long climbing times, high number of attempts, and short between-attempts rest in competitive bouldering could present a significant demand for forearm endurance. Moreover, as previously speculated [29], the fact that many athletes perform on a top world-ranking level in both lead- and boulder climbing supports the speculation that some common traits are shared between the two disciplines. Importantly, many athletes perform bouldering as part of their training regardless of prioritized discipline [63]. Thus, the incongruent findings of Papers III and IV could likely be explained by 1) intermediate climbers (Paper IV) being able to improve forearm endurance more by conducting lead climbing which could be regarded as a more endurance-specific training stimulus, and 2) advanced climbers (Paper III) displaying high levels of forearm endurance regardless of discipline specialization [17, 25].

Partially in line with the findings from Papers III and IV, Paper V showed that two weekly sessions of campus board training improved endurance, whereas dividing the same volume over four sessions did not. It is possible that the longer training sessions designed to maintain a high effort over a longer period, thus promoting a beneficial physiological response and a higher tolerance to fatigue [86]. The tolerance to fatigue might also be important for bouldering performance since only two weekly training sessions improved bouldering performance. It should be noted that both bouldering performance and endurance measured as number of moves on the campus board are affected to a large degree by technical and mental factors [44, 87]. Hence, one should use caution when interpreting these findings and applying them to forearm endurance.
10.5 Limitations of the studies

All participants included in the present investigations were healthy, young men and women who ranged from intermediate to elite climbers. Therefore, the findings from each paper may not be generalizable to other populations than the one examined. Furthermore, although both male and female participants were included in Papers III and IV, the accumulated study sample in the present thesis consisted mainly of men. Additionally, a potential limitation of Paper II-IV was the lack of a familiarization to the isometric pull-up test. Since the participants were experienced climbers and because isometric testing poses low technical demands [88], no familiarization session was performed. However, based on the relatively high variation in the RFD results, one could speculate that a familiarization session could have improved the reliability of the test. Furthermore, a relatively short training period with a low training volume was implemented in Paper IV. Although this could challenge the ability to detect differences, the study was designed to maintain a high ecological validity as five weeks is a common block-periodization duration [89]. Therefore, prioritizing one discipline over a very long period would not have been feasible among participants preferring to conduct both disciplines. Similarly, Paper V also involved only a five-week training period. However, as campus board training is extremely taxing on the finger and forearm muscles and tendons, longer intervention durations could result in overuse injuries among climbers who are not highly familiarized with the campus board. Finally, the scarcity in available literature for conducting the systematic review and meta-analysis in Paper I challenges the reliability of the findings.
10.6 Summary of the main findings

The findings from the studies that form this thesis can be summarized in the following conclusions:

- Maximal strength and rate of force development in the fingers and upper-body are greater among elite climbers and boulderers compared to sub-elite climbers and lead-climbers.

- Campus board training can improve bouldering performance and climbing-specific tests, and the training frequency may affect which parameters that are more developed

- Prioritizing either lead- or boulder climbing might emphasize different adaptations, and one discipline can be prioritized without reducing performance in the other discipline.

- Few intervention studies have been conducted on the field of climbing, many studies lack a clear description of the participants, and females are underrepresented in the literature.

- The current knowledge about training for climbing indicates that resistance-training of the fingers can improve forearm endurance, strength, and rate of force development.
10.7 Conclusions

**Paper I**

The meta-analysis revealed that RT of the fingers and forearms can improve strength and endurance measured using climbing-specific holds. Conversely, the results from the systematic review did not indicate that climbing-specific RT is an effective approach for improving strength or endurance of the finger flexors but may be highly effective for increasing RFD. However, the systematic review identified interval bouldering as a potentially effective method for improving climbing-specific endurance. Hence, any climbing-specific training may improve climbing- or bouldering performance, but an interval-style approach may be beneficial for improving climbing time to exhaustion.

**Paper II**

Advancing through the lower climbing grades may be achieved by improving characteristics not measured in the present study (e.g., mental or technical skills), whereas a progression to the elite grades (> 24 IRCRA) appears to entail a marked increase in RFD. The small difference in climbing experience and performance level, as well as the high variation, could explain the lack of differences in RFD between the intermediate and advanced climbers. The present test set-up may be better suiter for examining elite climbers as lower variability was observed in the elite group compared to the intermediate and advanced groups. Finally, using 100% of the force curve to calculate RFD appears to be the most reliable measurement during the current test set-up.

**Paper III**

When comparing the dynamic and isometric strength characteristics among lead and boulder climbers, significantly higher maximal strength, pull-up velocity and RFD was observed among the boulder climbers compared to the lead climbers. No significant difference was found between the groups for forearm endurance as measured with intermittent contractions. The findings likely represent adaptations to the physiological demands of the two disciplines.
Paper IV

Five weeks of prioritizing lead or boulder climbing improved maximal, isometric pull-up strength among intermediate-to-advanced climbers with considerable climbing experience. Although not significantly different between the groups, a five-week structured lead climbing training regime significantly improved intermittent forearm endurance, whereas only boulder climbing training improved isolated finger strength.

Paper V

Despite not displaying any significant differences between the training groups, dividing the training volume over four shorter sessions improved RFD to a greater extent than the active control group, whereas performing two longer sessions improved bouldering performance and moves to failure on the campus board more than the active control group that continued climbing training as usual. Implementing campus board training, regardless of frequency, improved bouldering performance, RFD, maximal reach, number of moves to failure and arm circumference more than just climbing among highly accomplished climbers.
11. Practical implications

The systematic review and meta-analysis included in this thesis revealed that very little intervention research including climbers has been conducted. Hence, evidence-based training recommendations (e.g., frequency, volume, and intensity) are lacking in the sport. The existing literature suggests that climbers should engage in supplemental RT to facilitate the development of climbing-related performance factors.

Maximal strength and RFD displayed significant differences between performance levels and disciplines in the cross-sectional studies. The findings may suggest that climbers, especially boulderers, should emphasize these attributes in their supplemental RT. Moreover, 100% of the force curve should be included in the calculation of RFD during an isometric pull-up test. The results from Paper III indicate that less demanding tests (e.g., isolated forearm tests and larger holds) may be beneficial to acquire reliable results when assessing intermediate climbers.

The intervention studies revealed that 1) intermediate climbers can prioritize one discipline in their training for a five-week period to improve specific parameters, without a decline in performance in the other discipline, and 2) that campus board training, regardless of training frequency, can improve performance in bouldering and climbing-related tasks in advanced-to-elite climbers.
12. Suggestions for future research

The field of climbing-research is still in its infancy and there is a scarcity of intervention studies. The current thesis provides novel insight into 1) discipline-specific adaptations, 2) testing procedures for assessing climbers, 3) potential training recommendations for climbers, and 4) the gaps in the current knowledge about training for climbing. Future research should attempt to provide general training recommendations (e.g., regarding volume, intensity, and frequency) for improving climbing performance. The recommendations should be specific to performance levels and disciplines. Moreover, like the papers included in this thesis, most climbing research comprises mostly male climbers. Hence, future research examining climbing-specific testing and training among female climbers is warranted.

Furthermore, this thesis includes two studies (Papers IV and V) that assessed changes in climbing performance whereas most of the available literature has neglected this measure. Some discrepancies between climbing performance and performance in climbing-specific tests were identified in Papers IV and V. Thus, future studies should consider testing climbing performance rather than assuming that improved performance in strength- or endurance-specific tests means that the training also improves climbing performance. Importantly, the knowledge provided by Papers IV and V is limited to the specific performance levels and training durations in the studies. Future research should examine the effects of campus board training and discipline prioritization among other performance levels and following longer intervention durations. As the results from this thesis provide implications for training recommendations, testing procedures, and limitations of the available literature, the findings should be of interest for climbers and coaches, as well as researchers.

Thank you for taking the time to read this thesis.
13. References


Paper I
Effects of climbing- and resistance-training on climbing-specific performance: A systematic review and meta-analysis

Running head: Training for climbing

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Abstract

The objective of this systematic review and meta-analysis was to examine the effects of climbing and climbing-and-resistance-training on climbing performance, and strength and endurance tests. We systematically searched three databases (SPORTDiscus, SCOPUS, and PubMed) for records published until October 2020. The search was limited to randomized-controlled trials using active climbers and measuring climbing performance or performance in climbing-specific tests. Data from the meta-analysis are presented as standardized difference in mean (SDM) with 95% confidence intervals (95% CI). Eight studies are included in the systematic review and three studies compared training to a control group and could be meta-analyzed. The meta-analysis revealed that climbing-specific forearm endurance (SDM 1.23, 95%CI 0.69 to 1.77) and strength (SDM 0.61, 95%CI 0.04 to 1.19) were improved by resistance-training of the finger flexors compared to climbing training. The systematic review showed that climbing performance may be improved by specific resistance-training or interval-style bouldering. Additionally, resistance-training of the finger flexors improved rate of force development, but not strength or endurance, in climbing-specific tests. The available evidence suggests that resistance-training may be more effective than just climbing-training for improving performance outcomes. Importantly, interventional studies including climbers is limited and more research is needed to confirm these findings.

Key words: Exercise; strength; skill; testing
Introduction

Rock climbing has gained increased attention in the past decade and a growing body of scientific literature is focusing on the physiological demands of the sport, as well as on the relationship between climbing performance and muscular strength and endurance. Performance in the sport relies on a complex interaction of physiological (e.g., mobility, strength, and endurance), mental (e.g., self-confidence and overcoming fear), and technical factors (e.g., footwork, body positioning, and movement efficiency). Moreover, the demands of the sport are influenced by factors such as the steepness of the route, the style of climbing, distance between holds, hold size, and the overall difficulty of the climb.

Competitive climbing consists of three disciplines (speed climbing, lead climbing and bouldering) which differ in their respective physiological demands. Of the three, lead climbing and bouldering are the two most practiced and researched disciplines. While bouldering is performed on lower walls (< 6 meters) and often consists of few, but highly explosive and difficult moves, lead climbing is performed on high walls (10-30 meters) and usually consists of 20 to 50 moves with repeated, sub-maximal force generation (often referred to as endurance).

The physiological demands of rock climbing, and the characteristics of climbers performing on different levels, have been described in previous systematic and narrative reviews. Characteristics such as flexibility, strength, and endurance have been identified as key determinants for performance in the sport. Whereas flexibility is challenging to measure and has not yet received much scientific attention, strength in finger, arm, shoulder and back
muscles is relatively easy to measure in a standardized manner and has been identified as an important determinant of performance in the sport.\textsuperscript{3, 17-22} Moreover, muscular endurance assessed by using sub-maximal, intermittent contractions of the finger flexors has been shown to be related to climbing ability.\textsuperscript{23, 24} Along with the recent growth of rock climbing as a competitive and recreational activity, a growing number of randomized controlled trials (RCTs) have investigated the effects of climbing- versus resistance-training on climbing performance and performance in climbing-specific tests.

To the best of our knowledge, no systematic literature review or meta-analysis on the effect of training on climbing performance and climbing-related factors has been performed. However, the adaptations to climbing and climbing-specific resistance-training has received increasing attention in the scientific literature. As the training and measurement techniques vary between studies, a systematic appraisal of the current knowledge could assist researchers and athletes in the selection of prospective training and research designs. Thus, the objective of the current systematic review and meta-analysis was to assess and compare the effects of climbing- and resistance-training on climbing performance and performance in sport-specific strength-and-endurance-tests.

**Materials and Methods**

**Literature search**

The study complies with the Preferred Reporting Items for Systematic Reviews and Meta Analyses.\textsuperscript{26} We systematically searched for published RCTs examining the longitudinal effects
of climbing- and resistance-training on climbing performance or performance in sport-specific
tests on October 20th, 2020. Peer-reviewed articles published in English were identified from
three electronic databases: SPORTDiscus, SCOPUS, and PubMed. The following search terms
were used: ("rock climb*" OR "sport climb*" OR "lead climb*" OR "climbers" OR "boulder*")
AND ("finger strength" OR "finger endurance" OR "forearm strength" OR "forearm endurance"
OR "grip strength" OR "crimp" OR "finger flexor*" OR "training" OR "fingerboard" OR
"hangboard"). The search identified 743 records (SPORTDiscus: 231; SCOPUS: 293; PubMed:
219). All identified records were imported to EndNoteX9 and merged into one valid library to
allow for removal of duplicate records. After elimination of duplicates, 232 records remained
(Figure 1).

Inclusion criteria and selection process
Three authors (NS, VA and AHS) independently assessed the titles and abstracts of the studies
for eligibility. In case of disagreement, subsequent consensus by discussion was reached. We
included only RCTs involving active climbers of any discipline and performance level
examining the effect of climbing- or resistance-training on climbing performance or climbing
related physical performance such as static and dynamic finger and core strength.

Methodological quality
The 11-item Physiotherapy Evidence Database (PEDro) scale was used to rate the
methodological quality of the included studies (Table 1). Four authors (NS, VA AHS, and AR)
assessed the methodological quality independently with subsequent consensus by discussion. Of
the 11 items, the first item of the PEDro scale concerns external validity and is not included in
the total score, leaving a maximal available score of 10. Studies with a total PEDro score > 6
were considered high-quality studies.

****TABLE 1 ABOUT HERE****

Data extraction and analysis

Data extraction was completed in accordance with the Cochrane handbook for systematic
reviews of interventions. NS and AR conducted data extraction of study results separately and
settled discrepancy by mutual agreement. Studies were found appropriate for meta-analysis if
they performed any climbing- or resistance-training method in the intervention group and
compared the changes to a passive (i.e., no climbing or climbing-specific training) or active (i.e.,
climbing- or resistance-training as usual) control group. Changes in finger strength were
extracted from Levernier and Laffaye and Medernach et al., while changes in dead hang
duration were extracted from Medernach et al. and Hermans et al. If several outcomes were presented after one intervention. Only one outcome was included in
each meta-analysis and dead-hang duration was prioritized over finger strength in the overall
analysis. Other parameters (e.g., rate of force development or bent-arm hang) that were only
examined in one study were excluded from the meta-analysis. Studies that fulfilled the inclusion
criteria but did not use a control group were excluded from the meta-analysis and included in
the systematic review.
Statistical analyses

Extracted data from individual studies were collated in Excel (Microsoft) and meta-analyses were performed in Comprehensive Meta-Analysis (CMA) V.3 (Biostat, Englewood, New Jersey, USA). The meta-analyses were performed with random effects models, and effect estimates are presented as standardized difference in mean (SDM) with 95% CI. Heterogeneity is presented as I² and p-values. Significance level was set to p < 0.05.

Results

Study characteristics

Nine studies were selected for full-text eligibility assessment after screening of all titles and abstracts, while no studies were included based on previous knowledge of the studies. Finally, the same three authors read the full-texts of the remaining nine studies and agreed to remove one due to not fulfilling the inclusion criteria of including active climbers. Thus, eight studies were included in the present systematic review (Figure 1). The reference lists of the included papers were manually searched to discover additional relevant studies. However, this method yielded no further results. The present systematic review consists of eight published studies comprising 168 climbers (Table 2). The overall meta-analysis comprised 67 climbers from 5 trials published in 3 studies. The trials compared the effect of resistance-training with climbing on performance in climbing-specific strength tests. Stratified analyses were performed on two studies investigating the effect of resistance-training on dead hang ability comprising 53 climbers, and two studies investigating the effect of finger resistance-training on finger strength.
comprising 37 climbers. The five studies\textsuperscript{33, 34, 36-38} not included in the meta-analyses, due to not including a control condition, comprised 101 climbers.

**TABLE 2 ABOUT HERE**

**Quality of the studies**

Five studies\textsuperscript{30, 32, 33, 35, 36} fulfilled five items on the PEDro scale and the remaining studies fulfilled 6\textsuperscript{31} or 7 items.\textsuperscript{31, 34} All studies had eligibility specified, concealed allocation, randomized the climbers into groups and the groups were similar at baseline (Table 1). None of the studies blinded the allocation of the climbers to the investigators and assessors, or the climbers themselves.

**Results from the meta-analysis**

In an overall analysis combining five trials from three studies comparing the effect of resistance-training,\textsuperscript{30-32} resistance-training improved performance in climbing-specific tests (dead-hang duration or finger strength) compared to regular climbing-training (SDM 0.80, 95\% CI 0.37 to 1.23; Figures 2 and 3). The included studies were not heterogeneous ($I^2 = 0 \%$, $p = 0.47$).

**Meta-analysis of dead-hang endurance**

For dead-hang endurance, stratified analysis of three trials from two studies\textsuperscript{31, 32} was performed. The training included isolated, isometric resistance-training on a climbing-specific hold,\textsuperscript{31} or
forearm curls using dumbbells. Dead-hang duration assessed on either a 19mm or 25mm deep rung was improved by resistance-training of the fingers and forearms compared to climbing training (SDM 1.23, 95% CI 0.69 to 1.77) (Figure 2).

**Meta-analysis of finger strength**

The meta-analysis of the effects of finger resistance-training included three trials from two studies. Both studies compared fingerboard training with a control group that continued climbing training as usual, and tested finger strength using a half-crimp grip and a climbing-specific hold. The analyses revealed that finger strength was improved by specific, isometric finger resistance-training compared to climbing training (SDM 0.61, 95% CI 0.04 to 1.19) (Figure 3). The SDM for the studies included in the stratified analysis were not heterogeneous ($I^2 < 3\%$, $p > 0.36$).

**RESULTS NOT INCLUDED IN THE META-ANALYSIS**

Five of the included studies could not be included in the meta-analysis as they did not include a control group. The findings of these studies are presented below. Further, some results from the studies included in the meta-analysis could not be analysed because the outcomes are presented in only one study and are, therefore, also presented here.
Three of the studies included in this review measured changes in climbing performance. Hermans et al. reported non-significant tendencies toward improved lead climbing performance following both low-resistance-high-repetitions (12.0 %, \( p = 0.088 \)) and high-resistance-low-repetitions (11.3 %, \( p = 0.090 \)) upper body resistance-training (e.g., pull-downs, biceps curl, and forearm curl). Neither training modality was superior to the other (\( p = 0.420 - 0.950 \)). Philippe et al. compared the effects of climbing-specific muscular endurance training (combination of hard and easy lead climbing) and muscular hypertrophy training (bouldering, campus board, and hard lead climbing). Both groups improved on-sight lead climbing performance (\( p < 0.001 \)), but the improvements were not different between the groups (\( p = 0.542 - 0.955 \)). Finally, Medernach et al. reported significantly greater improvements (\( p = 0.004 \)) in climbing time to exhaustion following interval bouldering (36.2 ± 14.1 seconds, \( p < 0.001 \)), compared to conventional bouldering (6.1 ± 19.3 seconds, \( p = 0.298 \)).

One study reported that rate of force development (RFD) of the finger flexors was improved (27.5 – 32.0 %, \( p < 0.005 \)) following four weeks of fingerboard training compared to their regular climbing training (\( p = 0.006 \)).

López-Rivera and González-Badillo reported no significant improvements in finger grip strength following four weeks isolated finger resistance-training (2.1 - 9.6 %).
significant change in force was significantly greater following dead hang training using maximal external load on a deep rung compared to dead hang training using no external load and the shallowest rung possible to hang from in the training.

**Forearm endurance**

López-Riviera and González-Badillo\(^3\) demonstrated that forearm endurance improved after four weeks of implementing intermittent dead hangs (25.2 %, \(p = 0.004\)), and not after maximal weighted dead hangs or a combination of the two. López-Riviera and González-Badillo\(^3\) found no change in dead hang endurance following minimal edge or maximal weighted dead hangs, whereas Medernach et al.\(^3\) observed improved intermittent finger hang time following interval bouldering (27.3 ± 18.4 seconds, \(p < 0.001\)), but not conventional bouldering (4.9 ± 11.5 seconds, \(p = 0.168\)). The intermittent finger hang time improvement was significantly greater following interval bouldering (\(p < 0.001\)).

**Discussion and Implications**

To the authors’ knowledge, this is the first systematic review and meta-analysis examining the effects of different resistance-training interventions on climbing performance and climbing-specific muscle strength and -endurance. Our systematic literature search identified eight intervention studies examining active climbers. The studies included in the systematic review and meta-analysis\(^3\) examined a diverse range of intervention methods including core training,\(^3\) upper body resistance-training,\(^3\) isolated finger training,\(^3\) interval
bouldering, and a combination of climbing and resistance-training. Climbing performance is influenced by myriad factors and is difficult to measure. Moreover, the generalizability of the findings is challenged by the varied training and testing methods. The main findings from this meta-analysis were that climbing-specific finger endurance was significantly improved following forearm resistance-training and isolated finger training, with isolated finger resistance-training improving finger strength more than climbing training alone. Three studies included a control group, thus the main meta-analysis included only five trials and the stratified meta-analysis included three trials from two studies each. The remaining studies compared two unique training interventions and could not be included in any meta-analysis but were still systematically reviewed.

Regarding the findings from trials included only in the systematic review, isolated finger resistance-training may have a beneficial effect on RFD and forearm endurance, but not on finger strength. Moreover, interval bouldering improved forearm endurance and climbing time to exhaustion compared to conventional bouldering, while climbing-specific muscular hypertrophy and endurance training similarly improved lead-climbing performance. Finally, a non-significant tendency for improved climbing performance following general upper-body resistance-training was reported, as well as improvements in climbing-specific test performance following core training. It should be noted that the individual studies include less participants than the meta-analysis and their results must also be interpreted with caution.
Quality scores of the included studies

Of the 232 studies discovered in the systematic search, only eight met all the inclusion criteria. The scores on the PEDro scale for the eight included studies ranged from 5 to 7 on the 10-point scale, and only three RCTs could be included in the meta-analysis. The relatively low sample size provides low statistical power, and even if the sample size in this systematic review and meta-analysis is larger than in most individual studies, the results should be interpreted with caution. Moreover, there is a need for more high-quality studies in the field of climbing-performance is evident.

Meta-analyses

The included studies reporting on finger strength\textsuperscript{30,31} examined highly trained climbers (IRCRA \textup{≥} 23). The results revealed that maximal finger strength can be improved following a four-week isolated finger resistance-training intervention. Although only a small effect was observed for finger strength, the improvements could be interpreted as meaningful due to the high performance level and long climbing experience (\textup{≥} 5 years) of the included climbers. Moreover, considering the short duration of the intervention, fingerboard training appears to be a highly effective training method that climbers can implement in a short training block to emphasize finger strength before competitions. The findings could be explained by the fact that fingerboard training prioritizes the finger flexors intensely in a structured and specific training program, whereas climbing training may provide a more varied approach that also trains, and is limited by, other muscles and skills. Furthermore, marked improvements in finger strength following isolated resistance-training of the finger flexors may be explained by the principle of specificity.\textsuperscript{39}
The two studies reporting forearm endurance\textsuperscript{31, 32} included in the meta-analyses comprised young climbers (age: \textasciitilde 23 – 26 years) on a lower grade and intermediate level,\textsuperscript{32} and highly advanced boulderers.\textsuperscript{31} The difference in the study samples makes comparisons of the two studies difficult. Both studies reported improved forearm endurance following two different approaches to the training. The forearm endurance training in the study by Hermans et al.\textsuperscript{32} consisted of forearm curls using a dumbbell, which is not an exercise commonly implemented among climbers and may lack specificity toward the endurance test performed on a shallow rung. One can speculate that the low performance level of the climbers allowed for a non-specific training method to produce significant improvements in the forearm endurance test. It is, however, unknown whether the same training program would improve forearm endurance among climbers performing on a higher level. Medernach et al.\textsuperscript{31} implemented four weeks of resistance-training of the fingers using a shallow rung which is a more specific training method, both for the dead hang endurance test and for climbing. The high specificity toward the dead hang endurance test is probably why this method proved efficient among the highly advanced boulderers included in the study following a short intervention.

\textit{Systematic review}

The trials that could not be included in the meta-analysis due to no comparison with a control group or the existence of no comparable trials were included in the systematic review. These trials include the effect of isolated finger resistance-training on RFD,\textsuperscript{30} the effect of core training on performance in climbing-specific tests,\textsuperscript{33} and the effect of isolated finger training on finger
strength and endurance.\textsuperscript{35, 36} Interestingly, and in contrast to the meta-analysis, none of the studies included in the systematic review demonstrated significant improvements in forearm endurance or finger strength,\textsuperscript{35, 36} likely due to the elite performance level of the participants and the low sample sizes. Conversely, the studies included in the meta-analysis\textsuperscript{30-32} examined a higher number of climbers performing on a level ranging from lower-grade to advanced, which could allow potential changes to be more easily detected.

One study has examined the effect of core strength training among climbers.\textsuperscript{33} The authors reported improvements in climbing-specific tests (e.g., body lock-off and body-lift) following both isometric and dynamic core strength training. Since climbing consists of a combination of dynamic moves and isometric lock-offs,\textsuperscript{39} and Saeterbakken et al.\textsuperscript{33} found no significant differences between dynamic and isometric core strength training, climbers may consider both training methods. Importantly, climbing performance was not tested in the study. The core has been described as a crucial factor for transferring force throughout the body\textsuperscript{40} and core strength has previously been identified as a secondary determinant of climbing performance after shoulder-strength and -power.\textsuperscript{5} Importantly, characteristics such as finger and arm strength were also secondary characteristics, suggesting that core strength might be as important for climbing performance as finger strength. Interestingly, Muehlbauer and colleagues\textsuperscript{41} found that MVIC of the trunk flexors improved among non-climbers following eight weeks of two weekly indoor climbing sessions. Taken together, these finding show the importance of core strength in climbing, and that ten weeks of core strength training can improve performance in climbing-specific exercises.\textsuperscript{7, 33, 41}
One study implemented general upper body resistance-training and compared the effects of performing low or high numbers of repetitions using high or low loads on climbing performance. The training program included the following exercises: pull-down, bench press, rowing, shoulder press, biceps curl, forearm press, and forearm curl. Among lower-grade and intermediate climbers, no significant improvements in climbing performance were observed. Importantly, the study suffered from a low sample size, heterogeneity in climbing level and a low climbing performance level of the participants (IRCRA = 8–13). With a performance level ranging from lower-grade to intermediate, it is possible that the climbers could benefit more from specific climbing training than from general resistance-training. However, cross-sectional studies have highlighted the importance of shoulder power and elbow flexor strength for climbing performance. Hence, it can be speculated that implementing a similar intervention among more accomplished climbers and using a larger sample size could demonstrate positive effects on climbing performance.

Study characteristics

Most of the intervention studies were of short duration (four to eight weeks) and the two longest studies lasted no more than ten weeks. Moreover, these were the only two studies that did not include climbing-specific finger resistance-training or changed the climbing routines of the participants in the intervention. Further, the two studies that lasted eight weeks compared two groups performing very similar training programs (a) intermittent vs. maximal weighted dead-hangs or b) endurance vs. hypertrophy training). The same was true for two of the studies with four-week interventions which also compared two similar training approaches (a) minimal edge vs. maximal weighted dead-hangs or b) interval bouldering vs. conventional
bouldering). This leaves two studies\textsuperscript{30, 31} that were able to identify possible effects of climbing-specific resistance-training of the fingers compared to the effects of continuing climbing training as usual. Thus, the long-term (>4 weeks) effect of climbing-specific finger resistance-training is currently unknown. Importantly, short interventions are not necessarily a limitation in climbing-research. Four weeks is a common duration of blocks in resistance training\textsuperscript{43} and as specific finger strength and endurance training involves very high intensity training on small muscles, periodization in four-week blocks is likely a reasonable method for avoiding overuse injuries.

A heterogeneity was observed for the study samples of the studies included in this systematic review and meta-analysis. Specifically, the performance levels ranged from lower-grade climbers\textsuperscript{32} to elite and top internationally-ranked athletes.\textsuperscript{30} However, the variability in performance levels within studies was generally low, meaning the studies included climbers of specific levels. This is important for being able to make valid recommendations for specific groups of climbers. Unfortunately, some studies\textsuperscript{32, 33, 37} failed to specify the predominant discipline of the participants. Current recommendations\textsuperscript{44} suggest that studies should report how climbers classify their participation in the sport (e.g., sport climber, boulderer, speed climber, etc.) to allow for more detailed interpretation of the findings. It is further recommended that studies report the percentage of time devoted to each discipline,\textsuperscript{44} which, unfortunately, none of the studies included in the present review did.

Regarding gender, female climbers are underrepresented in the literature and no interventional studies have included only females. Three studies included in this systematic review and meta-analysis included only males, whereas the remaining five combined males and females. Hermans
et al.\textsuperscript{32} did not report the distribution of males and females, while the remaining studies\textsuperscript{33, 35-37} had a majority of males (total: 59 males and 18 females). A difference in strength and hypertrophy between men and women with identical training background has been identified.\textsuperscript{45} However, it has been shown that physically active males and females respond similarly in the first weeks (up to 12 weeks) of high-intensity resistance-training programs.\textsuperscript{46, 47} Although males and females may respond similarly to climbing-specific resistance-training, the distinct effects on female climbers are yet unknown and should be investigated in future research.

Recommendations for future studies

This systematic review with meta-analysis provides an overview of the current knowledge of the effects of different training approaches on climbing performance and performance in climbing-specific tests. An important finding was the scarcity of scientific, longitudinal literature. Moreover, only three interventional studies could be included in the meta-analysis, due to many studies not including a control group, but rather a secondary training intervention. Hence, it is recommended that upcoming interventional studies include a control group to explicitly target the effects of the intervention compared to not changing the training routines of climbers. Further, female climbers are underrepresented in the literature and no study has yet examined the effects of climbing or climbing-specific training among only females. Another recommendation based on the current findings is for future research to examine the long-term effects of training interventions in climbers. Thus far, no study has had a duration longer than ten weeks, with most interventions lasting from four to eight weeks. From a practical point of view, future studies should include a measure of climbing performance. Although performance in climbing-specific tests is an indicator of climbing performance, the underlying aim of most research in the field is
to explore how climbing performance is improved. Finally, as previously recommended,44
studies should clearly describe their study population regarding preferred discipline, weekly
training and climbing volume, performance level, climbing experience and potential block
periodization implemented in their regular training routines.

Limitations

A major limitation of the present meta-analysis was the small number (n = 3/5) of studies/trials30-
32 that could be included due to several studies comparing different training modalities and not
comparing the effects to a control group, giving a low total sample size and low statistical power.
As the field of research examining climbing-specific resistance-training is relatively young and
only very few interventional studies have been conducted, it can be speculated that comparisons
of slightly different training methods are premature. At this point, interventional studies on
climbers should rather identify the effects of training than compare different but relatively
similar methods. For example, the effects of two36 or three35 highly similar finger resistance-
training modalities have been compared and revealed few or no differences in effect. Hence,
resources could be better spent comparing the effects to a control group, rather than to a training
group performing resembling training programs. Additionally, many of the interventional studies
performed on climbers comprise relatively few participants. However, by performing a meta-
analysis we increased the statistical power to detect differences compared to the statistical power
in the original individual studies. Another limitation is that differences in performance level of
the study populations (ranging from lower-grade lead climbers to highly advanced boulder
climbers) challenge the comparability between studies. Furthermore, the present study is limited
by the fact that only three of the included papers31, 34, 37 received a PEDro score that met the
criteria for high-quality studies (≥6). One inherent limitation of training studies is the difficulty in blinding of researchers and participants. However, researchers examining climbers should strive to avoid reporting bias in future studies. Finally, as only studies published in English were included, it is possible that papers written in other languages contain further information not included in this systematic review and meta-analysis.

Conclusions

Although the field of climbing research is still in its infancy, some conclusions can be drawn from the available literature. The meta-analysis revealed that resistance-training of the fingers and forearms can improve strength and endurance measured using climbing-specific holds. Conversely, the results from the systematic review did not indicate that climbing-specific resistance-training is an effective approach for improving strength or endurance of the finger flexors but may be highly effective for increasing RFD. Furthermore, only one study has so far demonstrated different effects after comparing two training programs. Hence, any climbing-specific training may improve climbing- or bouldering performance, but an interval-style approach may be beneficial for improving climbing time to exhaustion.

To our best knowledge, this was the first systematic review and meta-analysis examining the longitudinal effects of climbing and climbing-specific resistance-training on climbing performance and performance in climbing-specific tests. Eight studies could be included in the systematic review, of which only three could be meta-analyzed. Based on the available literature, it is evident that the addition of some systematic resistance-training can yield greater
Improvements than climbing-training alone across several performance levels. However, the scarcity of available literature must be considered when interpreting the current conclusions. The current systematic review and meta-analysis may assist researchers in designing prospective intervention studies examining climbers. Specifically, there is a need for 1) studies comparing training to a control condition, 2) studies including only female climbers, and 3) studies that more clearly describe the participants to allow for more precise comparisons and discussions of findings across studies.

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Disclosure statement

The authors declare no conflict of interest.
References


Table 1: The methodological quality of the included studies, as assessed using the PEDro scale.

<table>
<thead>
<tr>
<th>Study</th>
<th>Eligibility specified</th>
<th>Randomization</th>
<th>Allocation concealed</th>
<th>Similar at baseline</th>
<th>Blinding of subjects</th>
<th>Blinding of therapists</th>
<th>Blinding of assessors</th>
<th>&lt;15% drop-out</th>
<th>Intention to treat</th>
<th>Between groups statistics</th>
<th>Point and variability</th>
<th>Total score</th>
</tr>
</thead>
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<td>Hermans et al. 32</td>
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<td>5</td>
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<td>7</td>
</tr>
</tbody>
</table>

1 = criterion is satisfied/fulfilled
0 = criterion is not satisfied/fulfilled
### Table 2: Characteristics of the included studies.

<table>
<thead>
<tr>
<th>Subjects (n, sex, age)</th>
<th>Performance level</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>López-Rivera and González-Badillo</td>
<td>8 m, 1 f 30.4 ± 3.9</td>
<td>Advanced and elite sport climbers IRCRA ≥ 23</td>
<td>Fingerboard training 4 wk min edge dept (MED), 4 wk max added weight (MAW) 8 wk (4wk MED + 4 wk MAW)</td>
<td>Fingerboard training 4 wk MAW, 4 wk MED 8 wk (4 wk MAW + 4 wk MED)</td>
</tr>
<tr>
<td>Medernach et al.</td>
<td>23 m, 25.6 ± 4.4</td>
<td>Highly advanced male boulders IRCRA = 23</td>
<td>Fingerboard training 4 wk, 3 x 150 min per wk</td>
<td>Bouldering 4 wk, 3 x 150 min per wk</td>
</tr>
<tr>
<td>Medernach et al.</td>
<td>24 m, 25.2 ± 4.8</td>
<td>Advanced boulders IRCRA = 22</td>
<td>Interval bouldering, 4 wk, 3 x 150 min per wk</td>
<td>Conventional bouldering, 4 wk, 3 x 150 min per wk</td>
</tr>
<tr>
<td>Hermans et al.</td>
<td>30 m/f 23.3 ± 1.9</td>
<td>Lower-grade and intermediate climbers IRCRA = 8-13</td>
<td>Resistance training 10 wk 7 exercises x 4 sets x 5RM, 2 times per wk 10 wk 7 exercises x 2 sets x 20RM, 2 times per wk</td>
<td>Continued climbing/training as usual</td>
</tr>
<tr>
<td>Saeterbakken et al.</td>
<td>13 m, 6 f 27.4 ± 6.7</td>
<td>Elite and Advanced climbers IRCRA = 20.1 ± 3.1</td>
<td>Trunk training 10 wk 4 Isometric exercises, 3-4 sets x 4-10 reps, x 2 per wk</td>
<td>Trunk training 10 wk 4 dynamic exercises, 3-4 sets x 4-10 reps, x 2 pr wk</td>
</tr>
<tr>
<td>Levernier and Laffay</td>
<td>14 m, 26.1 ± 2.2</td>
<td>Elite and top world-ranking climbers IRCRA ≥ 25</td>
<td>Isometric finger strength (half crimp) 4 wk, 6 exercises, 2 series of 4-6s effort, 3 times pr wk</td>
<td>Continued climbing/training as usual</td>
</tr>
<tr>
<td>López-Rivera and González-Badillo</td>
<td>23 m, 3 f, 32.0 ± 6.2</td>
<td>Advanced and elite sport climbers Mean IRCRA = 22</td>
<td>Fingerboard training 8 wk max weight hangs</td>
<td>Finger training 8 wk intermittent hangs</td>
</tr>
<tr>
<td>Philippe et al.</td>
<td>15 m, 8 f, 25.5 ± 6.7</td>
<td>Elite climbers IRCRA = 20.8 ± 2.0</td>
<td>8 wk climbing-specific muscle endurance training</td>
<td>8 wk climbing-specific hypertrophy training</td>
</tr>
</tbody>
</table>

m = males, f = females, n = number, IRCRA = International Rock Climbing Research Association grade reported in the studies, wk = week, s = seconds.
Figures

Figure 1: Flow chart showing the study selection procedure.

1. Records identified through database searching (n = 743)
2. Records after duplicates removed (n = 232)
3. Records screened (n = 232)
   - Records excluded after reading title and abstract: (n = 223)
4. Full-text articles assessed for eligibility (n = 9)
   - Articles excluded after reading full-text:
     - Did not include climbers (n = 1)
5. Studies included in systematic review (n = 8)
   - Articles included in the meta-analysis (n = 3)
   - Did not include climbers (n = 1)
**Figure 2:** The effect of forearm resistance-training on dead-hang time (seconds).

<table>
<thead>
<tr>
<th>Study name</th>
<th>Outcome</th>
<th>Std diff in means</th>
<th>Standard error</th>
<th>Variance</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Z-Value</th>
<th>p-Value</th>
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<td>Medema et al 2015</td>
<td>DeadHang</td>
<td>1.591</td>
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<td>DeadHang</td>
<td>1.715</td>
<td>0.490</td>
<td>0.304</td>
<td>0.462</td>
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<td>0.910</td>
<td>0.496</td>
<td>0.216</td>
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<td>1.732</td>
<td>1.014</td>
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</table>

For arms holding

For arms strengthening
Figure 3: The effect of finger resistance-training on finger strength (Newton).

<table>
<thead>
<tr>
<th>Study name</th>
<th>Outcome</th>
<th>Std diff in means</th>
<th>Standard error</th>
<th>Variance</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Z-Value</th>
<th>p-Value</th>
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<td>Malenaich d.d. 2015</td>
<td>Finger strength</td>
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<td>0.415</td>
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<td>Leventer et al. 2019</td>
<td>Finger strength</td>
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<td>1.743</td>
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<tr>
<td>Leventer et al. 2019</td>
<td>Finger strength</td>
<td>1.298</td>
<td>0.342</td>
<td>0.119</td>
<td>2.416</td>
<td>2.794</td>
<td>0.030</td>
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</tr>
</tbody>
</table>
Paper II
Upper body rate of force development and maximal strength discriminates performance levels in sport climbing

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Abstract

The aim of this study was to assess and compare the maximal force and rate of force development (RFD) between intermediate, advanced and elite climbers using several different methods for calculating RFD. Fifty-seven male climbers (17 intermediate, 25 advanced, and 15 elite) performed isometric pull-ups on a climbing-specific hold while the RFD was calculated using several absolute (50, 100, 150, 200, and 250 ms from onset of force) and relative time periods (25, 50, 75, 95, and 100% of time to peak force). The maximal force was higher among elite climbers compared to advanced (ES = 1.78, p < 0.001) and intermediate climbers (ES = 1.77, p < 0.001), while no difference was observed between intermediate and advanced climbers (P = 0.898). The elite group also showed higher RFD than the other two groups at all relative time periods (ES = 1.02–1.58, p < 0.001–0.002), whereas the absolute time periods only revealed differences between the elite vs. the other groups at 50, 100 and 150 ms from the onset of force (ES = 0.72–0.84, p = 0.032–0.040). No differences in RFD were observed between the intermediate and advanced groups at any time period (p = 0.942–1.000). Maximal force and RFD, especially calculated using the longer periods of the force curve, may be used to distinguish elite climbers from advanced and intermediate climbers. The authors suggest using relative rather than absolute time periods when analyzing the RFD of climbers.

Introduction

Sport climbing will be introduced for the first time as an Olympic sport in 2021 and has received increased attention from researchers and athletes [1]. Researchers attempting to determine which factors influence sport climbing- and bouldering-performance have identified a combination of technical [2,3], neuromuscular [4–8], anthropometric [9–11], psychological [12], and physiological factors [13]. In general, higher performing athletes are stronger than intermediate climbers, especially when climbing-specific tests and hold types are implemented [8,10,14,15]. Moreover, in previous studies examining climbers, the strength and rate of force development (RFD) of the finger flexors has also discriminated between climbing performance levels [8] and disciplines [16].
RFD is defined as the rate of the rise in force during isometric contractions, and has been used to quantify the ability to generate force rapidly \[17\]. When climbing harder routes, the smaller holds and more difficult moves cause a need for more force to be exerted in a shorter time window to avoid falling off the route. RFD may, therefore, be a key factor for predicting climbing performance \[4,5,8\], and has discriminated between skilled and international performance levels when calculated using longer time periods \[8\]. Previous studies have implemented a variety of testing procedures for examining RFD \[8,16,18–20\]. In one recent study \[20\], RFD was measured using a hand dynamometer, which have been shown to be less valid than specific tests (e.g., using climbing-specific holds and common climbing-positions) \[21\]. Conversely, Fanchini et al. \[16\] and Michailov et al. \[19\] used climbing-specific holds but isolated the finger flexors, excluding the arm- and back muscles from the testing. This might reduce the validity as, when climbing, the fingers are only responsible for maintaining contact with the holds whilst the vertical propulsive force of the climber is produced mainly by other prime movers (i.e., elbow flexors and shoulder extensors). A more promising test was used by Levernier and LaFlaye \[8\] and Michailov et al. \[19\], examining maximal voluntary isometric contractions (MVIC) in a standing position. This removes constraints around the elbow and allows several prime movers to contribute to the VMIC, providing a higher validity \[19\]. To the authors’ best knowledge, only two studies \[18,22\] have assessed the RFD of the entire pulling-apparatus (finger-, arm-, shoulder- and back-muscles) in one exercise (isometric pull-ups on a climbing-specific hold). However, the authors compared climbers of different disciplines rather than performance levels.

In addition to varying test set-ups, differences in the calculation of RFD between studies limit the comparability of the findings. For example, the time periods used to calculate RFD have ranged between 150 ms to absolute RFD (RFD100%; calculated from the onset of force to peak force) \[8,18,20,22,23\]. While RFD calculated using longer time periods of the force curve may be strongly related to maximal force \[24\], the shorter time periods (50–250 ms) could be associated with the explosive strength required for hard and dynamic climbing moves \[6,17,23\], but might also be more prone to variability \[8,26\]. Finally, it has been suggested that RFD data should be normalized (RFD relative to maximal force) to highlight whether or not differences in RFD are caused by a difference in maximal strength alone \[27,28\].

While a variety of time periods have been examined in different sports and resistance exercises, no literature exists concerning which time period should be used when analyzing RFD of the entire pulling-apparatus in climbing. As varying times to reach peak force in climbing-specific tests have been observed \[8,18,20\], the use of relative (calculated at a given percentage of the time to reach peak force) rather than absolute time periods could be more reliable. Finally, to the authors’ best knowledge, no previous study has examined RFD among three different levels of climbers. Hence, the aim of this investigation was to assess and compare the RFD of three performance levels of climbers (intermediate, advanced, and elite), as well as examine the reliability and ability of several absolute and relative time periods to discriminate between performance levels. It was hypothesized that the advanced climbers would produce higher RFD than the intermediate climbers, and that the elite climbers would have higher RFD than the advanced and intermediate climbers. Finally, we expected RFD calculated using longer time periods of the force curve to be more reliable and more discriminatory between performance levels.

Materials and methods

Study design

To answer the research question, a cross-sectional between-subject comparative study was designed, including three different levels of lead climbers. To reach an adequate sample size,
the data was collected over the course of two years using a standardized protocol and trained test leaders.

Participants
Fifty-seven male amateur lead climbers volunteered for this cross-sectional study (characteristics are presented in Table 1). Participants were asked to report their climbing experience as the number of consecutive years for which they had been climbing regularly (at least one session per week). Many participants were also engaged in general resistance- or endurance training, but all included participants had climbing as their primary activity. To be included, participants had to be able to perform the experimental tests correctly (i.e., be strong enough to hang from the hold used and be able to perform a maximal-effort isometric pull-up without falling of the rung), and have a minimum self-reported climbing ability of 6b (International Rock Climbing Research Association (IRCRA) [29] = intermediate level). It has been reported that self-reported climbing grades are accurate and appropriate for use in research contexts [30]. Participants also had to be without any injuries or illnesses that could limit maximal performance in the testing. None of the participants were professional climbers, but several of the included climbers were competing on a national level.

Ethics statement
The participants were informed verbally and in writing about the potential risks and benefits of participation and signed and informed consent form before data collection commenced. The present research procedures were in accordance with the ethical guidelines of Western Norway University of Applied Sciences, conformed to the standards of treatment of human participants in research outlined in the 5th Declaration of Helsinki, and approved by the Norwegian Centre for Research Data.

Measurements and test procedures
Upon arrival to the laboratory, participants reported their age, climbing experience and climbing level. Their highest achieved climbing grade in the last year was reported using either the Scandinavian or French grading systems and the answers were converted to the numerical grading scale (1–32) proposed by the International Rock Climbing Research Association (IRCRA). Using the grouping system suggested by Draper et al., [29] the climbers were divided

| Table 1. Anthropometric data, climbing experience, weekly number of climbing sessions, and average onsight grade of the participants given according to the numerical grading scale (1–32) suggested by the International Rock Climbing Research Association (IRCRA). The values are presented as means (± standard deviation). |
|-----------------|-----------------|-----------------|
| Intermediate (n = 17) | Advanced (n = 26) | Elite (n = 14) |
| Age (years) | 26.18 ± 1.60 | 29.28 ± 2.74 | 27.40 ± 4.29 |
| Height (cm) | 184.47 ± 12.82 | 179.24 ± 2.81 | 179.40 ± 3.33 |
| Body mass (kg) | 73.39 ± 4.21 | 72.09 ± 3.29 | 72.25 ± 3.35 |
| Weekly sessions (n) | 2.43 ± 1.22 | 3.20 ± 1.02 | 4.4 ± 1.02† |
| Experience (years) | 4.18 ± 1.14 | 6.74 ± 2.09 | 11.47 ± 3.44‡ |
| Redpoint (IRCRA) | 15.82 ± 1.12 | 20.04 ± 0.96† | 24.87 ± 0.81‡ |

* = significantly greater than the intermediate group (P < 0.05).
** = significantly greater than the intermediate and advanced groups (P < 0.01).
† = significantly higher Redpoint grade than the intermediate group (P < 0.01).
‡ = significantly higher Redpoint grade than the advanced group (P < 0.01).

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into one of the following three groups based on their self-reported maximal achieved climbing grade: intermediate group (IRCRA 10–17; n = 17), advanced group (IRCRA 18–23; n = 25), and elite group (IRCRA 24–27; n = 15). Height and body mass were then measured using a wall mounted measuring tape and a bioelectric impedance scale (Tanita MC 780MA S, Tokyo, Japan), respectively. Following the anthropometric measures, the participants performed a 15-minute light-to-moderate warm-up consisting of bouldering and traversing. The participants selected the difficulty of the boulders themselves but were instructed to avoid fatigue.

After resting for five minutes, the experimental test began. The data was collected during an isometric pull-up performed on a 23mm deep rung (Metolius Climbing, Bend, Oregon, USA) with rounded edges using a half crimp grip with a passive thumb, self-selected width between the hands, and a 90° elbow angle [18,19,22] (Fig 1). The climbers could apply chalk (magnesium carbonate) to their hands and fingers before starting the test and the rung was regularly brushed to provide equal friction conditions for all participants. The force output was measured using a force sensor (Ergotest Innovation A/S, Porsgrunn, Norway) anchored to the ground (via an expansion bolt and hanger in the concrete floor) and attached to the participants via a static rope and the belay loop of a climbing harness positioned slightly (1–4 cm) below the iliac crest. The length of the rope was adjusted for each participant to achieve the correct elbow angle (measured with goniometer) and the placement of the harness was controlled between attempts.

Following verbal instructions, participants pulled themselves up to a 90° elbow angle (where the rope became taut) and maintained the position for approximately one second. They had to hang still (no more than ± 5N fluctuation in force for 1000 ms) before the contraction and an attempt was annulled if a dip in the force (small countermovement creating slack in the rope) was observed prior to the onset of force. The participants were then verbally encouraged to perform an isometric pull-up as quickly and forcefully as possible [28] and maintain maximal force for three-to-five seconds. For an attempt to be correctly executed, the force had to increase continually, without a plateau, to the peak force output (peak force coefficient of variation (CV) = 12.9%, 9.2%, and 9.1% for the intermediate, advanced and elite groups, respectively). As the participants were experienced climbers, no familiarization session was implemented, but three attempts were given to ensure that optimal performance was reached.

![Fig 1. Illustration showing a) the test set-up for the isometric pull up and b) the half crimp grip on the 23mm rung.](https://doi.org/10.1371/journal.pone.0249353.g001)
The best result was used in the between-groups analyses, while all three attempts were registered to calculate intra-class correlations (ICC) and CV within-participants during one testing session. The attempt with the steepest force curve (highest absolute RFD from onset to peak force) was considered the best attempt. Participants were shown the force curve after each attempt and given feedback on how to improve for their next attempt. Three minutes of rest were given between attempts [8].

The force output was recorded by the force sensor at 200Hz and analyzed using commercial software (MuscleLab v. 10.4.37.4073, Ergotest Innovation A/S, Porsgrunn, Norway). The onset of contraction was identified visually, which has been proposed as more sensitive and accurate than automated detection [28]. The onset was determined at the point when the force increased more than 5 N from the baseline over a 5 ms window. This manual method has been shown to be reliable [25] and has been previously implemented in similar investigations [8,20]. The baseline force could not exceed 100 N and the mean baseline force across all attempts was 58 ± 36N. The same researcher analyzed all the data to avoid inter-rater variability in determination of the onset. The RFD was collected from the recorded force curves at different time periods (0–50, 0–100, 0–150, 0–200 and 0–250 ms) from the onset of force [31]. Peak force (N) and the time to reach peak force (ms) was also registered in order to calculate relative time periods (25%, 50%, 75%, 95% and 100%) from the onset of contraction. Finally, the RFD100% was normalized to the peak force to investigate what influence the maximal strength had on the potential differences in RFD between groups. Every force curve was strictly evaluated before inclusion in the analyses.

Statistics
Kolmogorov-Smirnov test and visual inspection of the QQ-plots showed normally distributed data (P = 0.053–0.200). SPSS statistical software (Version 25.0, SPSS Inc., Chicago, IL, USA) was used for all analyses. The reliability of each RFD measure was assessed using ICC and CV ((population standard deviation / population mean) × 100). ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.9 were classified as poor, moderate, good, and excellent, respectively [32]. CV values less than 10% were considered acceptable [8]. A one-way analysis of variance (ANOVA) was used to examine whether there were differences between the three groups for the tested variables. When significant differences were detected, Bonferroni post-hoc tests were used to identify where the differences lay. The alpha level was set at 0.05 for statistical significance. The Cohen’s d effect sizes (ES) for the differences between the groups were calculated as the means divided by the pooled standard deviation. An ES of < 0.2 was considered trivial, > 0.2 small, > 0.5 moderate, and > 0.8 large [33].

Results
Reliability
The ICC and CV between the three attempts using the relative and absolute time periods are presented in Table 2A and 2B, respectively. The ICCs ranged from moderate to excellent for all levels of climbers. All CV values for the intermediate and advanced climbers were unacceptable (CV = 16.9 to 31.3%), whereas the CV values for the elite climbers were acceptable (< 10%) only when using the entire force curve (RFD100) and 250 ms from the onset.

Baseline results
No differences in anthropometric variables between the three groups of climbers were detected (p = 0.272–0.852). No significant difference in climbing experience was found between the
Table 2. a. The mean rate of force development (Newton x s\(^{-1}\)) from the three attempts for each group using the relative time periods with the mean rate of force development and the intra-class correlation (ICC) and coefficient of variation (CV) between the three attempts. b. The mean rate of force development (Newton x s\(^{-1}\)) from the three attempts for each group using the absolute time periods with the mean rate of force development and the intra-class correlation (ICC) and coefficient of variation (CV) between the three attempts.

<table>
<thead>
<tr>
<th>Intermediate group</th>
<th>Time period</th>
<th>Mean RFD</th>
<th>CV (%)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25%</td>
<td>610 ± 274</td>
<td>27.8 ± 15.3</td>
<td>0.798</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>948 ± 443</td>
<td>21.1 ± 12.1</td>
<td>0.914</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>1214 ± 563</td>
<td>21.0 ± 14.2</td>
<td>0.905</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>1209 ± 571</td>
<td>20.3 ± 11.7</td>
<td>0.916</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>1166 ± 549</td>
<td>20.0 ± 11.3</td>
<td>0.918</td>
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<table>
<thead>
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<th>Time period</th>
<th>Mean RFD</th>
<th>CV (%)</th>
<th>ICC</th>
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</thead>
<tbody>
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<td></td>
<td>25%</td>
<td>762 ± 381</td>
<td>28.2 ± 14.7</td>
<td>0.857</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>1084 ± 402</td>
<td>16.9 ± 12.2</td>
<td>0.817</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>1342 ± 472</td>
<td>18.0 ± 11.3</td>
<td>0.830</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>1311 ± 473</td>
<td>18.7 ± 10.6</td>
<td>0.858</td>
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<tr>
<td></td>
<td>100%</td>
<td>1272 ± 468</td>
<td>17.9 ± 9.5</td>
<td>0.877</td>
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<th>Elite group</th>
<th>Time period</th>
<th>Mean RFD</th>
<th>CV (%)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25%</td>
<td>1450 ± 740</td>
<td>19.7 ± 15.4</td>
<td>0.763</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>2259 ± 1224</td>
<td>13.9 ± 13.6</td>
<td>0.817</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>2662 ± 1074</td>
<td>10.6 ± 7.9</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>2390 ± 1030</td>
<td>10.7 ± 6.5</td>
<td>0.985</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>2519 ± 978</td>
<td>8.9 ± 5.2</td>
<td>0.985</td>
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<table>
<thead>
<tr>
<th>Intermediate group</th>
<th>Time period</th>
<th>Mean RFD</th>
<th>CV (%)</th>
<th>ICC</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>50ms</td>
<td>628 ± 490</td>
<td>27.7 ± 19.2</td>
<td>0.921</td>
</tr>
<tr>
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<td>100ms</td>
<td>906 ± 745</td>
<td>24.5 ± 13.9</td>
<td>0.957</td>
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<td>150ms</td>
<td>1154 ± 829</td>
<td>23.4 ± 16.9</td>
<td>0.955</td>
</tr>
<tr>
<td></td>
<td>200ms</td>
<td>1185 ± 585</td>
<td>24.4 ± 16.9</td>
<td>0.850</td>
</tr>
<tr>
<td></td>
<td>250ms</td>
<td>1107 ± 469</td>
<td>26.0 ± 14.9</td>
<td>0.744</td>
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<table>
<thead>
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<th>Time period</th>
<th>Mean RFD</th>
<th>CV (%)</th>
<th>ICC</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>50ms</td>
<td>626 ± 260</td>
<td>31.3 ± 15.8</td>
<td>0.687</td>
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<tr>
<td></td>
<td>100ms</td>
<td>917 ± 471</td>
<td>30.1 ± 17.1</td>
<td>0.776</td>
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<td>150ms</td>
<td>1197 ± 604</td>
<td>25.9 ± 18.0</td>
<td>0.691</td>
</tr>
<tr>
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<td>200ms</td>
<td>1364 ± 635</td>
<td>23.0 ± 17.6</td>
<td>0.746</td>
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<td></td>
<td>250ms</td>
<td>1222 ± 490</td>
<td>18.9 ± 12.1</td>
<td>0.860</td>
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<th>Elite group</th>
<th>Time period</th>
<th>Mean RFD</th>
<th>CV (%)</th>
<th>ICC</th>
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</thead>
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<tr>
<td></td>
<td>50ms</td>
<td>1180 ± 915</td>
<td>26.7 ± 24.1</td>
<td>0.802</td>
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<tr>
<td></td>
<td>100ms</td>
<td>1692 ± 1161</td>
<td>18.6 ± 15.1</td>
<td>0.934</td>
</tr>
<tr>
<td></td>
<td>150ms</td>
<td>2065 ± 1084</td>
<td>11.5 ± 9.7</td>
<td>0.986</td>
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<tr>
<td></td>
<td>200ms</td>
<td>1943 ± 778</td>
<td>11.4 ± 9.6</td>
<td>0.956</td>
</tr>
<tr>
<td></td>
<td>250ms</td>
<td>1547 ± 604</td>
<td>10.0 ± 8.6</td>
<td>0.966</td>
</tr>
</tbody>
</table>

RFD and CV values are presented with mean ± standard deviation.

https://doi.org/10.1371/journal.pone.0249353.t002
intermediate and advanced climbers (p = 0.279), while the elite group had a longer experience than the intermediate (ES = 1.74, p < 0.001) and advanced climbers (ES = 0.86, p = 0.006; See Table 1).

**RFD between groups**

Significant differences in RFD were found at all relative time periods (F = 10.197–16.631, all p < 0.001). Post hoc tests revealed no differences between the intermediate and advanced groups (p = 0.942–1.000, while the elite group had higher RFD than both the intermediate and advanced climbers at all measures (p < 0.001–0.002; Table 3).

For the absolute time periods, the analyses revealed significant differences between the groups for RFD50 (F = 4.128, p = 0.021), RFD100 (F = 4.368, p = 0.017), and RFD150 (F = 3.853, p = 0.027), but not for RFD200 (F = 2.362, p = 0.104) or RFD250 (F = 0.504, p = 0.608). No differences were found between the intermediate and advanced groups (p = 1.000). The elite climbers produced higher RFD than the intermediate group at RFD50 (p = 0.032) and RFD150 (p = 0.040), and higher RFD than the advanced group at RFD50 (p = 0.012) and RFD100 (p = 0.035; Table 3).

**Force and time**

To investigate the relative contribution of the two quotients of RFD, the peak force and the time to reach peak force were analyzed. Differences between the groups were found for the time (F = 3.377, p = 0.041) and force-factors (F = 16.932, p < 0.001). Post hoc tests showed that the intermediate group did not differ from the advanced (p = 0.767) or elite groups (p = 0.526) in the time to reach peak force, while the elite group reached peak force faster than the advanced climbers (ES = 0.88, p = 0.036; Fig 2). The elite group produced higher peak force output than the intermediate (ES = 1.77, p < 0.001) and advanced groups (ES = 1.78, p < 0.001), while no significant difference was found between the intermediate and advanced groups (p = 0.898; Fig 2).

**Normalized RFD**

Finally, the RFD relative to the peak force was significantly different between groups (F = 4.301, p = 0.018). There was no difference between the intermediate and advanced groups.

Table 3. The rate of force development (Newton × s⁻¹) from the best attempt for the elite intermediate (IG), advanced (AG) and elite groups (EG) and the effect sizes for the between groups differences.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Intermediate group</th>
<th>Advanced group</th>
<th>Elite group</th>
<th>Effect size IG vs. AG</th>
<th>Effect size AG vs. EG</th>
<th>Effect size EG vs. IG</th>
</tr>
</thead>
<tbody>
<tr>
<td>50ms</td>
<td>801 ± 625</td>
<td>799 ± 338</td>
<td>1457 ± 1269</td>
<td>0.00</td>
<td>0.82</td>
<td>0.70</td>
</tr>
<tr>
<td>100ms</td>
<td>1069 ± 837</td>
<td>1146 ± 588</td>
<td>1928 ± 1364</td>
<td>0.11</td>
<td>0.80</td>
<td>0.78</td>
</tr>
<tr>
<td>150ms</td>
<td>1364 ± 917</td>
<td>1495 ± 862</td>
<td>2236 ± 1154</td>
<td>0.15</td>
<td>0.73</td>
<td>0.84</td>
</tr>
<tr>
<td>200ms</td>
<td>1456 ± 749</td>
<td>1664 ± 852</td>
<td>2117 ± 873</td>
<td>0.26</td>
<td>0.52</td>
<td>0.82</td>
</tr>
<tr>
<td>250ms</td>
<td>1405 ± 713</td>
<td>1423 ± 605</td>
<td>1673 ± 671</td>
<td>0.03</td>
<td>0.39</td>
<td>0.39</td>
</tr>
<tr>
<td>25%</td>
<td>747 ± 332</td>
<td>952 ± 439</td>
<td>1719 ± 1065</td>
<td>0.53</td>
<td>1.02†</td>
<td>1.39†</td>
</tr>
<tr>
<td>50%</td>
<td>1092 ± 477</td>
<td>1272 ± 510</td>
<td>2555 ± 1899</td>
<td>0.36</td>
<td>1.16†</td>
<td>1.34†</td>
</tr>
<tr>
<td>75%</td>
<td>1426 ± 664</td>
<td>1562 ± 559</td>
<td>2889 ± 1196</td>
<td>0.22</td>
<td>1.51†</td>
<td>1.57†</td>
</tr>
<tr>
<td>95%</td>
<td>1426 ± 689</td>
<td>1548 ± 569</td>
<td>2807 ± 1085</td>
<td>0.19</td>
<td>1.52†</td>
<td>1.56†</td>
</tr>
<tr>
<td>100%</td>
<td>1372 ± 662</td>
<td>1492 ± 562</td>
<td>2709 ± 1051</td>
<td>0.20</td>
<td>1.51†</td>
<td>1.56†</td>
</tr>
</tbody>
</table>

All values are presented with mean ± standard deviation.
* = significant difference at the P < 0.05 level.
† = significant difference at the P < 0.01 level.

https://doi.org/10.1371/journal.pone.0249353.t003
Discussion

The aim of this study was to examine the ability of different RFD measures to discriminate between performance levels among climbers. In line with the primary hypothesis, the elite climbers produced higher RFD than the intermediate and advanced climbers. Conversely, no significant differences were found between the intermediate and advanced climbers. Based on these findings, RFD may not be a crucial component for climbing performance before reaching the more demanding grades (> 24 IRCRA). Whereas the shift from an intermediate to an advanced climber may be implemented by practicing other factors such as endurance, technical skills or psychological factors [2,3,13], a progression to the elite level seems to entail a prominent improvement in RFD.

The higher RFD produced by the elite climbers was accompanied by a notably higher peak force output than the other groups, while the time to reach peak force was only lower than the advanced climbers. Several years of climbing hard moves on shallow holds has likely produced a training stimulus for promoting maximal strength and RFD of the finger flexors and pulling apparatus. As the peak force output provided much clearer differences between the groups than the time to reach peak force, one could assume that using longer times from the onset of force would be better suited for distinguishing between performance levels. Indeed, it has been reported that RFD calculated using longer times from onset of force is more strongly related to maximal force [24]. Importantly, the RFD in the elite group was still greater than in the intermediate and advanced groups following normalization. Hence, the higher peak force alone did

**Fig 2.** The maximal force output (Newton) and the time to reach peak force (milliseconds) for the three groups. † = significantly higher than the intermediate and advanced groups (P < 0.01). * = significantly lower than the advanced group (P < 0.01).

(p = 0.855), while the elite group achieved a higher normalized RFD than both the intermediate (ES = 0.87, p = 0.020) and advanced groups (ES = 0.80, p = 0.017).
not cause the differences in RFD. However, it should be noted that the ES for the differences were reduced following normalization, suggesting that a meaningful portion of the differences in RFD is caused by the higher peak force output in the elite group. Since advanced and intermediate climbers possess less climbing-specific strength of the finger flexors than the elites, performing a maximal-effort contraction using the shallow rung might limit the RFD substantially [18]. This could reduce the potential differences between these two groups while enhancing the difference between the non-elite groups and the elite group.

In contrast to the hypothesis, the late phase of the absolute time periods did not produce more distinctive differences between the groups than the early phase. Conversely, differences between groups were only significant using the 50 ms, 100 ms and 150 ms absolute time periods, and the between-groups difference effect sizes were notably lower using the 200 ms and 250 ms time periods. One potential explanation could be that maximal strength accounts for less of the difference than neurological adaptations to years of attempting hard routes that require rapid force production [28]. In contrast to the absolute measures, the relative measures produced both lower CV values and more distinct between-groups differences, especially when examining the longer durations from the onset of force. As previously speculated [8], the maximal number of muscle fibers recruited while exerting maximal force is likely more reproducible than the time taken to recruit the fibers. As large variations between individuals’ times to reach peak force were observed in this (150 to 730 ms) and previous studies (~ 400 to 1000 ms) [8,18,22], using relative time periods should be the preferred method when examining the entire pulling apparatus of climbers. For example, if an individual uses ≥ 500 ms to reach peak force, the longest absolute time period (250 ms) would still represent the earlier phase of the force curve. Hence, relative time periods could be more practically applicable than the traditional division of early and late phases [28] in tasks typically requiring longer than 250 ms to reach peak force.

Examining the remaining relative (RFD$_{50}$—RFD$_{100}$) and absolute measures (RFD$_{100}$—RFD$_{250}$), the intermediate and advanced climbers produced notably higher CV values (16.9–30.1%) than the elite group (8.9–19.7%). These findings are in agreement with those of Levernier and Laffaye [8] who proposed that increasing skill level could be associated with an improved ability to reproduce similar force outputs across several attempts. More climbing experience probably also produces a more efficient recruitment of the available motor units [34], thereby allowing for a more rapid force production across attempts. Although physiological differences likely account for the difference between the elite and the non-elite climbers (intermediate and advanced), lack of differences between the intermediate and advanced group could partly be explained by the unacceptable CV values observed for these groups. Finally, the results could potentially be explained by the small difference in climbing experience between the intermediate and advanced groups, as well as the fact that the intermediate climbers had a self-reported redpoint grade of 15.82 (IRCRA suggests intermediate classification between 10 and 17) [29]. Hence, the participants in the intermediate groups could be described as higher intermediate.

For the elite group, lower CV values were found when calculating RFD using the relative measures compared to the absolute measures. The higher reliability using the relative time periods demonstrates that practitioners can be more confident that differences in data are true differences. As only the RFD$_{50}$ and RFD$_{250}$ produced good CV values (≤ 10%), results obtained using the remaining time periods should be interpreted with caution. When investigating the intra-class correlations of the climbing-specific test used in this study, moderate-to-excellent reliability was found for the absolute measures, and good-to-excellent reliability for the relative measures. Hence, RFD measured in the current test set-up was consistent across three attempts, especially when using ≥75% of the force curve (ICC = 0.830–0.985).
Importantly, the reliability of the measurements improved when increasing the time periods used to calculate RFD, suggesting that the early phase should not be used during the current and similar test set-ups. Importantly, testing the entire pulling-apparatus provides a highly climbing-specific task, but allows for more variation between attempts than when testing muscles isolated (e.g., with the elbow constrained). Researchers must, therefore, consider a potential trade-off between reliability and validity when selecting testing procedures. Finally, based on the observed CV results and lack of differences between the intermediate and advanced groups, the high finger-strength demands of performing a maximal-effort isometric pull-up on a shallow rung may be better suited for examining elite climbers. Although the current test set-up proved useful for discriminating elite climbers from the advanced and intermediate groups, the observed variation indicate that the test may be unreliable for detecting changes in RFD on an individual level. Interestingly, the current multi-joint isometric testing produced CV values (8.9–28.2% for RFD\textsubscript{100}) that were similar to what has been reported during isolated finger flexor RFD testing (7.8–28.3%) [8].

Although the present findings provide a new insight to the use of RFD when monitoring climbers, the study had some limitations that should be considered when interpreting the results. Importantly, only male climbers were included in this study and the findings might not necessarily be generalizable to female climbers at the same level. Furthermore, no familiarization session was performed as it was expected that experienced climbers would be able to perform the test adequately. Still, several attempts were given to ensure that maximal performance was reached. Importantly, it should be noted that different climbing test set-ups (e.g., isolated finger flexor tests, climbing-specific holds vs. dynamometers, seated position, etc.) likely produce different force curves, which makes it problematic to suggest a general recommendation for calculating RFD. For example, the isometric test used in the present study produces a distinctive force peak, not reported in studies testing the finger flexors in isolation [20] or near isolation [8]. The peak likely occurs due to elastic components within several muscle groups [35], and a slight shift of the body caused by alterations of the shoulder and elbow joints when applying maximal force. Still, the peak is consistent across attempts (mean CV = 10.3%). The low sampling rate (200 Hz) could potentially challenge the reliability of the results as it makes it difficult to perfectly identify the onset and peak forces. However, using the 5N threshold for onset determination, 200Hz resolution can accurately identify the onset (to the closest 5ms). Finally, as isometric testing is not technically difficult, different strategies or focus (e.g., trying to gain a high peak force output rather than RFD) could result in a meaningful change in force output. Therefore, a familiarization session could have improved the reliability and should be included in future studies.

The current study adds to the growing body of literature describing climbers of different performance levels and identifying RFD as a key discriminatory factor. To the authors’ best knowledge, this was the first study to compare three levels of climbers and demonstrate the meaningful differences in RFD between elite level and non-elite (advanced and intermediate) climbers. In comparison, Levernier et al. [8] also included three different groups, but one of the groups included non-climbers. Furthermore, although RFD has been suggested by many as a dependable method for assessing and classifying climbers [8,16,18,20], the methodological approaches vary between studies. For example, Levernier et al. [8] tested RFD unilaterally while standing on the ground, which mimics actual climbing to a lesser degree than the test used in our study. In line with our findings, the authors reported significant differences in RFD between performance levels. However, Levernier et al. [8] identified a varying ability of detecting between-levels differences between different absolute and relative time periods (50, 100, and 200 ms from onset, as well as 95% of max force). This provided a rationale for examining several measures of RFD and to assess which measure was the most discriminatory.
between climbers of different levels. Based on the present findings and the observed differences in the time to develop maximal force, we suggest using the longer (>75% of the time to peak force) and relative time periods rather than absolute time periods when assessing climbers. Importantly, and in agreement with previous findings [8,26], the CV values using the shortest durations from the onset of force were the least reliable measurements and may, therefore, not indicate true differences. Conversely, as differences were detected using the 50 ms, 100 ms and 150 ms time periods despite the high CV values, one could speculate that the actual difference between levels are particularly prominent during the early phase of force production. Researchers should consider the present findings when designing studies for monitoring climbers. Future research should examine the validity to climbing when using different time periods during demanding climbing specific tests. Finally, when testing the entire pulling-apparatus, video motion analysis could be a useful tool for detecting variations in technical execution.

Conclusion

No differences were found between the intermediate and advanced climbers, but the elite group reached a distinctly higher RFD and force output than both the other groups. Advancing through the lower climbing grades may be achieved by improving characteristics not measured in the present study (e.g., mental or technical skills), whereas a progression to the elite grades (> 24 IRCRA) appears to entail a marked increase in RFD and maximal force. The lack of differences in force and RFD between the intermediate and advanced climbers could be explained by the small differences in climbing experience and red-point grade, as well as the higher variability in results observed in these groups compared to the elite group. As lower variability was observed in the elite group, the present test set-up may be better suited for examining elite climbers than non-elite climbers.

Supporting information

S1 Dataset.

(XLSX)

Acknowledgments

The authors thank the climbers who participated in the study, and Dr. Tom Cullen for assisting with the statistical analyses.

Author Contributions

Conceptualization: Nicolay Stien, Atle Hole Saeterbakken, Espen Hermans, Matthew Peter Shaw, Vidar Andersen.

Data curation: Nicolay Stien, Matthew Peter Shaw.

Formal analysis: Nicolay Stien, Atle Hole Saeterbakken, Matthew Peter Shaw, Vidar Andersen.

Investigation: Nicolay Stien, Vegard Albert Vereide, Atle Hole Saeterbakken, Espen Hermans, Matthew Peter Shaw, Vidar Andersen.

Methodology: Nicolay Stien, Vegard Albert Vereide, Atle Hole Saeterbakken, Espen Hermans, Vidar Andersen.

Project administration: Nicolay Stien, Atle Hole Saeterbakken, Vidar Andersen.
References


Paper III
Comparison of climbing-specific strength and endurance between lead and boulder climbers

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Faculty of Education, Arts and Sports, Western Norway University of Applied Sciences, Sogndal, Norway

Abstract

Albeit differences in climbing-specific strength of the forearms have been demonstrated between lead and boulder climbers, little is known about the potential differences in force and power output of the upper body pulling-apparatus between disciplines. The aim of this study was to compare the climbing-specific upper-body strength and finger flexor endurance between lead and boulder climbers, as well as to examine the relative utilization of force when testing on a ledge hold compared to a jug hold. Sixteen boulder climbers (red-point climbing grade 17.9) and fifteen lead climbers (red-point climbing grade 20.5) performing on an advanced level volunteered for the study. Peak force, average force and rate of force development (RFD) were measured during an isometric pull-up, average velocity in dynamic pull-up, and finger flexor endurance in an intermittent test to fatigue. The isometric pull-up was performed on a ledge hold (high finger strength requirements) and on a jug hold (very low finger strength requirements). Boulder climbers demonstrated a higher maximal and explosive strength in all strength and power measurements (26.2–52.9%, ES = 0.90–1.12, p = 0.006–0.023), whereas the finger flexor endurance test showed no significant difference between the groups (p = 0.088). Both groups were able to utilize 57–69% of peak force, average force and RFD in the ledge condition compared to the jug condition, but the relative utilization was not different between the groups (p = 0.290–0.996). In conclusion, boulder climbers were stronger and more explosive compared to lead climbers, whereas no differences in finger flexor endurance were observed. Performing climbing-specific tests on a smaller hold appears to limit the force and power output equally between the two groups.

Introduction

Sport climbing and bouldering have greatly increased in the last decades [1]. Competitive climbing consist of three disciplines; lead climbing, bouldering and speed climbing. Of the three, lead climbing and bouldering currently are the two most practiced disciplines [2]. Indoor bouldering routes typically consist of less than eight-to-ten climbing moves and is performed without ropes on a less than five-meter high wall [2, 3]. Lead climbing consists of
multiple climbing moves and is performed on higher walls (>10m) [4]. Still, only a few studies have compared the physical characteristics of climbers specializing in the two disciplines [3, 5–7].

Factors such as hold type (size and shape) and the gradient of the wall determine the difficulty of boulder and lead climbing routes [8–11]. In order to apply the force generated from the back, shoulder and arm muscles (prime movers) to the holds during moves, sufficient finger strength is required. Therefore, it is generally accepted that finger flexor strength is a crucial factor for performance in climbing and climbing-specific tests [3, 5, 12–21]. For example, Vigouroux et al. [20] demonstrated that smaller climbing holds have a negative impact on force and power output in addition to number of pull-ups to failure among elite climbers. To the authors’ knowledge, however, no previous studies have examined the percentage of isometric force generated by the prime movers that can be utilized on a ledge hold (high level of finger strength requirement) compared to a jug hold (very low level of finger strength requirement). If there is room for improved utilization of force through increased finger strength, it is possible that an augmented climbing performance can be achieved without increasing the strength of the prime movers.

Whereas the average contact times in climbing competitions are 8–10 seconds [2, 4], the typical ledge dead-hang time for an elite climber is over 60 seconds. Therefore, tests attempting to mimic the typical contraction/relaxation ratios used in sport climbing have been developed. Specifically, 40% of max force in a 10:3 ratio [5, 17, 18, 32], 60% of max force in an 8:3 ratio [19, 23] and 80% of max force in a 5:5 ratio [24] have been used in previous studies. These intermittent forearm muscle endurance tests have demonstrated greater endurance among climbers compared to non-climbers, but no difference between climbing disciplines [5, 17–19, 22–24].

In addition to forearm muscle endurance and maximal strength, the ability to exert force quickly has been suggested as a crucial component for climbing performance [9, 25, 26]. Especially for performing long moves and quickly having to grip a hold [26]. One frequently used parameter to examine explosive strength characteristics is rate of force development (RFD) [27]. Still, only one study has examined RFD as a measure for detecting differences between climbers of different disciplines [3]. The authors demonstrated that boulder climbers were able to develop finger flexor force at a higher rate than lead climbers and that finger flexor peak RFD was a crucial factor for discriminating between the two disciplines [3]. Contrastingly, the mean RFD value has been suggested as a more accurate measurement than peak values for assessing climbing ability due it being less sensitive to variability [26]. Still, little is known about the rapid force production characteristics of the prime movers in a climbing-specific test among lead and boulder climbers.

Previous studies comparing lead and boulder climbers have been limited by few test parameters focusing mainly on the finger flexors, and only one study has examined the effect of hold size when performing pull-ups [20]. Thus, a negligible knowledge exists about the upper-body strength characteristics of lead and boulder climbers and the impact of hold type on the utilization of the force generated by the prime movers during climbing-specific tasks. The aims of the present study were, therefore, 1) to examine maximal and explosive strength in dynamic and isometric pull-up, 2) to identify the utilization rate of force using a ledge hold compared to a jug hold, and 3) to compare forearm muscle endurance between lead and boulder climbers. On the basis of previous research [3, 5] and the specificity of the two disciplines, boulder climbers were hypothesized to demonstrate greater maximal force, RFD and pull-up velocity, while lead climbers were expected to demonstrate greater climbing-specific forearm muscle endurance. Both groups were also expected to demonstrate reduced force output and RFD in the isometric pull-up using the ledge hold compared to the jug hold.
Materials and methods
Study design
To determine the possible differences in forearm muscle endurance and climbing-specific strength characteristics (maximal and explosive) between lead and boulder climbers, a cross-sectional study was conducted with group as the independent variable. The climbers were tested for maximal isometric pull-up strength (average rate of force development (RFDavg), Peak force (Fpeak) and average force (Favg)), explosive dynamic pull-up strength (average velocity (Vavg)), and finger flexor endurance (intermittent test to fatigue) during one laboratory session. All subjects performed the tests in a standardized order: 1) isometric pull-up on a ledge, 2) isometric pull-up on a jug, 3) dynamic pull-up on a ledge, and 4) intermittent test. Three to five minutes of rest was allowed between each trial and test condition. All tests were performed bilaterally. The subjects were instructed to refrain from climbing and climbing-related training for 48 hours before testing.

Subjects
Thirty-one recreational climbers (28 males and 3 females) volunteered for the study and were allocated to the boulder climbers (n = 16) or lead climbers (n = 15) groups, based on their self-reported main practiced discipline. For details of anthropometric data, self-reported climbing ability and number of weekly climbing sessions, see Table 1. Climbing ability, experience and number of weekly sessions were not different between the groups (p = 0.056–0.401). The subjects reported their climbing ability using the French grade system (1-9a/b/c) and the grades were converted into the numeric reporting scale (1–32) proposed by the International Rock Climbing Research Association (IRCRA) [28]. The minimal self-reported accomplished climbing grade (red-point) to be included in the study had to be no less than 7a (IRCRA 17) for men and 6b (IRCRA 13) for women. All subjects were informed about the study orally and in writing and signed an informed consent form prior to collection of data. The consent form and the testing procedures were confirmed with the Regional Committees for Medical Health and Research Ethics in Norway (2018/1345 REK Sør-est D), were in accordance with the ethical guidelines of Western Norway University of Applied Sciences and conformed to the standards of treatment of human participants in research, outlined in the 5th Declaration of Helsinki.

Procedures

Body composition and anthropometric data. Body composition (relative fat mass and fat-free mass) and body mass were measured using a bioelectrical impedance scale (Tanita MC 10) and self-reported climbing ability (IRCRA scale). Data are given as mean (± SD).

Table 1. Anthropometric data, number of weekly climbing sessions, climbing experience and self-reported climbing ability (IRCRA scale). Data are given as mean (± SD).

<table>
<thead>
<tr>
<th></th>
<th>Boulder Climbers</th>
<th>Lead Climbers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 male, 1 female</td>
<td>13 male, 2 female</td>
</tr>
<tr>
<td>Age (years)</td>
<td>25.31 (3.44)</td>
<td>28.60 (6.72)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.52 (7.90)</td>
<td>175.77 (7.00)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>72.29 (7.80)</td>
<td>68.52 (8.53)</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>11.68 (4.20)</td>
<td>12.17 (4.13)</td>
</tr>
<tr>
<td>Fat-free mass (%)</td>
<td>83.93 (3.99)</td>
<td>83.45 (3.93)</td>
</tr>
<tr>
<td>Climbing experience (years)</td>
<td>5.91 (4.58)</td>
<td>9.00 (4.58)</td>
</tr>
<tr>
<td>Weekly climbing sessions</td>
<td>3.88 (1.61)</td>
<td>3.43 (1.24)</td>
</tr>
<tr>
<td>Red-point (IRCRA)</td>
<td>17.85 (3.4)</td>
<td>20.47 (3.54)</td>
</tr>
</tbody>
</table>

https://doi.org/10.1371/journal.pone.0222529.t001
Isometric pull-up. Before measuring strength performance, the subjects performed a 15-minute warm-up consisting of bouldering and traversing on self-selected routes. The subjects were instructed to maintain a light-to-moderate intensity in the warm-up to avoid fatigue. The $F_{avg}$, $F_{peak}$ and $RFD_{avg}$ measurements were collected from the same attempt, performing a five seconds maximal, isometric pull-up with elbows flexed at 90 degrees and an open crimp grip (Fig 1). To measure force output, subjects wore a climbing harness anchored to the floor via a static rope and a force sensor (Ergotest Innovation A/S, Porsgrunn, Norway) to remain in an isometric position. The length of the rope between the climbing harness and force sensor was adjusted to maintain a correct elbow angle (measured with goniometer). The subjects pulled themselves up to a 90 degrees angle (i.e. where the static rope became taut) in the elbow joint and maintained the position for approximately one second before being verbally encouraged to perform a maximal isometric pull-up and maintain maximal force for five seconds. This test produces a clear $F_{peak}$ early in the contraction (Fig 2). Elastic components within the muscles and a small shuttle caused by alterations of the shoulder and elbow joints when applying maximal force likely contribute to the prominent $F_{peak}$.

The testing procedures were conducted using two different conditions; 1) On a wooden jug grip (Fig 3A) (Beastmaker 1000 series, Beastmaker Limited, Leicester, United Kingdom), and 2) on a 43 cm wide and 23 mm deep wooden ledge with rounded edges (Fig 3B) (Metolius Climbing, Bend, Oregon, USA). The ledge was regularly brushed to provide equal friction conditions for all subjects. Three attempts were given in each condition, with one minute rest between each attempt and three minutes rest between conditions [29]. The results from the best attempt for each condition was used in the analyses. The $F_{avg}$, $F_{peak}$ and $RFD_{avg}$ were recorded by the force sensor at 200Hz and analyzed with the MuscleLab software (v. 10.4.37.4073, Ergotest Innovation A/S, Porsgrunn, Norway). $RFD_{avg}$ was calculated as the mean increase in force from the onset of force generation after pulling themselves up to the 90 degrees elbow angle and to the $F_{peak}$ (Fig 2). The onset of force was determined visually, which has been proposed as more sensitive and accurate than automated detection [30]. The $F_{peak}$ was registered from the highest force output on the curve and $F_{avg}$ was calculated as the mean force over a two seconds period, excluding the peak (Fig 2). The recorded force values including the gravitational force of the body (body mass $\times$ 9.807) were used in the analyses. The relative utilization of force on the ledge relative to the jug was calculated as follows; (ledge results / jug results) $\times$ 100.

Dynamic pull-up. The $V_{avg}$ was measured during a dynamic pull-up performed on the same ledge used in the isometric pull-up test (Metolius Climbing, Bend, Oregon, USA). The subjects performed one concentric pull-up as fast as possible from a dead-hang position (elbows fully extended) until the eyes were above the hands. Kipping with the legs was not allowed. A linear encoder (ET-Enc-02, Ergotest Innovation A/S, Porsgrunn, Norway) with a resolution of 0.075 mm and counting the pulses with a 10-millisecond interval was attached to a climbing harness and recorded the displacement of the body and the movement velocity performing the pull-up. The results were instantaneously analyzed using the MuscleLab software (v. 8.13, Ergotest Innovation A/S, Porsgrunn, Norway). One-minute rest was given between each attempt and the results from the attempt with the highest values were used in the analyses.

Intermittent forearm muscle endurance test. The intermittent forearm muscle endurance test was conducted in a seated position with the shoulders fully adducted, a 90 degrees flexion in the elbow and an open crimp grip (Fig 4). A padded barbell was placed in front of
Fig 1. Position with 90 degrees elbow flexion for the isometric pull-up.

https://doi.org/10.1371/journal.pone.0222529.g001
the subjects’ chest and behind the distal part of the upper arms to prevent any movement or involvement of the shoulders or back muscles. A 46 cm wide and 23 mm deep custom-built wooden ledge was attached to a force cell (Ergotest Innovation A/S, Porsgrunn, Norway) that measured the applied force of the finger flexors to the ledge. Before starting the intermittent test, the subjects’ maximal isometric finger flexion force was determined in the same position. The test consisted of seven seconds contraction at 60% of maximal isometric force intermittently with three seconds rest (7:3 ratio) to fatigue. This contraction/relaxation ratio is similar to that observed in climbing competitions [2, 4]. Between each bout of work, the subjects could rest, but not let go of the ledge or change their grip technique. A phone application (Beastmaker Training App v. 2.0.1, Beastmaker Limited, Leicester, United Kingdom) and a computer screen mirroring the MuscleLab software (v. 10.4.37.4073, Ergotest Innovation A/S, Porsgrunn, Norway) were placed in the subjects’ field of vision to give visual information about work/rest periods and real-time feedback of the generated force. The researchers also gave verbal start-and-stop instructions. Watching the computer screen, the subjects were able to adjust their applied force to the hold continuously. If the force dropped below their individual threshold value for more than a second, the test was stopped [23]. The total effective work time was used in future analyses.

![Fig 2. Schematic force curve produced in the isometric pull-up. Markers indicate rate of force development (RFDavg), peak force (Fpeak) and average force (Favg).](https://doi.org/10.1371/journal.pone.0222529.g002)
Statistical analyses
Except from $V_{avg}$ in the dynamic pull-up (Shapiro-Wilk test; $p=0.001$), no other variables revealed deviations from normality ($p=0.060–0.946$). SPSS statistical software (Version 25.0, SPSS Inc., Chicago, IL, USA) was used for the analyses. Differences between the groups were identified using an independent student’s t-test for the parametric variables and using a Mann-Whitney U Test for the non-parametric variable (i.e. $V_{avg}$). For statistical significance, the alpha level was set at 0.05. The data is presented as mean (± SD) and Cohen’s d effect size ($ES$). An $ES$ of < 0.2 was considered trivial, 0.2 small, 0.5 medium, and > 0.8 large [31].

Results
In the isometric tests, boulder climbers demonstrated 28.7–52.9% higher $F_{peak}$, $F_{avg}$ and $RFD_{avg}$ than lead climbers using the 23 mm ledge and the jug ($p=0.013–0.015$; see Table 2). Boulder climbers also demonstrated significantly higher $F_{peak}$, $F_{avg}$ and $RFD_{avg}$ than lead climbers (23.1–48.4%, $ES=0.78–0.97$, $p=0.016–0.044$) when the data was analyzed relative to the body mass (Fig 5A, Fig 5B, Fig 5C and S1 File).

Both groups demonstrated lower $F_{peak}$, $F_{avg}$ and $RFD_{avg}$ in the ledge condition compared to the jug condition ($ES=1.79–2.02$, $p<0.005$). However, the utilization of force in the ledge condition relative to the jug condition (57–69%) was not different between the groups ($p=0.290–0.996$).

In the dynamic pull-up test, boulder climbers achieved a 26.2% higher $V_{avg}$ than lead climbers ($p=0.014$; see Table 2, S1 File).

In the intermittent forearm muscle endurance test, the time to fatigue demonstrated no difference between lead and boulder climbers ($p=0.088$; see Table 2, S1 File).
Discussion

In accordance with the hypothesis, the boulder climbers exhibited greater maximal (F_{peak} and F_{avg}) and explosive strength (V_{avg} and RFD_{avg}) than the lead climbers, whereas the analyses showed no difference in forearm muscle endurance between the groups.

Greater maximal isometric strength (F_{peak} and F_{avg}) for the boulder climbers compared to lead climbers was not surprising. Importantly, lead climbing is typically performed more static.
with slow and controlled movements over a longer period of time than bouldering [2]. Contrarily, bouldering contains steep, but short routes and a higher frequency of moves performed with maximal effort [2, 3, 8, 32]. Thus, especially regarding intensity and repetitions per set (moves per attempt), the physiological demands of bouldering are more similar to the recommendations for maximal strength training [33] and is likely a more appropriate training stimulus than lead climbing for improving force output [7, 34]. This was demonstrated by a

Table 2. Absolute values from the dynamic and isometric pull-up and the forearm endurance test.

<table>
<thead>
<tr>
<th></th>
<th>Boulder Climbers</th>
<th>Lead Climbers</th>
<th>P</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Isometric ledge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fpeak (N)</td>
<td>1249</td>
<td>175</td>
<td>1079*</td>
<td>187</td>
</tr>
<tr>
<td>Favg (N)</td>
<td>1106</td>
<td>175</td>
<td>946*</td>
<td>172</td>
</tr>
<tr>
<td>RFDavg (Ns⁻¹)</td>
<td>1537</td>
<td>548</td>
<td>1057*</td>
<td>485</td>
</tr>
<tr>
<td>Isometric jug</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fpeak (N)</td>
<td>1501†</td>
<td>185</td>
<td>1289†</td>
<td>308</td>
</tr>
<tr>
<td>Favg (N)</td>
<td>1334†</td>
<td>181</td>
<td>1131†</td>
<td>228</td>
</tr>
<tr>
<td>RFDavg (Ns⁻¹)</td>
<td>2869†</td>
<td>939</td>
<td>1876†</td>
<td>1050</td>
</tr>
<tr>
<td>Utilization rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fpeak (%)</td>
<td>69</td>
<td>14</td>
<td>69</td>
<td>12</td>
</tr>
<tr>
<td>Favg (%)</td>
<td>64</td>
<td>16</td>
<td>58</td>
<td>16</td>
</tr>
<tr>
<td>RFDavg (%)</td>
<td>57</td>
<td>20</td>
<td>64</td>
<td>27</td>
</tr>
<tr>
<td>Dynamic pull-up</td>
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<td></td>
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<tr>
<td>Vavg (m.s⁻¹)</td>
<td>0.96</td>
<td>0.26</td>
<td>0.76*</td>
<td>0.15</td>
</tr>
<tr>
<td>Intermittent test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (s)</td>
<td>83</td>
<td>18</td>
<td>107</td>
<td>40</td>
</tr>
</tbody>
</table>

The results are presented as mean (± SD) with Cohen’s d effect size (ES) and P value for the difference between groups. Fpeak = peak force, Favg = average force output, RFDavg = rate of force development from the onset of force to the peak force output, utilization rate = ledge performance relative to jug performance, Vavg = average velocity. Time = total work time to fatigue.

* = Significantly lower than boulder climbers (P < 0.05).
† = Significantly different from ledge condition (P < 0.01).

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Fig 5. Results relative to body mass from average force (Favg) (a), peak force (Fpeak) (b) and rate of force development (RFDavg) (c) between the groups for the isometric ledge and jug conditions. White bars represent boulder climbers and black bars represent lead climbers. Error bars represent standard deviations. (* p < 0.05; ** p < 0.01).

https://doi.org/10.1371/journal.pone.0222529.g005
29–45% greater absolute and relative strength (force / body mass) for the boulder climbers compared to the lead climbers. Interestingly, both groups demonstrated a similar utilization rate in the ledge condition relative to the jug condition (57–69% of jug results), suggesting that despite boulder climbers being stronger in the prime movers, both groups are equally limited by finger strength when testing on a smaller hold. These results support previous findings that the hold size and shape is a crucial factor for performance in climbing-specific tests [20].

Frequent explosive moves on steep walls require boulder climbers to apply force rapidly to perform dynamic moves and ensure the subsequent stabilization of the body [2, 35]. Additionally, the available time to generate force during bouldering (contact time) will often be shorter than the time it takes to reach maximal force [25]. Hence, being able to generate as much force as possible in a short time is crucial for performance in bouldering. Therefore, RFD has been proposed as an important discriminatory factor between lead and boulder climbers [2, 3, 9]. The current observations support this claim, with RFDavg demonstrating the largest difference between the two groups (38–53%). Likewise, the dynamic measure of explosive strength (Vavg) was 26% higher for the boulder climbers compared to the lead climbers. The marked differences for explosive strength parameters between the groups likely reflect the specific requirements of the two disciplines [34]. As bouldering offers a higher frequency of explosive and gymnastic moves than lead climbing [2, 36], this sub-discipline of climbing is likely better suited for improving RFD through mechanisms such as increased firing rate of motor units, changes in muscle fiber composition or muscle-tendon stiffness [27, 37]. Repeated exposure to these stimuli have likely resulted in chronic adaptations that separate boulder climbers from lead climbers. However, and as pointed out by a previous study [3], one cannot rule out the possibility that climbers have chosen their discipline based on their predisposed abilities. The present study supports several previous findings [3, 5–7], suggesting boulder climbers are stronger and more explosive compared to lead climbers. However, further research is needed to determine whether this is a result of genetic predisposition or distinct adaptations to performing lead or boulder climbing.

While a boulder route ascend typically lasts around 30 seconds, leading a route may take anywhere between 2–7 minutes [2, 9]. Therefore, we expected forearm muscle endurance to distinguish between climbing disciplines. However, the present findings showed no difference in forearm muscle endurance between lead and boulder climbers. In the intermittent test, 60% of the maximal finger flexor force had to be generated in the seven seconds work period. This resulted in a mean work time of 107 seconds vs 83 seconds for lead and boulder climbers, respectively. It is possible that the short work time was not sufficient to detect differences in forearm muscle endurance between the climbing disciplines. For example, Fryer et al. [22] used 40% of maximal force in a 10:3 contraction/rest ratio, which resulted in a work time of 264–332 seconds in subjects with a similar climbing performance level as the present study population. An endurance test with longer duration or lower force threshold could, therefore, be more useful for distinguishing between climbers of the two disciplines [19]. Contrastingly, Viguéroux et al. [24] used a 5:5 ratio with 80% of maximal force as the threshold and demonstrated a higher forearm muscle endurance among elite climbers compared to non-climbers (180 vs. 90 seconds work time). Owing to the lower performance level among the current study population, however, a higher force threshold with a 7:3 ratio might have been too heavy for the subjects and reduced in a much shorter work time. Furthermore, by increasing or decreasing the threshold and thereby changing the total work time, the test would likely favor either boulder climbers or lead climbers, respectively. Lastly, albeit the subjects performed on an advanced level, the current study population consisted of recreational climbers. It is possible that more distinct differences could be observed in elite climbers that are more specialized in their respective disciplines.

Some potential limitations of this study should be outlined. Only recreational climbers were recruited and, therefore, the findings cannot necessarily be generalized to other
populations of climbers. Furthermore, the subjects were not asked to report their bouldering performance level. By examining potential differences in lead and boulder climbing ability, it could have been possible to determine the specific importance of different physical attributes for the two disciplines. Lastly, the slope of the force curve displayed an elevated $F_{\text{peak}}$ compared to $F_{\text{avg}}$. The prominent $F_{\text{peak}}$ likely occurred owing to elastic components within the muscle and displacement of the joints when applying maximal force from a hanging position.

Although this force curve may be perceived as unusual, the test set-up closely mimics the mechanics of climbing where forceful moves are performed from a hanging position with pre-activation of the muscles.

In conclusion, the current findings demonstrated greater maximal and explosive strength in the boulder climbers compared to the lead climbers, whereas no differences were noted for forearm muscle endurance. As RFD revealed the most marked difference between the two disciplines, this measure should be considered in future studies assessing muscular characteristics among rock climbers. The results likely reflect the specific adaptations to the physical demands of the two disciplines with regard to ascent duration, number of moves, distance between holds and steepness of the route.

Practical applications
Differences in isometric and dynamic strength characteristics were observed in a study population performing on an advanced level (~19 IRCRA scale). A rather novel finding in this study was that maximal and explosive strength in both dynamic and isometric pull-up are higher among boulder climbers compared to lead climbers. On the basis of the current findings, bouldering might be a more appropriate training stimulus for maximal and explosive strength compared to lead climbing. The specific adaptions and strength characteristics of the two climbing disciplines need to be recognized and emphasized among trainers. As both groups demonstrated a relative force utilization of 57–69% in the ledge condition relative to the jug condition, finger flexor strength training can likely benefit climbers of both disciplines. Resistance training focusing on maximal and explosive strength of both the finger flexors and the prime movers can likely benefit climbers of both disciplines. Lead climbers might benefit more from focusing their training on other properties, such as forearm muscle endurance. Future research should further examine the maximal and explosive strength of the prime movers and examine the relative utilization of the force generated from the prime movers on different holds among climbers of different disciplines on an elite level.

Supporting information
S1 File.
(XLSX)

Acknowledgments
We would like to thank all the climbers for giving their time and effort to participate in the study, and especially the bachelor students Are Wergeland and Mari Meslo for their contribution in the lab.

Author Contributions
Conceptualization: Nicolay Stien, Atle Hole Saeterbakken, Vidar Andersen.
References


Paper IV
The Effects of Prioritizing Lead or Boulder Climbing Among Intermediate Climbers

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Department of Sport, Food and Natural Sciences, Institute of Education, Arts and Sports, Western Norway University of Applied Sciences, Sogndal, Norway

This study compared the effects of prioritizing lead climbing or boulder climbing on climbing-specific strength and endurance, as well as climbing performance. Fourteen active climbers were randomized to a boulder climbing training group (BCT: age = 27.2 ± 4.4 years, body mass = 65.8 ± 5.5 kg, height = 173.3 ± 3.8 cm) or a lead-climbing training group (LCT: age = 27.7 ± 6.1 years, body mass = 70.2 ± 4.4 kg, height = 177.7 ± 4.4 cm). The groups participated in a 5-week training period consisting of 15 sessions, performing either two weekly bouldering sessions and one maintenance-session of lead-climbing (BCT) or two weekly lead-climbing sessions and one maintenance-session of bouldering (LCT). Pre- and post-training, maximal force and rate of force development (RFD) were measured during isometric pull-ups performed on a jug hold and a shallow rung, and during an isolated finger-strength test. Lead-climbing and bouldering performance were also measured, along with an intermittent forearm endurance test. The pre-to-post changes were not significantly different between the groups for any of the parameters (P = 0.062–0.710). However, both the BCT (ES = 0.30, P = 0.049) and LCT (ES = 0.41, P = 0.046) groups improved strength in the isometric pull-up performed using the jug, whereas neither group improved force in the rung condition (P = 0.054 and P = 0.084) or RFD (P = 0.060 and P = 0.070). Furthermore, climbing and bouldering performance remained unchanged in both groups (P = 0.210–0.895). The LCT group improved forearm endurance (ES = 0.55, P = 0.007), while the BCT group improved isolated finger strength (ES = 0.35, P = 0.015). In addition to isometric pull-up strength, bouldering can increase isolated finger strength while lead-climbing may improve forearm endurance. A 5-week period prioritizing one discipline can be safely implemented for advanced to intermediate climbers without risking declined performance in the non-prioritized discipline.

Keywords: strength, isometric, sport, training, physical performance

INTRODUCTION

In the last decades, rock climbing has become increasingly popular among athletes, recreational practitioners, and researchers. The most practiced disciplines of the sport are lead climbing and bouldering. Whereas boulder problems usually include 5–10 very powerful moves on short routes (<5 m) (White and Olsen, 2010), lead climbing is typically performed on higher walls and requires...
Researchers have examined different training interventions for improving the aforementioned factors among climbers. Fingerboard training is the most examined form of climbing-specific training in the scientific literature and has proven efficient for improving maximal finger strength and forearm endurance (López-Rivera and González-Badillo, 2012, 2019; Medernach et al., 2015; Levernier and Laffaye, 2019; Philippe et al., 2019). Importantly, the improvements have been in climbing-specific tests (e.g., dead-hang endurance or dynamometer finger-grip strength) similar to the implemented fingerboard training (López-Rivera and González-Badillo, 2012, 2019; Levernier and Laffaye, 2019a), which, according to the principle of specificity (Sale and MacDougall, 1981), may not transfer directly to actual climbing performance. Moreover, the fingerboard training in the mentioned studies only involved isometric training and thereby lack specificity to the dynamic movement pattern in climbing. Improved climbing performance has yet to be demonstrated following improvement in climbing-specific tests. To the authors knowledge, only one study (Anderson and Anderson, 2015) has reported a correlation between improvements in finger strength and forearm performance. However, the training was unsupervised and the changes in strength and performance were self-reported, meaning the findings should be interpreted with caution.

Previous assessments of athletes specializing in either bouldering or lead climbing have found distinctive physiological differences between disciplines (Fanchini et al., 2013; Laffaye et al., 2014; Fryer et al., 2017; Stien et al., 2019). Likely due to the different physiological demands of the two disciplines (White and Olsen, 2010), boulderers have performed better than lead climbers in isometric (maximal voluntary isometric contraction [MVIC] and rate of force development [RFD]) and dynamic tests (pull-up velocity and power output), with RFD being the most discriminative factor (Fanchini et al., 2013; Laffaye et al., 2014; Stien et al., 2019). Conversely, no difference in forearm endurance or oxidative capacity has yet been detected between disciplines (Fryer et al., 2017; Stien et al., 2019). Cross-sectional studies are inherently unable to answer whether the differences between lead- and boulder climbers are physiological adaptations specific to the discipline, or a result of climbers choosing to engage the discipline best suited to their inherent physiological abilities. Currently, only one study (Philippe et al., 2019) has examined the effects of prioritizing lead or boulder climbing for 8 weeks among advanced climbers. The authors reported similar lead-climbing performance improvements in both groups. However, the bouldering group performed both disciplines (i.e., lead-climbing and bouldering), whereas the muscular endurance group only performed lead climbing, thereby possibly confounding the results.

Still, implementing a maintenance-session in which the non-prioritized discipline is performed with low intensity in both groups, could preserve specific qualities whilst emphasizing the prioritized discipline, as shown among cyclists and soccer players (Rannestad et al., 2011, 2014). On the basis of the previously observed differences between athletes specializing in the two climbing disciplines and the scarce scientific literature on the effects on lead-climbing or bouldering, the aim of this study was to compare the adaptations to performing mainly lead climbing or boulder climbing for a 5-week period among intermediate and advanced climbers. Based on the previous findings (Fanchini et al., 2013; Fryer et al., 2017; Stien et al., 2019), it was hypothesized that the bouldering group would demonstrate superior improvements in RFD and MVIC during an isometric pull-up and an isolated finger-grip strength test, whereas the two groups would similarly improve forearm endurance measured in an intermittent test. Both groups were further expected to improve climbing performance more in their prioritized discipline than in their non-prioritized discipline, as well as to improve their prioritized discipline more than the other group.

MATERIALS AND METHODS

Experimental Approach to the Problem

A randomized trial was designed to examine the effects of prioritizing either lead climbing or bouldering for 5 weeks. Before and after the intervention, subjects underwent the following tests: (1) maximal average force over 2 s ($F_{avg}$) was measured while performing an isometric pull-up on a 23 mm rung, (2) $F_{avg}$ and RFD were collected during an isometric pull-up using a jug hold, (3) isolated finger-grip strength was collected using a custom built apparatus, (4) forearm muscle endurance was measured using an intermittent finger flexion test to failure, (5) bouldering performance was assessed on three boulder problems, and (6) lead-climbing performance was tested on an 18 m indoor climbing wall. The order of the tests was standardized to avoid variations in fatigue.

Subjects

With a statistical level set to 0.05, a statistical power of 80%, and using the 25–30% change in RFD in a comparable study (Levernier and Laffaye, 2019a), a total of 10 subjects (five in each group) was the minimum number of subjects required to detect a significant difference. Fourteen climbers (seven in each group) were recruited and completed the training and testing. All included subjects conducted both bouldering and lead climbing regularly and were not specialized in either discipline. Following pre-testing, subjects were randomly allocated to the lead climbing training group (LCT) or the boulder climbing training group (BCT) by drawing lots from a non-transparent container. See Table 1 for group characteristics. The inclusion criteria were a minimum self-reported red-point grade of 6b+ (IRCRA: 14) for women and 6c (IRCRA: 15) for men, as well as absence of injuries in the last 6 months. Subjects were informed

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
<th>Gender</th>
<th>Sport Experience</th>
<th>Priorization</th>
<th>Training Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>John</td>
<td>25</td>
<td>Male</td>
<td>5 years</td>
<td>Lead</td>
<td>LCT</td>
</tr>
<tr>
<td>Mary</td>
<td>26</td>
<td>Female</td>
<td>4 years</td>
<td>Boulder</td>
<td>BCT</td>
</tr>
<tr>
<td>Tim</td>
<td>27</td>
<td>Male</td>
<td>6 years</td>
<td>Lead</td>
<td>LCT</td>
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<tr>
<td>Sue</td>
<td>28</td>
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<td>Boulder</td>
<td>BCT</td>
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<tr>
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<td>Tom</td>
<td>35</td>
<td>Male</td>
<td>10 years</td>
<td>Lead</td>
<td>LCT</td>
</tr>
</tbody>
</table>
verbally and in writing about the potential risks and benefits of participation and signed and informed consent form before data collection commenced. The research procedures were in accordance with the ethical guidelines of the university, approved by the Norwegian Center for Research Data (reference number: 252152), and conformed to the standards of treatment of human participants in research as outlined in the 5th Declaration of Helsinki.

Methodology

Upon arrival to the laboratory, subjects were interviewed about their climbing performance and weekly climbing volume before anthropometric variables (height and body mass) and body composition (fat percentage and muscle mass) were measured using a wall mounted measuring tape and a bioelectric impedance weight (Tanita MC780MAS, Tokyo, Japan), respectively. Following the interview and anthropometric measurements, a 15-min light-to-moderate warm-up consisting of bouldering and traversing was performed. The subjects selected the difficulty of the boulders themselves but were instructed to avoid fatigue. The warm-up and testing were separated by 5 min of passive rest.

The subjects performed two conditions (rung and jug holds) of three maximal voluntary isometric pull-ups, each separated by 3 min rest intervals. All tests were conducted using both hands. In the rung condition, a 23 mm deep rung with rounded edges was used (Metolius Climbing, Bend, Oregon, USA) with a half crimp grip and a passive thumb. This test intends to measure the maximal, isometric pull-up strength in a climbing-specific condition where finger strength is the limiting factor (Stien et al., 2019). For the jug condition, a Beastmaker 1000 Series (Beastmaker Limited, Leicester, United Kingdom) was used. This test allows the subjects to fully engage the pulling apparatus without being limited by finger strength. The subjects wore a climbing harness anchored to the ground via an expansion bolt, a static daisy-chain and a force cell with 200 Hz resolution (Ergotest Innovation A/S, Porsgrunn, Norway; Figure 1). The force cell was regularly calibrated using a 20 kg weight. The force was registered using a computer with the commercial software MuscleLab (v.10.4.37.4073, Ergotest Innovation A/S, Porsgrunn, Norway). The daisy chain was adjusted to allow each subject to remain in a 90° elbow angle (measured with goniometer).

On verbal command, the subjects pulled themselves up to a 90° elbow angle (where the daisy-chain became taut) and remained in that position 1–3 s to create a stable baseline (no more than ±0.5 N fluctuations in baseline force) before being instructed to perform an isometric pull-up as fast and as hard as possible and maintain the force output for ∼3 s (Figure 2A). An attempt was annulled if any chipping of the legs was used to create upward momentum (Figure 2B), or if the force output plateaued before reaching peak force (Figure 2C). The Favg was extracted from the 2-s window with the highest average force output. The Favg in the best attempt on the rung [coefficient of variation (CV) = 8.41%] and jug conditions (CV = 4.73%) were used in the analyses. The RFD (CV = 4.49%) was extracted from

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Baseline anthropometric characteristics, climbing experience, number of weekly climbing sessions, and best achieved red-point grade at pre-test for the two groups.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lead climbing group (6 male and 1 female)</strong></td>
<td><strong>Bouldering group (5 male and 2 female)</strong></td>
</tr>
<tr>
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<tr>
<td>Height (cm)</td>
<td>177.7(4.4)</td>
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<td>Body mass (kg)</td>
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<td>Fat mass (%)</td>
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<td>Muscle mass (%)</td>
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<td>Experience (years)</td>
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<td>Weekly sessions (n)</td>
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<tr>
<td>Best red-point (IRCRA)</td>
<td>17.5(1.9)</td>
</tr>
</tbody>
</table>

IRCRA = grade given using the numerical grading system proposed by the International Rock Climbing Research Association.

Values are presented as means (±95% confidence intervals).

FIGURE 1 | Schematic presentation of the maximal pull-up strength test set-up showing (1) the force cell, (2) the climbing harness, and (3) the hold used (the rung condition is presented, but the set-up was identical for the jug condition).
the same force curve in the jug condition and calculated as the rise in force output during the first 200 ms (RFD200) from the onset of the contraction (Levernier and Laffaye, 2019a,b). The onset was determined manually as the point when the force rose with more than 5 N over a 5 ms window after keeping a steady baseline for 1,000 ms (Andersen and Aagaard, 2006; Levernier and Laffaye, 2019a,b). The same researcher performed all the tests and analyses to avoid inter-subject variability.

After performing the pull-ups, maximal isolated half crimp grip force ($F_{\text{crimp}}$) was measured while leaning over a table with the elbows fixed in a 90° angle and the arms fully adducted (Figure 3). The elbows were constrained to avoid inclusion of the back and shoulder muscles and only allow the distal phalanges to reach over the rung. The distance between the constrain and the rung was adjustable and was registered to the closest 0.5 mm to allow for identical conditions at pre- and post-test. Subjects held on to the 23 mm rung on a custom fingerboard (Climbro, Innovative Hangboards, Sofia, Bulgaria) with built-in force sensors mounted to the table, using a half crimp grip with a passive thumb. On verbal command, they pulled as hard as they could with the fingers and maintained the maximal force for 3–5 s. One attempt was given, and the highest registered force output was used in the analyses.

After resting for 3–5 min, intermittent forearm endurance was assessed in the same test set-up as the $F_{\text{crimp}}$, using 60% of $F_{\text{crimp}}$ as the threshold (Balas et al., 2016). The contractions were held for 7 s separated by 3 s rest intervals, and a test was terminated if the force dropped below the 60% threshold plus for more than 1 s (Medernach et al., 2015). The fingerboard registered the force output and real-time visual feedback was provided via a screen to allow subjects to adjust their force output. The total work-time (i.e., not including rest-periods) was analyzed. Due to the high level of fatigue and very low technical demands, one attempt was given in this test.

At least 48 h and no more than 5 days after the laboratory tests, climbing performance was assessed on three boulder problems and one lead route. Before testing, a 15-min warm up consisting of light traversing and light-to-moderate bouldering was performed, followed by 10 min of rest. The three boulder problems (A: 6B+, 7 moves; B: 6C, 12 moves; C: 6C+, 6 moves) were performed on a 5-m high wall in a randomized, counter-balanced order. The subjects were given 4 min to work each problem and each problem was separated by 3 min rest. Verbal encouragement was provided, but subjects were never given tips on how to improve their performance. The number of completed moves from the best attempt was recorded and the accumulated score from the three problems was used in the analyses (maximal score = 25). The boulder problems were removed from the indoor wall between pre- and post-test.

After resting for ~15 min, subjects performed the lead climbing performance test. The route was 24 m long on an 18 m high wall and consisted of 66 moves on a progressively steeper wall. The grade of the route was suggested by two independent, highly experienced climbers to be 6c+ (IRCRA 16). Only one attempt was given, and the highpoint (last hold subjects held in a controlled manner) was recorded as a percentage of the total route length. Unexpectedly, two subjects (LCT group) topped the route at both pre- and post-test and were excluded from the analyses. None of the subjects in the BCT group topped the route.

FIGURE 2 | Illustrations showing an acceptable force curve (A), a curve produced while chipping the legs to create upward momentum (B), and a curve in which the force plateaus before reaching peak force (C).

FIGURE 3 | Schematic presentation of the maximal finger-grip strength and intermittent forearm endurance test set-up showing (1) the constraining of the elbow, (2) the fingerboard, and (3) the screen providing real-time feedback of the force.
Training
As the anecdotal evidence for climbing training currently far outweighs the scientific evidence, the training program was developed in cooperation with highly experienced climbers. The program included a low-to-medium intensity to ensure that the intermediate climbers were able to complete the high-volume training intervention without risk of overuse or acute injuries (Horst, 2016). The subjects were not allowed to perform any climbing or climbing-specific resistance training outside the intervention. They could, however, continue activities such as endurance training and lower-limb resistance training with a low intensity and weekly volume. The researchers had regular contact with the subjects to monitor their training attendance. Both groups trained three times per week for 5 weeks. The BCT group performed two bouldering sessions and one lead climbing session while the LCT group performed two lead climbing sessions and one bouldering session. The session performing the opposite discipline (maintenance-session) was self-regulated by the subjects, but they were instructed to maintain a very low intensity (rating of perceived exertion (RPE) ≤3 on a 1–10 scale). The two primary training sessions consisted of one quality session (RPE >7) emphasizing harder climbs and high effort, and one quantity session (RPE 6) prioritizing a high volume of climbing.

During the 90-min quality session, the BCT group was instructed to perform several quality attempts on a hard boulder and take long rests (3–5 min) between attempts. Subjects were instructed to choose a project that was near their physical limit and maintain an RPE of at least 7. In the 60-min quantitative session, the BCT group completed five sets of four consecutive boulder problems with 5 min rest between sets. The intensity was RPE ≤6.

For the LCT group, the quality session lasted for 1 h with an intensity of RPE 7 or higher. The subjects performed three sets of two consecutive lead climbs with 10 min of rest between sets. A total of six lead climbs were performed in each session. Finally, the 75-min LCT quantity session consisted of completing as many lead climbs as possible within 1 h. Short rests (>3 min) were allowed between attempts and the intensity was RPE 3 to 6 depending on fatigue levels.

Statistical Analysis
A Kolmogorov-Smirnov test revealed no deviations from normality in the dataset (p = 0.117–0.200). SPSS statistical software (V.25, SPSS Inc., Chicago, IL, USA) was used for the statistical analyses. A mixed-model repeated measures analysis of variance (ANOVA) was used to identify potential differences between the groups. When a group × time interaction or main effect was revealed, Bonferroni post-hoc tests were applied to detect the differences. If a main effect for time was revealed, the Bonferroni post-hoc tests were applied to identify the within-groups changes. The results are presented as means ±95% confidence intervals (95% CI) with Cohen’s d effect size (ES). Cohen’s d ES was calculated as the mean pre-post difference divided by the pooled standard deviation of the change scores and were interpreted as follows: <0.2 = trivial; 0.2–0.5 = small; 0.5–0.8 = medium; >0.8 = large. Statistical significance was accepted at P < 0.05 (Cohen, 1988).

RESULTS
None of the anthropometric or performance-related variables were different between the groups at pre-test (P = 0.099–0.990).

The analyses revealed of lead- and boulder climbing performance revealed no group × time interactions (F = 1.768, P = 0.208 and F = 0.079, P = 0.784), nor main effects for time (F = 1.949, P = 0.188 and F = 1.717, P = 0.215) or group (F = 2.127, P = 0.170 and F = 0.050, P = 0.784; Table 2). Intermittent forearm endurance showed no group × time interaction (F = 4.227, P = 0.062) or main effect for group (F = 0.039, P = 0.848), but a main effect for time was found (F = 8.061, P = 0.015). Post-hoc tests showed that intermittent forearm endurance remained unchanged from pre- to post-test in the BCT group (P > 1.000), while the LCT group improved by 25× (P = 0.014, 95% CI = 9.7–40.3, ES = 0.55, Table 2). Finally, the analyses of Fcrimp revealed no group × time interaction (F = 0.145, P = 0.710) or main effect for group (F = 0.398, P = 0.540), but did reveal a main effect for time (F = 8.157, P = 0.014). Further analyses showed that Fcrimp was improved by 48 N following BCT (P = 0.030, 95% CI = 13–82), but not LCT (P = 0.416; Table 2).

The analyses of Favg in the rung and jug conditions showed no group × time interactions (F = 2.662, P = 0.129 and F = 0.347, P = 0.567), nor main effects for group (F = 0.072, P = 0.793 and F < 0.001, P = 0.992). However, a main effect for time was found for both conditions (F = 13.605, P = 0.003 and F = 17.539, P = 0.001). Further analyses showed that Favg in the jug condition improved by 49.7 N for the LCT group (P = 0.046, 95% CI = 9.7 N–89.7 N), and by 66.0 N for the BCT group (P = 0.049, 95%
FIGURE 4 | Individual pre- to post-test changes in the rate of force development (RFD) test on the jug holds for (A) the lead climbing training group (LCT) and (B) the boulder climbing training group (BCT).

CI = 11.5 N–120.5 N). Contrarily, \( F_{\text{avg}} \) in the rung condition did not improve for either the LCT \( (P = 0.084, 24.9 \text{ N}, 95\% \text{ CI} = 1.2–48.5 \text{ N}) \) or the BCT group \( (P = 0.054, 64.3 \text{ N}, 95\% \text{ CI} = 10.1–118.5 \text{ N}; \text{Table 2}) \). Regarding RFD, no group × time interaction \( (F = 0.377, P = 0.551) \), or main effects for group \( (F = 0.056, P = 0.817) \) was detected, but there was a main effect for time \( (F = 15.196, P = 0.002) \). Further analyses showed that neither group significantly improved RFD (Figure 4).

DISCUSSION

This study compared the effects of prioritizing lead climbing or boulder climbing for 5 weeks. Despite no changes in climbing performance, both training groups improved climbing-specific strength as assessed during isometric pull-ups using the jug holds. In accordance with the prioritized discipline (Fanchini et al., 2013; Stien et al., 2019), only the LCT group increased intermittent forearm endurance, whereas only the BCT group improved isolated finger-grip strength. In disagreement with the hypotheses and acute studies that have identified differences between training modalities in improving climbing performance (Hermans et al., 2017; Philippe et al., 2019) or performance in climbing-specific tests (López-Rivera and González-Badillo, 2012, 2019), the changes in the tested variables were not statistically different between the groups. The findings could be attributed to the relatively short training period, low intensity, or the small changes to the subjects’ regular training volume. However, the aim of the study was to examine the effects of prioritizing one discipline while maintaining a high ecological validity. Making considerable changes in other factors (e.g., climbing volume) would have confounded the findings. The study population had considerable climbing experience (~5–8 years), but at an amateur level. Due to the intermediate-to-advanced performance level, one could have expected more rapid and distinct changes. Unfortunately, the current results add to the body of literature not being able to demonstrate differences between training modalities in improving climbing performance (Hermans et al., 2017; Philippe et al., 2019) or performance in climbing-specific tests (López-Rivera and González-Badillo, 2012, 2019). Taken together, these findings highlight the need for interventions with higher intensities and longer durations in prospective climbing research. Future studies should also consider monitoring the climbing volume more directly (i.e., vertical meters climbed and number of moves).

Both the LCT \( (ES = 0.41) \) and BCT groups \( (ES = 0.31) \) meaningfully improved \( F_{\text{avg}} \) in the jug condition. However, and in contrast with the hypotheses, the improvement was not significantly different between the groups. Moreover, \( \text{RFD}_{200} \) and \( F_{\text{avg}} \) in both the rung condition did not improve in any of the groups. Previous investigations have reported RFD and \( F_{\text{avg}} \) being discriminatory factors between lead- and boulder-climbers (Fanchini et al., 2013; Fryer et al., 2017; Stien et al., 2019; Levernier et al., 2020), the changes in the tested variables were not statistically different between the two groups. The findings could be attributed to the relatively short training period, low intensity, or the small changes to the subjects' regular training volume. However, the aim of the study was to examine the effects of prioritizing one discipline while maintaining a high ecological validity. Making considerable changes in other factors (e.g., climbing volume) would have confounded the findings. The
more accomplished climbers than the current investigation, their discipline-specific attributes may have been more distinct. The current findings are in line with those of Philippe et al. (2019) who reported similar improvements in two groups who participated in either a lead- (muscular endurance) or boulder climbing-specific (muscular hypertrophy) training program. Despite not reaching statistical significance it should be noted that the observed effect sizes for the Fcrimp in the rung and jug conditions might reflect different adaptations to the two training interventions. For example, the LCT group displayed effect sizes of 0.23 (16.2%) and 0.41 (31.8%) in the rung and jug conditions, respectively, while the BCT group achieved effect sizes of 0.41 (28.7%) and 0.31 (18.9%). Whereas, increased isometric pull-up strength might have been mostly mediated by increased pulling-apparatus strength for the LCT group, the finger strength could have been a more important factor for the BCT group. Importantly, one should consider the low sample size when interpreting the results. Researchers may consider these findings when designing prospective studies aimed at identifying possible differences between the two disciplines and strive to include a higher number of participants.

Although the change in forearm endurance was not significantly different between groups, only the LCT group achieved an improvement in this parameter. Moreover, only the BCT group demonstrated improved Fcrimp. Whereas the short, steep and explosive nature of boulder problems might represent a highly strength-specific training stimulus (White and Olsen, 2010), Garber et al. (2011), Fanchini et al. (2013), the longer duration maintaining a lower average intensity during lead climbing is likely a more specific training stimulus for the intermittent forearm endurance test (Sale and MacDougall, 1981). Importantly, the threshold for the intermittent forearm endurance test was calculated at pre- and post-test to maintain an identical relative intensity (i.e., 60% of pre-Fcrimp at pre-test and 60% of post-Fcrimp at post-test). Since an improvement in the Fcrimp was observed in the BCT group, one may speculate that an increase in the threshold force at post-test would reduce potential improvements in forearm endurance. However, since the threshold of the forearm endurance test was to assess the capability of maintaining force at a given relative intensity (60% of Fcrimp), using the same absolute force threshold at post-test would render the pre- and post-tests incomparable. Finally, it is possible that using a threshold lower than 60% of maximal force, thereby allowing for a longer test duration, could have favored the LCT group. This could have resulted in a significant difference between the training groups due to the higher specificity of lead climbing with regards to climb duration (i.e., 120–420 s for lead climbing competitions and only around 30 s for bouldering) (White and Olsen, 2010).

This study adds to the scarce body of interventional studies unable to produce distinct differences between lead- or boulder climbing, or resistance training specific to the two disciplines. Hence, it could be speculated that longer periods prioritizing one discipline is needed, whereas an intervention of limited duration may not be sufficient to cause distinctive differences between groups. Moreover, the fact that some athletes perform on a world class level in both disciplines could indicate that the two disciplines do not represent as different demands as previously assumed (Philippe et al., 2019). Indeed, hard lead climbing undoubtedly requires high levels of finger- and pulling-apparatus strength (as demonstrated by the fact that more accomplished lead climbers are stronger than lower-level lead climbers) (Fryer et al., 2015; Levernier and Lafaye, 2019b), and it is reasonable to assume that bouldering performance is influenced by forearm endurance, considering an attempt in competition style bouldering often lasts around 30 s (White and Olsen, 2010).

The present is one of very few studies (Hermans et al., 2017; Philippe et al., 2019) examining actual climbing performance following climbing-specific training, whereas most of the literature have only assessed strength in climbing-related exercises (López-Rivera and González-Badillo, 2012, 2019; Medernach et al., 2015; Saeterbakken et al., 2018; Levernier and Lafaye, 2019a). Both groups maintained climbing ability in both disciplines and improved most of the tested variables despite having the same weekly climbing training frequency as before the intervention. Hence, the observed improvements in climbing-specific strength could result from the changes in the structure of their climbing sessions. Importantly, despite emphasizing one discipline and only performing one weekly low intensity (RPE = 3) maintenance-session of the other, no reduction in performance was observed in either discipline. The results suggest that specific climbing training can increase climbing-specific strength, but increased strength may not be directly associated with improved climbing performance. These findings have implications for researchers designing studies examining the effects of climbing-specific strength training, suggesting that climbing performance should be examined alongside climbing-specific strength and endurance. It should be noted that the lead climbing test used in the present study may not have been suited for identifying changes among the included climbers as several subjects reported falling due to other factors (e.g., difficulties clipping quickdraws or fear of climbing past the last clipped quickdraw in difficult terrain). Following the low-intensity (i.e., easy lead climbing) training in this study, it is likely that the climbers did not achieve improvements specific to difficult lead-climbing. To more directly examine physiological adaptations such as endurance, it may be preferable to perform lead climbing testing using an auto-belay or tread-wall to exclude psychological factors (Gjadolik et al., 2020). However, climbing past the last clipped quickdraw in difficult terrain is an important ability in lead-climbing, suggesting that future research should include high-intensity climbing training to improve performance in demanding climbing-situations.

Although the present study provides novel insight into the effects of climbing training on climbing performance and performance in climbing-specific tests, the study has some potential limitations that should be considered when interpreting the results. First, intermediate and advanced climbers were included in the study and the findings may therefore not be generalizable to elite climbers. Another potential limitation was the heterogeneity of the included participants at baseline (see Figure 4) which challenge the ability to detect significant differences with the relatively low study-sample. Moreover, the
relatively short intervention period, low training intensity and small study sample could challenge the statistical power of the study. Future studies may be able to detect differences between groups using a larger population or a longer intervention period. The fact that no familiarization was performed prior to the experimental session could be viewed as a limitation. However, the three attempts were consistent (CV = 4.49–8.41%), and the tests required very low technical performance. Moreover, the subjects performed both disciplines, which could reduce the potential between-groups differences. Still, as the included subjects conducted both lead- and boulder-climbing before the study, excluding one discipline in the intervention period could produce differences between the groups through a decreased performance in that discipline. Finally, although the intensity and duration of the sessions were regulated, the climbing style (e.g., hold types and steepness) were self-selected. Hence, inter-individual differences in climbing style may have influenced the results.

**PRACTICAL APPLICATIONS**

This study was one of the first to examine the effects of climbing training on climbing performance, whereas many previous investigations have focused only on climbing-specific strength or endurance training on performance in climbing-specific tests. Interestingly, meaningful improvements were observed for many of the measured strength and endurance variables while climbing performance remained unchanged. Researchers should be aware of these findings when designing future interventional studies and consider including climbing performance in the testing. Further, block periodization could be a viable training method in complex sports such as rock climbing which require development of different properties (e.g., muscular endurance and explosiveness) (Issurin, 2016). The current findings suggest that block periodization in rock climbing (i.e., prioritizing most of the training within a 5-week period on one discipline) can be safely implemented among intermediate and advanced climbers without risking a declined in performance in the other discipline. One very low volume and intensity (RPE ≤3) session performing the other discipline may be sufficient for maintaining performance. Of note, the BCT group achieved larger ES for the change in both lead climbing and bouldering performance, suggesting that a longer bouldering training period could result in superior improvements in both disciplines in this group of climbers. Future research should examine the effects of periodized vs. non-periodized climbing or climbing-specific training.

**REFERENCES**


**CONCLUSIONS**

In conclusion, no significant differences were produced between the groups in either climbing performance nor climbing specific strength- and endurance tests after the intervention period. However, 5 weeks of performing either mainly lead or boulder climbing improved pull-up strength among intermediate-to-advanced climbers with considerable climbing experience. Although not significantly different between the groups, a 5-week structured lead climbing training regime significantly improved intermittent forearm endurance, whereas only boulder climbing training improved isolated finger strength. Future research is needed to identify whether similar effects occur among elite climbers.

**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

**ETHICS STATEMENT**

The studies involving human participants were reviewed and approved by Norwegian Centre for Research Data. The patients/participants provided their written informed consent to participate in this study.

**AUTHOR CONTRIBUTIONS**

NS, TF, EH, and VV were responsible for the data collection. NS, VA, and AS performed the data curation and statistical analyses. NS drafted the article, while all remaining authors critically revised the draft. All authors contributed to the design and conceptualization of the study.

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**SUPPLEMENTARY MATERIAL**

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2021.661167/full#supplementary-material


Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Paper V
Effects of Two vs. Four Weekly Campus Board Training Sessions on Bouldering Performance and Climbing-Specific Tests in Advanced and Elite Climbers

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Abstract
This study examined the effects of two or four weekly campus board training sessions among highly accomplished lead climbers. Sixteen advanced-to-elite climbers were randomly allocated to two (TG2), or four weekly campus board training sessions (TG4), or a control group (CG). All groups continued their normal climbing routines. Pre- and post-intervention measures included bouldering performance, maximal isometric pull-up strength using a shallow rung and a large hold (jug), and maximal reach and moves to failure. Rate of force development (RFD; absolute and 100ms) was calculated in the rung condition. TG4 improved maximal force in the jug condition (effect size (ES) = 0.40, p = 0.043), and absolute RFD more than CG (ES = 2.92, p = 0.025), whereas TG2 improved bouldering performance (ES = 2.59, p = 0.016) and maximal moves to failure on the campus board more than CG (ES = 1.65, p = 0.008). No differences between the training groups were found (p = 0.107–1.000). When merging the training groups, the training improved strength in the rung condition (ES = 0.87, p = 0.002), bouldering performance (ES = 2.37, p = 0.006), maximal reach (ES = 1.66, p = 0.006) and moves to failure (ES = 1.43, p = 0.040) more than CG. In conclusion, a five-week campus board training-block is sufficient for improving climbing-specific attributes among advanced-to-elite climbers. Sessions should be divided over four days to improve RFD or divided over two days to improve bouldering performance, compared to regular climbing training.

Key words: Isometric, pull-up, rate of force development, strength.

Introduction
Rock climbing has gained increased interest as both a recreational and competitive activity over the past decade, with an increasing amount of scientific literature focusing on performance-related factors of the sport. Although technical and mental factors certainly contribute to climbing outcomes (Baláz et al., 2012; Mermier, 2000; Philippe et al., 2012; Quaine et al., 2003; Saul et al., 2019; Vigouroux and Quaine, 2006). Specifically, high levels of maximal and explosive strength of the fingers and forearms, elbow flexors, and shoulder- and back muscles (pulling apparatus) have been identified as significant attributes of highly accomplished climbers (Deyhle et al., 2015; Grant et al., 2001; Lafaye et al., 2014; 2016; Levernier and Lafaye, 2019b; Vigouroux et al., 2018).

A number of intervention studies have examined the effects of different resistance-training interventions on maximal and explosive upper-body strength among climbers (Hermans et al., 2017; Levernier and Lafaye, 2019a; López-Rivera and González-Badillo, 2012; 2019; Medernach et al., 2015; Philippe et al., 2019; Saeterbakken et al., 2018). Most of the existing literature has focused on specific, isolated finger flexor strength and endurance training (Levernier and Lafaye, 2019a; López-Rivera and González-Badillo, 2012; 2019; Medernach et al., 2015). Although improvement in climbing-specific tests have been reported after training interventions, most studies have neglected climbing performance as an outcome (Levernier and Lafaye, 2019a; López-Rivera and González-Badillo, 2012; 2019; Medernach et al., 2015). Further, finger strength has been measured using a handheld dynamometer (Medernach et al., 2015; Mermier, 2000) or during isometric hanging from shallow rungs with an external load (López-Rivera and González-Badillo, 2012), which do not mimic actual climbing where the pulling apparatus is used to produce vertical propulsion while the fingers are responsible for maintaining contact with the holds.

One method of climbing-specific strength training that has not received much scientific attention, but has been frequently used by highly accomplished climbers, is campus board training. Campus board training involves a series of upper-body moves on shallow rungs, without assistance from the feet. In addition to challenging the finger flexors, this training method involves dynamic, highly climbing-specific movements of the entire pulling apparatus. To the authors’ knowledge, only one previous study has examined the effects of campus board training among climbers (Philippe et al., 2019). The authors reported similar improvements in on-sight lead climbing performance following hypertrophy- and endurance-focused training. Unfortunately, the researchers included several other training methods in the intervention (i.e., lead climbing, bouldering and pull-ups) and only tested performance through climbing, while neglecting measures of finger strength and endurance. Thus, the specific effects of the campus board training on finger strength and endurance remain unknown. Some available evidence suggests that a higher number of weekly resistance training sessions might mediate gains in muscular strength and hypertrophy, possibly through more frequent elevations in muscle protein synthesis (Dankel et al., 2017). More frequent and shorter sessions could induce less fatigue and thereby allowing for
greater adaptions, as maximal effort and velocity in the training is necessary for improving explosive strength (Behn and Sale, 1993; Sale and MacDougall, 1981). This could be of particular importance for campus board training, which is typically performed with maximal effort and highly explosive movements. Importantly, it has been suggested that dividing the training load over several shorter sessions might reduce the risk of overtraining and injuries (Hartman et al., 2007). This aspect has special relevance to campus board training, as this activity involves highly explosive movements placing extreme stress on the fingers, shoulders and elbows, which are the most frequent sites of injury among climbers (Gronhaug, 2018). Still, fewer and longer sessions could promote a higher tolerance to fatigue (Kraemer and Ratamess, 2005), which might benefit forearm endurance.

Despite a growing body of scientific literature examining climbing-specific resistance-training, the effects of training frequency have not yet been examined in relation to climbing, and many existing studies do not present actual climbing performance. Therefore, the aim of this study was to compare the effects of five weeks of campus board training performed either twice or four times per week on bouldering performance, upper-body pull-up strength (finger-, arm-, shoulder-, and back muscles) and campus board performance. We hypothesized that both training groups would improve their strength, rate of force development (RFD), bouldering performance and campus board performance (maximal reach and number of moves to failure) more than the control group. We expected that dividing the training volume over four days would improve bouldering performance, RFD and maximal reach more than two days, and that two weekly training sessions would produce the greatest gains in campus board moves to failure. The changes in maximal strength were expected to be similar between the training groups.

Methods

Participants

The inclusion criteria were a minimum self-reported red-point grade of 7a+ (IRCRA 18) and to have been free of climbing-related injuries in the last six months. Self-reporting grades have been shown to be highly reliable and acceptable for use in scientific contexts (Draper et al., 2011). Seventeen advanced-to-elite, amateur, male lead climbers volunteered for the study. Although a higher number of participants was desirable, the availability of high level climbers able to correctly perform the campus board training was limited. During the intervention, one participant from TG4 (IRCRA red-point 23) acquired an injury unrelated to the study, leaving sixteen participants who finished all training and testing. Sample characteristics by group are presented in Table 1. The participants were familiar with the campus board but had not used it as a part of their training routine in the last six months. However, they were familiar with intense finger strength training (e.g., loaded fingerboard training) and experienced in subjectively monitoring the training load. After pre-testing, the participants were randomized to either a training group that trained twice per week (TG2; n = 6) or four times per week (TG4; n = 5), or to a control group (CG; n = 5). All groups were encouraged to continue their normal climbing and training routines, but the CG had to refrain from campus board and fingerboard training.

Experimental design

A randomized controlled trial was designed to investigate the effects of performing campus board training either two or four days per week for five weeks with equated volume. The pre-testing was divided over two days, separated by at least 48 - 72 hours. During the first visit, anthropometric variables, bouldering performance and maximal reach on the campus board were tested, in addition to a familiarization to the maximal force test using the rung hold. Finally, maximal isometric pull-up strength was tested in an isometric pull-up using the jug hold. During the second visit, maximal average force and RFD were collected from an isometric pull-up on a climbing-specific hold, followed by a number of moves to failure test on the campus board. The tests were performed in the order described above to avoid inter-subject variations in exhaustion. The participants were informed verbally and in writing about the potential risks and benefits of participation and signed and informed consent form before data collection began. The present research procedures were in accordance with the ethical guidelines of the university and conformed to the standards of treatment of human participants in research, outlined in the 5th Declaration of Helsinki. The preservation of the participants’ safety and privacy was approved by the Norwegian Centre for Research Data (941687).

| Table 1. Anthropometric variables, climbing experience, weekly climbing frequency and self-reported climbing ability for the three groups at baseline. Values are presented as means ± standard deviation. |
|-----------------|-----------------|-----------------|-----------------|
|                 | CG (n = 5)       | TG2 (n = 6)     | TG4 (n = 5)     |
| Age (years)     | 30.6 ± 7.4       | 28.0 ± 5.8      | 32.6 ± 9.9      |
| Height (m)      | 1.84 ± 0.08      | 1.80 ± 0.06     | 1.80 ± 0.06     |
| Body mass (kg)  | 74.4 ± 4.7       | 73.7 ± 7.2      | 75.6 ± 2.7      |
| Fat mass (%)    | 5.5 ± 2.4        | 7.5 ± 2.6       | 10.0 ± 4.7      |
| Muscle mass (%) | 89.7 ± 2.3       | 88.0 ± 2.5      | 85.5 ± 4.7      |
| Experience (years) | 10.0 ± 6.5   | 8.3 ± 2.4       | 8.6 ± 5.6       |
| Weekly sessions (n) | 3.6 ± 0.9      | 3.2 ± 0.8       | 3.4 ± 0.9       |
| Best on-sight (IRCRA) | 18.6 ± 3.2     | 18.2 ± 2.8      | 17.8 ± 2.9      |

On-sight and red-point grades are given using the grading system suggested by the International Rock Climbing Research Association (IRCRA) (Draper et al., 2016).
Procedures
An overview of the procedures (i.e., testing and training order) is presented in Figure 1. Upon initial visit to the laboratory, participants were interviewed about their climbing performance (best red-point and on-sight), climbing experience (consecutive years of regular climbing, defined as at least one weekly session on average), and number of weekly climbing sessions on average in the last two months. Weekly climbing sessions was collected again at post-test to detect any changes in training volume during the intervention. Thereafter, height was measured using a wall mounted measuring tape body mass, followed by fat mass and muscle mass measured using a bioelectric impedance scale (Tanita MC 780MA S, Tokyo, Japan). Finally forearm circumference was measured at 2/3rd the distance between the ulnar styloid process and the coronoid process using a measuring tape. Limb circumference has previously demonstrated good-to-excellent reliability (Bakar et al., 2017). The participants were then instructed to perform a 15- to 30-minute warm up in the bouldering wall using self-selected boulders and holds but maintain a low intensity and avoid fatigue.

Following the warm-up, bouldering performance was tested on two boulder problems that were suggested as grade 7A (IRCRA 20-21) by two independent, highly experienced route-setters. The two boulder problems consisted of five and ten moves using small holds (5 – 20 mm). Both were set on an artificial wall with an overhang of 25°. The order of the boulders was randomized and counter-balanced, but identical at pre- and post-test. The participants were given four minutes to work each boulder problem, and three minutes to rest between the two boulders. Participants could use as many attempts as they desired and the best attempt from each boulder was registered. The total number of completed moves (controlled contact with hold and attempting the next move) from the two boulder problems combined was used in the analyses (max score = 15). Three participants (one in each group) completed both problems on their first try and were therefore excluded from this analysis.

Approximately ten minutes after the boulder performance test, a maximal reach test was performed on the campus board with 20 mm deep and 60 cm wide rungs. The distance between rungs was 13 cm and the board had an overhang of 15°. Participants started with both hands on the lowest rung and were instructed to hang still before pulling themselves up and reaching as far as possible with a self-selected hand. Four attempts were given with at least one minute rest between the attempts. The highest rung they could reach and hang on to with one hand for two seconds was used in the analyses. The rung number was used as the unit of measurement.

Finally, participants were familiarized to the isometric pull-up on a 23 mm rung with rounded edges (Metolius Climbing, Bend, Oregon, USA), in which four-to-six trials were given, with feedback provided after each attempt. This rung size was chosen because it resembles the campus board rung size used in training (i.e., 15–25 mm). After being familiarized with the procedure, we measured the maximal isometric pull-up strength in a 90° elbow angle on the jug holds (depth: 30 mm, height: 30 mm, width: 70 mm) on a Beastmaker 1000 fingerboard (Beastmaker Limited, Leicester, United Kingdom) using the same protocol. A more extensive description of the pull-up test is provided below. Only one attempt was given in the jug condition as data from a pilot study showed a coefficient of
variation (CV) of only 1.07% in this test. Participants were instructed to avoid performing strenuous climbing or climbing-related training in the 48 hours leading up to the second test-day.

The warm-up for the second day was identical as that for the first day. After the warm-up, the isometric pull-up was performed using a half crimp grip on the 23 mm deep rung (Metolius Climbing, Bend, Oregon, USA). A self-selected hand width was used, but the width had to be identical for all trials. The participants were anchored to the floor through a static system consisting of an expansion bolt in the concrete floor, a force cell with 200 Hz resolution (Ergotest Innovation A/S, Porsgrunn, Norway), a daisy chain, and a climbing harness (Figure 2) (Saeterbakken et al., 2020; Stien et al., 2019). The force output was registered using a computer with the commercial software MuscleLab (v. 10.4, Ergotest Innovation A/S, Porsgrunn, Norway). The harness was placed directly below the iliac crest and its position was controlled between attempts.

![Figure 2. Schematic presentation of the test set-up during the isometric pull-up showing 1) expansion bolt in the concrete floor, 2) the force cell, 3) the static daisy chain, 4) the climbing harness, and 5) the 23 mm rung. The gray figure represents the climber before (a) and while (b) exerting maximal force. No horizontal or vertical displacement occurs between the two images.](image)

Before performing the isometric pull-up, the participants stood on two step cases that were adjusted so that they could have their fingers on the rung and a 90° angle in their elbows (measured using a goniometer; Figure 2). The cases were used so that participants would not have to use arm muscle force to maintain the 90° angle before exerting maximal force. The participants were given real-time biofeedback of the force produced via a computer screen and had to maintain a steady baseline (no more than 4 N fluctuations in force) for one second before pulling. When a steady baseline was reached, the participants were instructed to pull as hard and as fast as possible for three-to-four seconds. These instructions were chosen to optimize both maximal force and RFD within the same attempt (Fanchini et al., 2013), in order to reduce the total number of attempts needed and to avoid excessive fatigue. For an attempt to be deemed acceptable, the following criteria had to be fulfilled: 1) no changes >4 N in baseline force before exerting maximal force, 2) continuous rise in force without a plateau before peak force output, and 3) no excessive peak force (> 20% of average force) as a result of creating momentum using hip flexion. Three acceptable attempts were required, and all participants were able to reach this within five attempts or less. A three-minute rest period was given between attempts.

All force curves were analyzed manually by the same researcher to avoid inter-subject variability. The absolute RFD (CV = 8.11%) was calculated as the change in force output from the onset of contraction to the maximal force output. The time used to reach maximal force was also registered to determine whether changes in RFD would be a result of increased maximal strength or decreased time to reach maximal force. Further, the RFD during the first 100ms from the onset (RFD0:CV = 11.83%) was analyzed to examine the portion of RFD, which likely is more driven by neural factors rather than muscular properties (Levernier and LaFaye, 2019b). The onset was determined manually and identified as the point in time when the force rose by more than 4 N over the course of five milliseconds (Andersen and Aagaard, 2006; Levernier and LaFaye, 2019a; Levernier and LaFaye, 2019b). All force curves were enhanced (showing only a 100ms window) to accurately view the time of onset. The maximal average force was calculated as the highest average force across 1500ms (CV = 4.72%). The mean maximal force, RFD, and RFD0 across three attempts were used in the analyses.

Finally, we tested the maximal number of moves to failure on the campus board. For this test, participants started with both hands on the first rung and performed single moves until matching on the top rung before moving downward using the same pattern. Due to the fatigue of this test, only one attempt was given. For a move to be accepted as successful, the participants had to be in controlled contact with the hold and attempt to move to the next rung. The number of completed moves was registered and used in the analyses.

The exercises performed on the campus board were developed in cooperation with highly accomplished climbers who regularly used the campus board in their training. The campus board had three different depths of rungs (25, 20, and 15 mm) and participants were instructed to use the shallowest rung they could, and to progress to a shallower rung when possible. Each of the four exercises (see Table 2) was performed for a total of four sets within each session, leading with alternate hands. The TG2 performed all exercises twice per week over two days, whereas the TG4 performed two of the four exercises within each session, but trained four times per week and reached an identical volume as the TG2. The participants were instructed to rest for two-to-three minutes between sets, as regulated based on their perceived exhaustion. The duration of the training sessions, excluding the warm-up, were approximately 20
and 40 minutes for TG4 and TG2, respectively. All exercises were performed with maximal effort and velocity. The first training session was supervised to ensure correct execution of the exercises (e.g., not using a full crimp grip) and that the intensity (depth of rung) was high enough. All groups were instructed to continue their current climbing and training activity, but the CG was not allowed to commence campus board training during the intervention period. In week three, all participants were contacted to ensure that they were performing the prescribed sessions and did not experience any injury.

Statistical analysis
SPSS statistical software (Version 25.0, SPSS Inc., Chicago, IL, USA) was used for the statistical analyses. Except for bouldering performance (p = 0.001), maximal reach (P = 0.001) and number of moves to failure (p = 0.002), the data material did not demonstrate deviations from normality (Shapiro-Wilk test: p = 0.071 – 0.815). Between-groups differences in the parametric variables were analyzed using an analysis of covariance (ANCOVA) with pre-test results as the covariate. When a significant main effect for group was found, Bonferroni post-hoc corrections were used to detect where the differences occurred. Between-groups differences in the non-parametric variables were analyzed using a Kruskal Wallis Test, followed by independent Mann-Whitney U-tests to detect the differences. Paired samples t-tests were used to determine if there were differences between the pre- and post-test results for the parametric variables, while a Wilcoxon signed rank test was used for the non-parametric variables. Statistical significance was accepted at P ≤ 0.05. All data are presented as means ± standard deviation. For the within- and between-groups differences, Hedges’ g effect size (ES) was calculated as the mean difference divided by the pooled and weighted standard deviations. The Hedges’ d ES were interpreted as follows: <0.2 = trivial; 0.2 – 0.5 = small; 0.5 – 0.8 = medium; >0.8 = large (Cohen, 1988).

Table 2. The exercises performed throughout the intervention. The numbers represent the number of the rungs, with 1 being the lowest one on the board. All exercises started with both hands on rung number 1 and ended with both hands on the same top rung. The difference between rungs was 13 centimeters.

<table>
<thead>
<tr>
<th>Order</th>
<th>Exercise</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-4-7-10</td>
<td>Start with both hands on rung 1. Pull through each move and match hands on rung number 10.</td>
</tr>
<tr>
<td>2</td>
<td>Ladder</td>
<td>Keep one hand on the start rung and move the other hand up one rung at the time until max reach and reverse until the hands are matched on rung 1.</td>
</tr>
<tr>
<td>3</td>
<td>1-2-3</td>
<td>Move ca. 75% of max reach with one hand, then pull through as far as possible with the other hand. Follow with the first hand and match the top.</td>
</tr>
<tr>
<td>4</td>
<td>10 RM</td>
<td>Perform 10 consecutive moves of self-selected length so that the 10th move is near exhaustion.</td>
</tr>
</tbody>
</table>

Note: The group that trained twice per week performed all the exercises within one session, while the group that trained four times per week alternated between exercises 1 and 2, and 3 and 4.

Results

Baseline results
Anthropometric variables, climbing frequency and self-reported climbing ability were not different between the groups at baseline (F(2,13) = 0.018 – 2.242, P = 0.146 – 0.982).

Training
The self-reported training attendance in TG2 and TG4 was 96.7% and 99.1%, respectively. None of the three groups changed their number of weekly climbing sessions outside of the campus board training (average across groups: 3.6 ± 0.8 and 3.6 ± 0.9 at pre- and post-test, respectively) during the intervention (p = 0.178 – 0.374).

Performance outcomes
There was a difference between groups for the change in bouldering performance (p = 0.024). Bouldering performance improved in TG2 (ES = 0.25, p = 0.042), but not in TG4 (p = 0.109) or in the CG (p = 0.157). Further analyses revealed that TG2 improved bouldering performance more than the CG (ES = 2.01, p = 0.016). All groups improved the maximal number of moves to failure on the campus board (ES = 0.68 – 0.80, all p < 0.043), and TG2 increased number of moves more than the CG (ES = 0.87, p = 0.008). None of the groups significantly improved maximal reach (p = 0.083 – 0.317). No other differences between the three groups were found (p = 0.095 – 0.556, Table 3).

Pull-up force
The change in force output in the isometric pull-up performed on the 23mm rung demonstrated no differences between groups (F(2,12) = 1.743, p = 0.217). In the jug condition, a tendency for differences between groups at post-test was found (F = 3.618, p = 0.059). Post-hoc analyses revealed a tendency for greater improvement in force in TG2 compared to the CG (ES = 0.36, p = 0.090), while no other differences were found (p = 0.140 – 1.000; Figure 3).

Table 3. Results for maximal reach, maximal moves to failure, and bouldering performance with effect sizes (ES) for the pre-post change. Maximal reach is given as number of the rung reached, whereas moves to failure and bouldering performance are given as the total number of moves performed successfully before failure.

<table>
<thead>
<tr>
<th>Control group (n = 5)</th>
<th>2 weekly sessions (n = 6)</th>
<th>4 weekly sessions (n = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Max reach</td>
<td>7.6 ± 0.6</td>
<td>7.4 ± 0.6</td>
</tr>
<tr>
<td>Max moves</td>
<td>17.2 ± 5.6</td>
<td>23.2 ± 7.8*</td>
</tr>
<tr>
<td>Bouldering</td>
<td>10.1 ± 3.5</td>
<td>9.9 ± 3.5</td>
</tr>
</tbody>
</table>

* = Significantly different from pre-test results (p < 0.05).
Arm circumference

The analyses revealed no significant between groups differences in the change in arm circumference (F(2,12) = 2.380, p = 0.135).

Training vs. Control

When merging the two training groups and comparing them to the CG, bouldering performance (ES = 1.42, p = 0.006), force in the jug condition (ES = 1.01, F(1,13) = 7.835, p = 0.015), absolute RFD (ES = 1.22, F(1,12) = 6.795, p = 0.023), maximal reach (ES = 1.51, p = 0.040) and number of moves to failure (ES = 0.85, p = 0.040) improved more in the training groups compared to the CG. Force in the jug condition (ES = 0.86, F(1,13) = 3.428, p = 0.087) and arm circumference (ES = 2.21, F(1,13) = 4.636, p = 0.051) demonstrated tendencies for a greater increase in the training groups. The change in RFDₜₐₜ (F(1,12) = 0.918, p = 0.357) and time to reach peak force (F(1,12) = 2.402, p = 0.145) were not significantly different between groups.

Discussion

This study examined the effects of performing a five-week block of campus board training either two or four times per week with equated training volume. The main finding was that no differences occurred between the two training groups. However, only TG2 improved bouldering performance more than the control group, whereas only TG4 improved RFD more than the CG. When combining the training groups, the campus board training improved bouldering performance, maximal pull-up strength, RFD, maximal reach, and number of moves to failure more than the CG, while tendencies for greater improvements in arm circumference and rung strength were observed.

Although the change in RFD was not statistically different between the training groups, the ES for TG4 (ES = 0.63) was distinctly greater than for TG2 (ES = 0.12). Moreover, only TG4 improved RFD more than the active control group. By dividing the total training volume over several shorter sessions, it is possible that TG4 was able to maintain a higher effort and velocity throughout all sets compared to TG2 (i.e., higher campus board training quality), which has been shown to evoke greater improvements in RFD (Blazevich et al., 2020). The accumulated fatigue following a longer session could have reduced the ability of TG2 to maintain a high velocity throughout the session. Theoretically, the lack of difference between the training groups could be explained by the longer between-sessions rest for TG2, which could potentially have allowed for greater neural and muscular recovery and, thereby, been beneficial for the development of RFD (Rhea et al., 2003).

It is possible that had we examined a longer training period and a higher number of climbers, four short sessions may have been proven significantly more effective for improving RFD. As no significant changes occurred in maximal pull-up force or the time to reach maximal force in the rung condition, the improved absolute RFD in TG4 was likely a result of neuromuscular adaptations in the early phase of
the contraction. This speculation is supported by the fact that only TG4 improved RFD_{100}, which is more closely related to neural factors (e.g., motor unit discharge rate) than maximal strength (Maffulli et al., 2016). Of note, the available lab equipment dictated that the force sensor had to be anchored to the floor. A placement in direct contact with the fingers could possibly have provided a more sensitive measuring protocol for RFD.

Since previous investigations have identified high levels of RFD as an important attribute of boulder climbers (Fanchinini et al., 2013; Stien et al., 2019), we expected the same group (TG4) to improve both RFD and bouldering performance. The difficult and steep boulder problems used for testing boulder performance were expected to require high levels of explosive strength (RFD), which only TG4 acquired to a greater extent than the CG. However, no difference between the training groups was found, and only TG2 demonstrated an improvement in bouldering performance that was greater than the CG. Importantly, a small ES for the improvement in bouldering performance was found for TG2 (ES = 0.30), which was only slightly larger than that observed for TG4 (ES = 0.21). It is possible that the maximal score of 15 moves did not provide a sufficiently sensitive test for detecting short-term improvements in bouldering performance. Still, the small effect and few participants are likely the main explanation for the lack of between-groups differences. This speculation is supported by the fact that increasing the statistical power (i.e., combining the training groups) demonstrated a distinctly greater improvement in the training groups compared to the CG. However, it is important to note that the study population comprised highly trained climbers, meaning that even a small improvement after only five weeks is practically meaningful.

As hypothesized, TG2 improved their number of moves to failure on the campus board more than the CG, while TG4 did not. The difference potentially occurred because the longer sessions performed by TG2 compared to TG4 produced a higher tolerance for fatigue (Kraemer and Ratamess, 2005), and thereby a more specific training stimulus toward this test. Specifically, the 10RM exercise (i.e., the exercise with the highest number of consecutive moves) was performed at the end of a longer session for TG2, meaning the moves were likely performed with a greater amount of fatigue than for TG4. Since the CG also improved in this test, one could speculate that familiarization to the campus board might be responsible for the improvement. Importantly, the CG continued their regular climbing training, which could explain the improvement for this group. Further, the improvement in all three groups was accompanied by quite large inter-individual variability. This could indicate that other factors, such as individual preference in technical execution of the test could have influenced the results more than forearm endurance. Thus, the findings from this test should be interpreted with caution. The same is true for the maximal reach performance, which is likely impacted by a combination of physiological, coordinative, and technical factors. This test is further limited by the distance between the rungs (13 cm) requiring large improvements for detecting potential changes. Moreover, although not measured in the present study, the campus board training might also have targeted attributes such as coordination and muscle synergy, which could impact bouldering performance. Therefore, it is problematic to directly link the findings from the lab test to the bouldering performance test.

Following the five-week training block, we were unable to detect differences in strength when analyzing the isometric pull-up on the 23mm rung and on the jug hold. The lack of differences between the two campus board training groups is likely a result of the identical volume between the groups, as evidence indicates training frequency does not influence strength gains under volume-equated conditions (Grgic et al., 2018). It could have been expected that the shorter exercise duration in TG4 would allow a higher intensity and effort, thus producing more prominent improvements in maximal strength of the fingers. However, given that all included participants had multiple years of climbing experience and performed at an advanced-to-elite level, the short-term training period was probably too short to achieve significant improvements in finger strength. Finally, it should be noted that the test set-up includes a complex task in which strength of both the fingers and shoulder girdle are challenged. While this probably allows for a highly climbing-specific task, it renders differentiation between the fingers and shoulders difficult. If possible, prospective studies should incorporate a measure of isolated finger- as well as shoulder girdle-strength to further elucidate which muscle groups are primarily impacted by campus board training.

The strength results from the present study may be difficult to compare with previous climbing interventions, where fingerboard training has been the most frequently examined resistance training method among climbers, with isolated testing of finger strength and endurance (Levernier and Laffaye, 2019a; Lopez-Rivera and Gonzalez-Badillo, 2012; 2019). Hence, changes in strength or RFD reported in these studies is reserved for the finger flexors. In line with the previous findings, when merging the two training groups the campus board training improved strength in the jug condition compared to the CG, with a tendency for a greater improvement in the rung condition. Hence, campus board training could be a viable option for improving climbing-specific strength. In contrast to the fingerboard (i.e., isometrically hanging from the fingertips), which is likely a more finger strength-specific exercise, campus board training can also improve maximal strength of the entire pulling apparatus in a climbing-specific task. Of note, performing climbing-related tasks (e.g., pull-ups) on small holds have been shown to reduce force production and impact the contraction strategies compared to larger holds (Stien et al., 2019; Vigouroux et al., 2018). Since the fingers are the weakest link in the pulling apparatus, potential training effects in the arms- and back muscles may not have been as clear using the rung test.

Although this study was, to the authors’ knowledge, the first to examine the effects of campus board training frequency, some limitations should be considered when interpreting the results. The main limitation of this study was the low study sample size. One could speculate that the differences between groups would be more prominent with a greater statistical power. However, the aim of the study
was to examine the effects among advanced and elite climbers and in order to increase the study population, less experienced climbers would have had to be included. Further, only male advanced and elite climbers were included in this study and the results may not be generalizable to females or climbers performing on other levels. Moreover, as only the first training session was supervised, the intensity was not monitored further during the intervention. However, the participants were experienced climbers and were familiar with performing high-intensity climbing-specific training (e.g., fingerboard), so we are confident that the protocol was carried out as directed. Importantly, the findings for bouldering performance are difficult to generalize as the routes and overhang differ between facilities. Future research examining bouldering performance should use equipment such as the Kilter board, allowing for identical routes to be compared across different locations. The effects of campus board training on speed- and lead-climbing performance should also be examined. Finally, the measuring method (i.e., isometric pull-up) could be considered unspecific to a dynamic training stimulus. Assessing power and velocity during a campus board-related task would likely have been more appropriate and should be considered in prospective studies. However, a non-specific exercise may provide additional information about isolated performance factors and the transferability of the training.

From a practical point of view, the findings of the present study suggest that campus board training can be an efficient training form that should be implemented in the training program of highly accomplished climbers. However, due to the great stress on the finger flexor muscles, it could be advisable to incorporate this training method in a block-periodized program. Emphasizing campus board training in a short block (e.g., five weeks) appears to be sufficient for improving several climbing-specific attributes regardless of training frequency. Importantly, no injuries occurred in the present study. Still, the authors suggest that climbers who are inexperienced to campus board approach the training method with a low training volume and moderate intensity and progress these variables as they gain more experience. Also, in a training block where campus board training is emphasized, climbers should consider reducing the volume of other climbing-related activities. Importantly, to the authors’ knowledge, this is the first study to examine the specific effects of campus board training and future research should be conducted to confirm and expand on the findings.

Conclusion

In conclusion, the different training frequencies produced no significant differences between the training groups. However, among highly accomplished climbers, dividing the training volume over four shorter sessions improved RFD to a greater extent than the active control group, whereas performing two longer sessions improved bouldering performance and moves to failure on the campus board more than the active control group that continued climbing training as usual. Implementing campus board training, regardless of frequency, improved bouldering performance, RFD, maximal reach, number of moves to failure and arm circumference more than just climbing.

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References


### Key points

- **Five weeks of volume equated campus board training may similarly improve finger strength, maximal reach and number of campus moves to failure regardless of training frequency.**

- **Four weekly sessions may be more effective than two weekly sessions for improving rate of force development in an isometric pull-up using a climbing-specific hold**

- **Two weekly sessions could be more effective than four weekly sessions for improving bouldering performance when volume is equated.**
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