TRAINING AND TESTING IN CLIMBING

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TRAINING AND TESTING IN CLIMBING

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Editorial: Training and testing in climbing

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Editorial on the Research Topic
Training and testing in climbing

Climbing is often introduced as a naturally activity in childhood and to some extent follow us throughout the lifespan. For some climbing becomes more time consuming either as a hobby or a sport. Climbing has grown in popularity in the recent decades (Stien et al., 2022) and the popularity will probably continue to grow as climbing has been enrolled in the Olympics Games. Importantly, climbing is a relatively young area of research, and the evidence-based knowledge is limited. Performance in climbing is affected by multiple physiological, psychological, and technical factors (Vigouroux and Quaine, 2006; Baláš et al., 2012; Philippe et al., 2012). To develop reliable tests, improve performance, and avoid injuries in climbing, several gaps of knowledge need to be filled. Therefore, the Research Topic "*Training and testing in climbing*" aimed to increase the scientific knowledge of climbing related to testing and training.

Forty-eight authors originating from Europe and North America have contributed to the 13 manuscripts being published in this Research Topic. The study design includes one mini-review, eight cross-sectional studies, two randomized control trials (RCT), one longitudinal follow-up, and one case study. These studies provide new knowledge to different fields (i.e., training methodology, physiology, psychology, and medicine). Thus, the Research Topic's interdisciplinary evidence has several applications: (a) increasing the informativeness of tests for assessing and monitoring climbing-specific fitness; (b) optimization climbing-specific training; (c) development of new training methods based on the physiological functions as well as motor and mental abilities that most strongly determine climbing performance.

In sport climbing, there are three different disciplines (Woollings et al., 2015). Winkler et al. conducted a cross-sectional study to determine the external load's volume characteristics in the different disciplines at an international level. Video recordings from the 2018 World Cup and the 2018 World Championships showed great variations between the disciplines according to number of moves, time per move and the ratio between activity and rest.

To be able to assess performance related factors, valid and reliable tests are essential (Baechle and Earle, 2008). Three of the studies presented in this Research Topic focus on testing procedures. The mini-review of Stien et al. provided an overview of the climbing-specific tests, procedures and outcomes used to assess climbing performance and training effects. Twenty-five studies were included, and the tests were categorized into climbing-specific endurance-, strength, and power tests. The review showed a disagreement between protocols, and multiple approaches to assess climbing-related strength, power and endurance. Importantly, few studies have reported the reliability and validity of their tests. Regarding testing, Augste et al. conducted a cross-sectional study aiming to find procedures for an intermittent finger flexor endurance test to optimize the correlation with lead climbing performance. The authors concluded that the highest correlations were found for women when 9% deviation in the required force and 1 second deviation in the pulling time was tolerated. For men, the optimum was reached with the same time deviation and a force deviation of 6%. Maciejczyk et al. also evaluate distinct performance indicators in addition to energy system contributions in four different finger flexor tests: maximal finger strength, a 30-s all-out, a continuous, and an intermittent endurance. The authors concluded that maximal grip force and all-out isometric contractions are equally decisive indices of climbing performance. Further, maximal grip force reflects maximal anaerobic power, while all-out average force and force time integral of constant isometric contraction at 60% of maximal force are functional measures of anaerobic capacity. Aerobic energy demands for the intermittent exercise are dominated by the aerobic re-phosphorylation of high-energy phosphates.

Finger flexor strength has been considered as one of the most important physiological factors for climbing performance (Saul et al., 2019). Three of the included studies in the Research Topic focused on finger flexor strength. In a cross-sectional study, Vereide et al. investigated the difference of maximal force and rate of force development (RFD) in male sport climbers. Seventy-eight climbers performed an isometric pull-up on a rung. The authors concluded that maximal force and RFD are greater among climbers on higher performance levels. Further, there is a moderate-to-strong association between maximal and rapid force production and climbing performance. Both Hermans et al. and Devise et al. conducted RCTs aiming to evaluate the effect of hangboard training. Hermans et al. concluded that among intermediate to advanced climbers, 10 weeks of hangboard training increases the maximal finger strength to larger extent than regular climbing training. Devise et al. reached a similar conclusion when they conducted a 4-week intervention among advanced to elite climbers comparing regular climbing to training at an intensity of 60, 80, or 100% of MVC. Of the three intensities, 80% of MVC was the only intensity improving both maximal strength, endurance and stamina. In prolongation of intensity in climbing, Baláš et al. examined the possibility of applying the mathematical model of critical power to the estimation of a critical angle as a measure of maximal metabolic steady state (critical angle) in climbing. Twenty-seven climbers at an intermediate to advanced level conducted multiple ascents at different angles on a treadwall. The authors concluded that a predefined route with three to five different wall angles may be used to estimate critical angle as an analog of critical power. Moreover, using muscle oxygen breakpoint determined by near-infrared spectroscopy from a climbing test with progressive increases in wall angle also appears to provide a valid estimate of critical angle.

Two studies focused on other factors that may affect training and performance. Limmer et al. examined the use of compression garments. Compression garment has received scientific interest in the recent years (Brown et al., 2017) and may improve sport performance (Yang et al., 2020). Limmer et al. compared the immediate effects between forearm compression sleeves, non-compressive placebo forearm sleeves, or no forearm sleeves on sports climbing performance. Based on the results it was concluded that forearm compression has no effect on climbing performance. Marcen-Cinca et al. compared the visual perception system in climbers at different levels through a psychophysical optical test. The findings indicated that elite to high elite climbers performed better at the visual perception tasks compared to the advanced climbers. There were no differences between the groups in the visual acuity and contrast sensitivity tests.

Two studies focused on some of the less positive sides of training and elite sports. Joubert et al. aimed to determine the prevalence of amenorrhea among elite level competitive sport climbers. An online survey was distributed with a response rate of 114 female sport climbers. A total of 18 athletes were presented with current amenorrhea in addition to 14 athletes provided information that indicated irregular cycles. Pastor et al. focused on the longitudinal effects of climbing conducting a 10-year follow-up study where they aimed to investigate the 10-year changes in cortical bone thickness, base osteophyte occurrence and radiological signs of osteoarthritis in the fingers of male sport climbers. The results showed that climbing at the elite level likely induces mechano-adaptation of cortical bones in the fingers, and build-up takes place over the career. Further, climbers show higher frequencies of base osteophytes compared to none-climbers. Radiographic signs of osteoarthritis seem to increase throughout the climbing career. Regarding rehabilitation, Vagy conducted a case study on evaluating and treating a female climber with posterior elbow pain using Telehealth. Exercises were reviewed during the initial evaluation with video and verbal feedback to confirm correct exercise performance. After 10 weeks, the climber's pain decreased from 4/10 to 0/10. Further, she made a full recovery back to her previous grade and was able to perform at the same level as before the injury.

As this Research Topic is finalized, we, the guest editors, believe it has strengthened the evidence-based knowledge concerning training and testing in climbing. Further, we hope that it has brought valuable and practical information which coaches, athletes and recreational climbers can benefit from. Finally, as the research-area of climbing is still in an early stage, we hope the included studies can motivate other researchers around the world to start new projects, bringing the evidence-based knowledge of climbing forward.

Author contributions

VA, JB, MM, and AS wrote and edited the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

Authors MM and JB are currently affiliated with Climbro, a private company who provides hangboards with integrated force sensors and mobile application for climbing specific training.

The remaining 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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The Estimation of Critical Angle in Climbing as a Measure of Maximal Metabolic Steady State

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Purpose: Sport climbing is a technical, self-paced sport, and the workload is highly variable and mainly localized to the forearm flexors. It has not proved effective to control intensity using measures typical of other sports, such as gas exchange thresholds, heart rate, or blood lactate. Therefore, the purposes of the study were to (1) determine the possibility of applying the mathematical model of critical power to the estimation of a critical angle (CA) as a measure of maximal metabolic steady state in climbing and (2) to compare this intensity with the muscle oxygenation breakpoint (MOB) determined during an exhaustive climbing task.

Materials and Methods: Twenty-seven sport climbers undertook three to five exhaustive ascents on a motorized treadwall at differing angles to estimate CA, and one exhaustive climbing test with a progressive increase in angle to determine MOB, assessed using near-infrared spectroscopy (NIRS).

Results: Model fit for estimated CA was very high ($R^2 = 0.99$; SEE = 1.1°). The mean peak angle during incremental test was −17 ± 5°, and CA from exhaustive trials was found at −2.5 ± 3.8°. Nine climbers performing the ascent 2° under CA were able to sustain the task for 20 min with perceived exertion at 12.1 ± 1.9 (RPE). However, climbing 2° above CA led to task failure after 15.9 ± 3.0 min with RPE = 16.4 ± 1.9. When MOB was plotted against estimated CA, good agreement was stated (ICC = 0.80, SEM = 1.5°).

Conclusion: Climbers, coaches, and researchers may use a predefined route with three to five different wall angles to estimate CA as an analog of critical power to determine a maximal metabolic steady state in climbing. Moreover, a climbing test with progressive increases in wall angle using MOB also appears to provide a valid estimate of CA.

Keywords: sport climbing, muscle oxygenation, near infrared spectroscopy, critical power, oxygen kinetics, finger flexors

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INTRODUCTION

Sport climbing is a technical, self-paced sport, and the workload is highly variable and mainly localized to the forearm flexors. Both maximal finger flexor strength and endurance have been found to be strong predictors of climbing ability (Fryer et al., 2018; Michailov et al., 2018), with lead climbers demonstrating greater endurance and boulderers maximal strength and power

(Fanchini et al., 2013; Fryer et al., 2017). The recent debut of competition format climbing at the Tokyo Olympics 2021 (the combined performance of speed, lead, bouldering) has highlighted the divergent requirements of different disciplines, forcing athletes to pay special attention to concurrent training of strength or power and endurance to improve their combined performance.

An ascent of a climbing route is rarely "standardised" with numerous changes in wall angle and speed, and also the types, shapes, orientation, and distributions of handholds, and opportunities for partial recovery during an ascent. As such, performance requires the interaction of multiple technical, tactical, neuromuscular, and metabolic factors (Orth et al., 2016; Saul et al., 2019). However, during training, climbers still seek to stimulate these factors in an isolated manner using intensity-controlled devices such as hangboards, campus boards, and climbing walls of different angles (Medernach et al., 2015; Levernier and Laffaye, 2019; Stien et al., 2021). Diagnostic and training methods for climbing-specific strength have been well described in the literature (López-Rivera and González-Badillo, 2012; Medernach et al., 2015; Michailov et al., 2018; Levernier and Laffaye, 2019; Lopez-Rivera and Gonzalez-Badillo, 2019; Philippe et al., 2019; Stien et al., 2021). In contrast, research on adaptations from endurance training is scarce (Lopez-Rivera and Gonzalez-Badillo, 2019). Endurance training in climbing requires systemic and localized adaptations (Thompson et al., 2014; Fryer et al., 2018), and ensuring appropriate intensity of exercise, particularly for the finger flexors, is challenging. Indeed, it has been shown that intensity control during climbing using measures typical from other sports, such as gas exchange thresholds, heart rate, and blood lactate, are not effective (Schöffl et al., 2006; Limonta et al., 2018; Baláš et al., 2021).

Only two studies have proposed a test to determine functional aerobic metabolic capacity in climbers using intermittent isometric handgrip contractions at differing intensities (Giles et al., 2019, 2020). The authors calculated critical force (CF), the force analog of critical power (CP) to determine maximal metabolic steady state for climbing-specific handgrip exercise (Poole et al., 2016; Jones et al., 2019). The CF tests proposed by Giles et al. (2019, 2020) are useful; however, they may only be applied to isolated forearm models and so far have only been tested for one specific hold size and work-recovery ratio, and therefore, their practical use is currently limited.

Applying the CP concept (Poole et al., 2016), its mathematical models to a whole-body climbing test may offer a potential solution to determine maximal metabolic steady state in climbing. Although climbing intensity has often been increased by elevating the velocity of an ascent (Booth et al., 1999; España-Romero et al., 2009; Rosponi et al., 2012), it has recently been shown that local muscle oxygen utilization may not be altered during faster climbing; however, it does rise with steeper wall angles (Gajdošík et al., 2021). Small incremental changes in climbing angle offer a valid means of altering the intensity of a climb while maintaining its multifaceted characteristics (Noé et al., 2001; Baláš et al., 2014). Combined with the measures of climbing time to exhaustion (TTE), it may be possible to calculate a "critical angle" (CA) analogous to CP (Poole et al., 2016). The CA should correspond to a metabolic transitional zone below which climbing does not induce task failure for a prolonged period, and above which fatigue occurs in a finite predictable period. Moreover, with an increased angle, more pronounced finger flexor contractions stimulate mitochondrial respiration and higher intramuscular pressure restricts capillary blood flow and, thus, muscle oxygen delivery (Fryer et al., 2013; Gajdošík et al., 2021). Recently, muscle oxygenation breakpoints (MOBs) have been measured locally using near infrared spectroscopy (NIRS) during an incremental climbing task (Baláš et al., 2021). These MOBs were suggested to represent an intensity around localized CP; however, they have not been associated with any systemic metabolic threshold indicators, and as such validation of such a MOB is needed.

Knowledge of CA in climbers may help coaches and researchers to set climbing intensities on routes with preset hold configurations (specific type, shape, orientation, and distribution of handholds and footholds) in the heavy or severe exercise domains during training; something, which would be extremely advantageous for training, yet is currently not possible. Moreover, the use of NIRS may allow for the instantaneous control of intensity during an ascent. We hypothesize, that if a climbing CA exists, the difference in intensity will also elicit changes in muscle oxygen dynamics. Moreover, climbing slightly over CA will lead to a finite and predictable time to failure, and climbing under the CA will not induce exhaustion for a prolonged, indefinite period. Consequently, the purposes of the study were to (1) determine the possibility of applying the mathematical model of CP to the estimation of a CA as a measure of maximal metabolic steady state in climbing and (2) to compare this intensity with the MOB determined during an exhaustive climbing task.

MATERIALS AND METHODS

Participants

Twenty-seven sport climbers of an intermediate to advanced level [11–25 International Rock-Climbing Association (IRCRA) scale; 6a–8b French/Sport scale] volunteered (19 men: age 30.3 ± 8.5 years, body mass 70.5 ± 7.1 kg, height 177 ± 6 cm; 8 women: age 26.2 ± 3.0 years, body mass 57.4 ± 6.9 kg, height 169 ± 5 cm). Training characteristics of the participants reported during the initial questionnaire are depicted in **Table 1**. All participants were informed of the experimental risks and provided informed consent prior to the commencement of data collection. Climbers were healthy non-smokers who were not taking any vascular acting medication. The study conformed to the recommendations of World Medical Association and the Declaration of Helsinki and was approved by the Ethics Committee of Charles University, Faculty of Physical Education and Sport under the N^o EK 61/2019.

Procedures

All participants completed several exhaustive climbing tests during 5–7 laboratory visits separated by 2–5 days. During visit one, climbers undertook a maximal finger strength test and a familiarization session on the motorized climbing ergometer (treadwall) at several speeds and angles on a predetermined route. This route was also subsequently used for the exhaustive testing protocol. On visit two, climbers performed an incremental exhaustive exercise test, which progressed from a positive angle (+6°), through vertical (0°) to negative (overhanging) angle, the angle at which failure occurred was termed the "peak-angle." Climbers were fitted with a NIRS device on their forearms to assess muscle oxygen dynamics. During the next 3–5 visits, one of the preset angles was climbed at a constant speed until failure so that TTE occurred between 2 and 15 min (Vanhatalo et al., 2011; Jones et al., 2019). Furthermore, the TTE range between the steepest and the least steep angle was aimed to be as broad as possible (8–12 min) (Jones et al., 2019).

Moreover, to validate the CA determination from the mathematical model, nine participants completed two additional laboratory visits to climb the same route 2° above and below CA in randomly assigned order.

Finger Strength

Maximal finger flexor strength was assessed on a climbing-specific dynamometer using methods previously shown to be reliable (Baláš et al., 2018; Michailov et al., 2018). Climbers were asked to progressively transfer their maximum weight ("hang") on a wooden rung (23 mm deep) for 5 s with their dominant hand. Maximal strength was determined as the highest (peak) value from two trials.

Climbing Tests

Climbing tests were conducted on a motorized treadwall (ClimbStation generation 1, Forssa, Finland). The route was technically simple with positively oriented and slightly crimped holds (2–3 cm size depth which enabled both the open and half-crimp grip positions) and was graded 8 on IRCRA grading scale at vertical angle (0°) by a professional routesetter. During all ascents, a speed of 9 m·min^{-1} was applied to minimize the opportunity for static resting positions during the climbs (Baláš et al., 2021). The incremental test started at +6° (positive angle), and after each minute, the belt was stopped for 10 s to allow climbers to dry their hands with chalk, following which the angle was decreased by −3° to become progressively vertical (0°) and then negative (overhanging), therefore requiring progressively greater finger flexor and upper-body strength involvement. Climbers were not allowed to touch the ground during rest periods. The exhaustive tests at given angles were completed at the same speed and the angle of each remained constant during the whole ascent. Participants were verbally encouraged to climb for as long as possible. Each test ended when a climber reached volitional exhaustion and stepped onto the safety mattress.

TABLE 1 | Performance and training characteristics (mean ± SD) in male and female climbers.

	Males	Females	Differences	
	***N* = 19**	***N* = 8**	***P***	**Cohen's *d***
Climbing ability lead (IRCRA scale)	17.9 ± 4.2	16.3 ± 2.9	0.326	0.43
Climbing ability boulder (IRCRA)	21.4 ± 3.6	18.1 ± 3.3	0.036	**0.94**
Experience (years)	12.1 ± 7.6	8.3 ± 4.1	0.188	**0.59**
Climbing-specific training (h/ week)	6.7 ± 4.7	5.3 ± 1.8	0.445	0.35
Endurance training from total climbing time (%)	55 ± 28	64 ± 32	0.486	0.31
F_{max} (kg)	57.5 ± 11.2	38.0 ± 8.3	**<0.001**	**1.88**
CA mathematical model (°)	−2.5 ± 4.3	−2.6 ± 2.1	0.990	0.01
CA NIRS (°)	−2.7 ± 3.0	−2.3 ± 2.7	0.728	0.15
Peak angle (°)	−16.7 ± 5.3	−16.5 ± 4.5	0.913	0.05
W′ (°s)	3, 491 ± 1, 303	2, 685 ± 1, 455	0.168	**0.60**

Statistically (p < 0.05) significant, and effect sizes greater than medium (d > 0.5) are in bold format.
CA, estimated critical angle; IRCRA, International Rock Climbing Association; F_{max}, maximal finger flexor strength; NIRS, near infrared spectroscopy.

Muscle Oxygenation Breakpoint

During all ascents, a NIRS device (Portamon, Artinis Medical System, BV, Netherlands) was placed over the belly of the flexor digitorum profundus (FDP) (Fryer et al., 2018) and covered by a black forearm garment to shield the optodes from ambient light. Deoxy[heme], muscle tissue oxygen saturation (StO_2), and total[heme] were used to assess muscle oxygen dynamics and perfusion. Due to the irregular intermittent nature of finger flexor contractions during climbing, deoxy[heme] and StO_2 were averaged over 10-s periods. Raw and corrected NIRS signals are depicted in **Figure 1**. The MOB was determined visually from deoxy[heme] inflection points by three independent evaluators (**Figure 1**). The changes in slope signify that Δ deoxy[heme] had begun to change faster or slower with increased wall angle. If there was not an agreement on a determined CA, the following procedures were used: (1) if two evaluators were in agreement and one not, then the CA from two evaluators was used; (2) if all three reviewers were differing, then the mean score was used as the CA.

Perceived Exertion

Rate of perceived exertion (RPE) during the ascents 2° above and under CA was used to assess subjective perception of exertion intensity. Perceived exertion was assessed on a scale from 6 to 20 as suggested by Borg (1982). Immediately after the test, climbers were shown a table with numbers and corresponding verbal description of the exertion and indicated their exertion rating to the researcher.

Statistical Analysis

Performance and NIRS characteristics were described using mean ± standard deviation (SD). Possible differences between men and women were evaluated using independent t-tests and Cohen's d. To calculate CA, a similar approach for CF was applied (Giles et al., 2019) and the equation with best fit was used for determination of CA:

$$1. \quad A = W' \times \frac{1}{TTE} + CA,$$

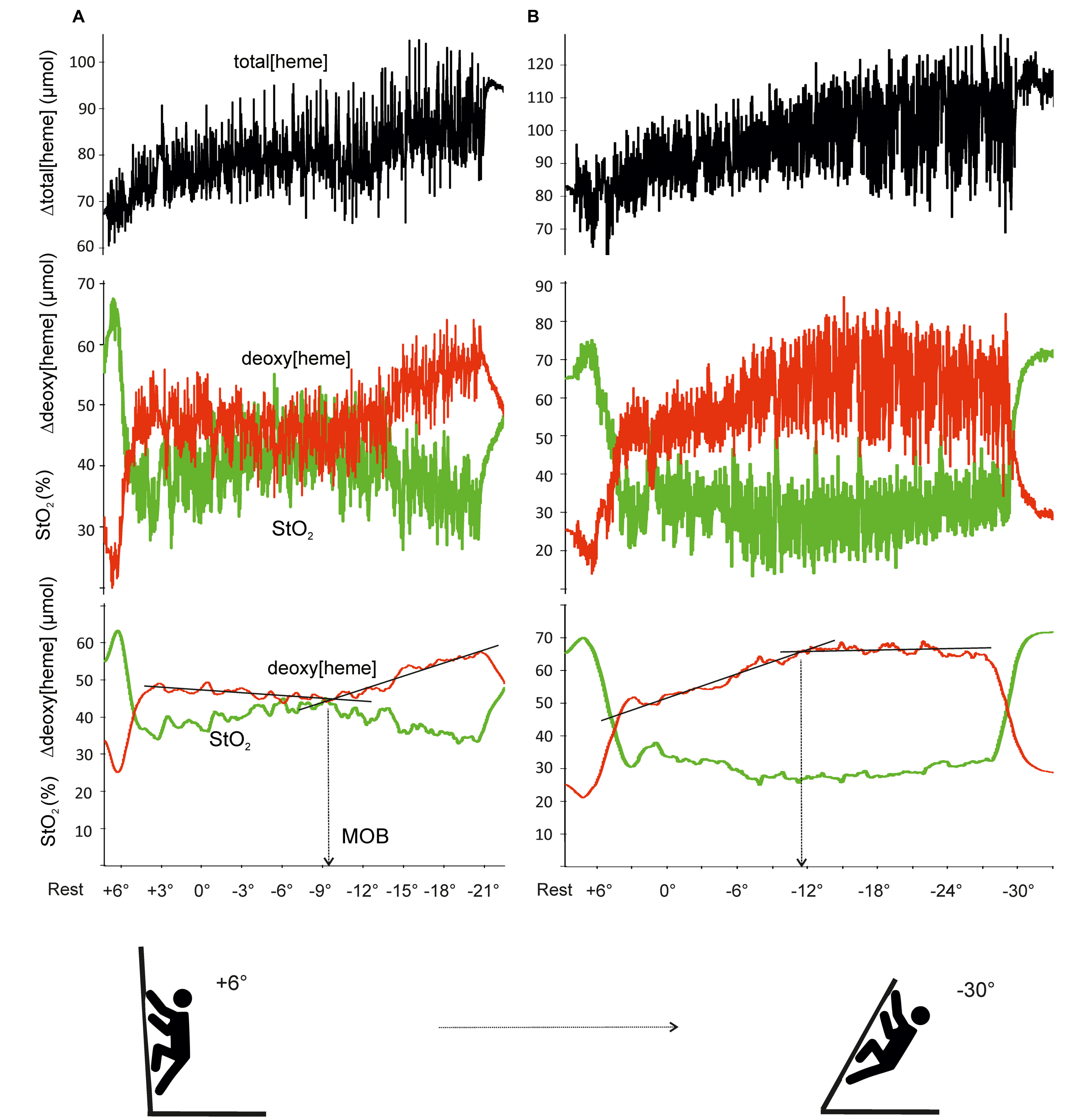

FIGURE 1 | Example of raw and averaged (10-s interval) signal for deoxy[heme], total[heme], and muscle tissue oxygen saturation (StO_2) during exhaustive climbing test with progressive increases in angle. MOB was detected as an inflection point of deoxy[heme] with progressive wall angle. Two typical responses represent sudden increase **(A)** and onset of a plateau **(B)** in Δdeoxy[heme].

2. $W = \text{TTE} \times \text{CA} + \text{W}'$,

where "A" is the angle of the ascent (°), "CA" is the critical angle (°), "TTE" is the time to exhaustion (s), "W′" is the capacity to climb over CA (°s) and represents the finite time a climber can sustain the ascent at steeper angles than CA, while "W" (°s) can be approximated as "total work" completed by a climber during the incremental exhaustive test. This first equation model plots angle of the ascent against l/TTE (**Figure 2B**); CA is given by the *y*-intercept and W′ by the slope of the regression line. The second equation model plots W against TTE (**Figure 2C**); CA is given

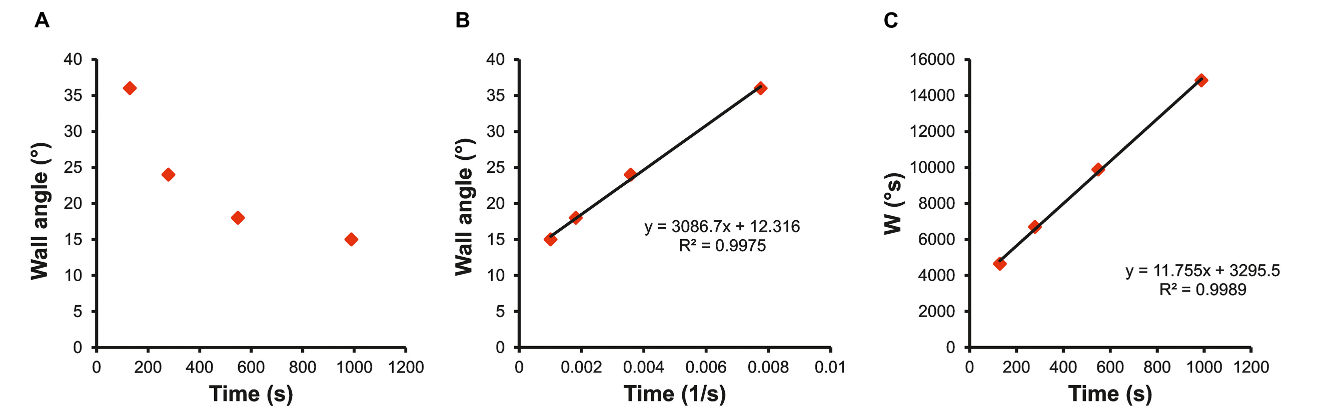

FIGURE 2 | Example of hyperbolic relationship between wall angle and TTE **(A)** and the calculation from linear models using **(B)** wall angle (°) against time to failure (1/s); and **(C)** work limit W(°s) against time to failure (s). Coefficient of determination (R^2) indicates the fit of the linear model.

by the slope of the regression line and W′ by the intercept. Both models were applied to all participants, and a model with higher fit was used to estimate individual CA.

To determine validity of CA from the mathematical model, nine climbers were asked to climb 2° above and under CA. The limit of 2° was calculated as 95% confidence interval (95% CI) from standard error of CA estimate (SE = 1.1), therefore 1.96 SE (95% CI = ±2.2°).

Subsequently, the agreement between the CA determination ›m mathematical model and NIRS was evaluated using Bland–tman plot and intraclass correlation (ICC). The ICC was calculated as follows:

$$ICC = \frac{MSB - MSW}{MSB + (k-1)\,MSW},$$

where MSB and MSW correspond to mean squares between and within subjects from a repeated measure ANOVA, respectively, and k is the number of trials (2 in this case). This equation encompasses both the variability due to systematic changes between trials and error variability. ICC was expressed with 95% CI.

The association among climbing ability, TTE, CA, and W′ were evaluated using Pearson's correlation coefficients or linear regression coefficient of determination. Statistical significance was set to $p < 0.05$.

RESULTS

When TTE was plotted against wall angle, the typical hyperbolic function as for power–duration relationship was found (**Figure 2A**). The linear transformation (wall angle against 1/TTE, **Figure 2B**) showed high model fit ($R^2 = 0.99$; 95% CI 0.96–1.00) and low standard error of CA estimate (SE = 1.10°; 95% CI 0.83°–1.35°). The second linear model (W against TTE, **Figure 2C**) provided less fit ($R^2 = 0.72$; 95% CI 0.61–0.83), and a low standard error of CA estimate was found (SE = 0.99°; 95% CI 0.72°–1.25°).

Time to exhaustion at the steepest angle was 118 ± 52 s (wall angle range from −25° to −45°), and the least steep angle was 808 ± 192 s (wall angle range from 0° to −18°). The mean estimated CA (−2.5° ± 3.8°) was significantly associated with climbing ability in lead climbing but not in bouldering ($R = -0.406$ and -0.282, respectively); however, W′ (3251°s ± 1373°s) was related to both lead climbing and bouldering ability ($R = 0.580$ and 0.695, respectively).

The mean peak angle during the incremental test was −17° ± 5° and was moderately related to both lead climbing and bouldering ability ($R = -0.661$ and -0.587, respectively). Training and performance characteristics for both men and women are depicted in **Table 1**.

All nine climbers performing the ascent 2° under CA were able to sustain the task for the maximum test duration of 20 min with perceived exertion (RPE = 12.1 ± 1.9). However, climbing 2° above CA led to task failure (TTE = 954 ± 177 s; RPE = 16.4 ± 1.9) (**Figure 3**). Only 2 climbers were able to sustain the task for 20 min which was in agreement with their exceptionally high W′ (W′ > 3,500°s) as their TTE was predicted to last more than 30 min (**Figure 3**).

The MOB was detectable in all 27 climbers during the incremental exhaustive test; 18 showed inflection points as a faster increase in Δdeoxy[heme], whereas 9 climbers as an onset of a plateau (**Figure 1**).

Good agreement was found between angle at MOB and CA (ICC = 0.80, 95% CI 0.61–0.90, SEM = 1.5°). Limits of agreement plot showed no meaningful differences between the two methods, and nearly all estimates were within ± 3° (**Figure 4**). The estimate of MOB as an onset of deoxy[heme] plateau provided larger variability than the inflection point of faster Δdeoxy[heme] increase (**Figure 4**).

DISCUSSION

The main findings of this study were that (1) multiple tests to exhaustion with differing climbing angles allow for the estimation of CA at which a maximal metabolic steady state occurs when

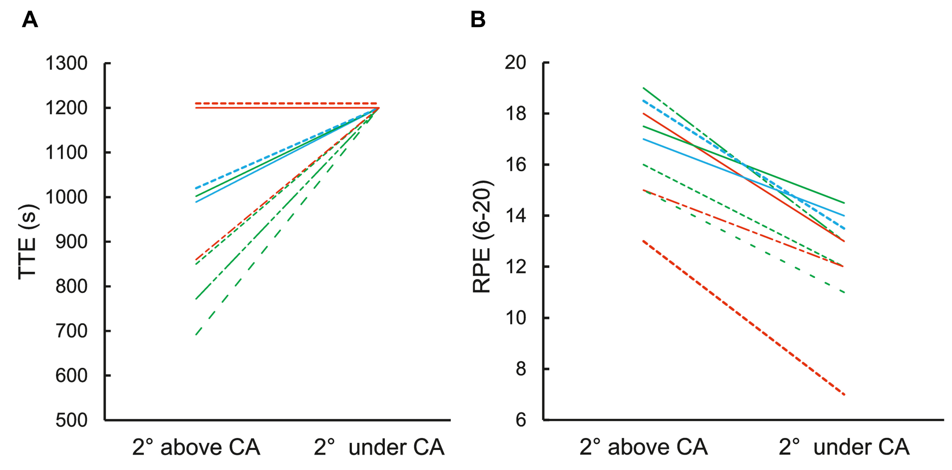

FIGURE 3 | (A) TTE during climbing 2° above and under CA. The time of 20 min (1,200 s) was set as maximal irrespective exhaustion occurred or not. Immediately after the climb, RPE was assessed in both conditions **(B)**. Color of individual lines represents climbers with different level of W′: red (W′ > 3,500°s), blue (W′ > 2,500–3,500°s), green (W′ < 2,500°s).

climbing; (2) MOB representing a metabolic transition state in the finger flexors is in good agreement with CA.

Manipulating wall angle has previously been shown to be a simple quantitative tool for changing intensity in climbing (Watts and Drobish, 1998). Noé et al. (2001) reported that an increase of 10° (−10° from vertical) induced ∼47% increase in mean vertical force on handholds and, therefore, more intense finger flexor contractions. Furthermore, an increase of wall angle by 15° from vertical elevated heart rate by an average of ∼24 beats per min, oxygen uptake by ∼9 $mL \cdot min^{-1} \cdot kg^{-1}$ and lowered muscle oxygen saturation of the FDP by 7% (Baláš et al., 2021). In this study, TTE decreased with steeper wall angle and the association between TTE and wall angle followed a hyperbolic function (**Figure 2**) same to the power or speed and duration relationship (Jones et al., 2019). The existence of a CA as a metabolic transitional zone between steady- and nonsteady-state conditions provides further support for using climbing angle to adjust intensity during climbing training. However, it should be noted that the same wall angle may induce different forces on handholds even among climbers who have similar characteristics such as body mass and finger strength endurance. In fact, the whole-body model assessment may encompass not only the metabolic capacity of the forearm flexors but also other factors such as movement economy. For instance, movement economy in more advanced climbers has been shown to reduce vertical forces on handholds (Baláš et al., 2014), which would lead to a steeper CA in more "technical" than "stiff" climbers despite their similar metabolic predispositions. Consequently, comparisons among climbers of estimated CA account not only for the level of aerobic capacity, but also for other factors such as movement economy. This is in contrast to the isolated forearm model CF determination (Giles et al., 2019, 2020), where only metabolic factors in specific hanging conditions are assessed. However, the primary aim of the CA determination is not the between-subject comparisons but individual threshold intensity in ecological valid setting. Although movement economy may differ among climbers, the CA is set for each climber individually as it is expected that each climber has similar movement economy across all trials on the same route. Therefore, technically easy routes should be preferred for individual training prescription to ensure that the shift in CA is due to metabolic adaptations and not a learning effect. Moreover, it should be noted that values of estimated CA will be only valid for a predefined route, as different hold sizes, more complex moves, or different climbing speeds may induce different physiological responses. Using motorized treadwalls appear especially appropriate for the standardization of training, where the primary aim is to influence metabolic adaptations of finger flexors during whole-body climbing movement which may differ from isolated training on hangboards or campus boards (Medernach et al., 2015; Levernier and Laffaye, 2019; Giles et al., 2020).

Repeated exhaustive ascents over several days are needed to determine CA and this places high-training loads on individuals.

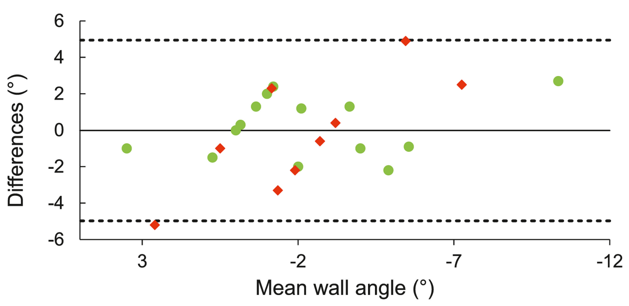

FIGURE 4 | Limits of agreement plot of estimated CA from MOB and CA from mathematical model. The solid horizontal line represents differences between the two estimates of CA, the dashed lines upper and lower 95% limits of agreement. Green and red circles designate participants with MOB determined as a sudden increase and onset of a plateau in Δdeoxy[heme], respectively.

Therefore, using MOB during one exhaustive incremental test may be more advantageous for trainers and climbers to set a climbing-specific maximal metabolic steady state. The MOB during an exhaustive climbing incremental protocol has been described previously (Baláš et al., 2021); however, the authors could not associate the inflection point of Δdeoxy[heme] to any intensity threshold as no relationship to any ventilatory or cardiac responses was found. In this study, the MOB comparison was made with the CP concept as the local forearm muscle fatigue rather than respiratory exhaustion is the main determinant of failure during climbing (Watts, 2004). We found good agreement between MOB and CA (SEM = 1.5%), particularly considering 3° was the smallest change used during the incremental test. However, there were 2 of the 27 climbers who demonstrated differences of ∼5°. The explanation may be linked to several mechanisms such as reliability error, error of CA determination or simply that the MOB cannot precisely reflect metabolic steady-state intensity. Therefore, repeated testing or climbing slightly below the CA for extended periods of time appears useful to confirm the correct determination of CA.

Deoxy[heme] has been recommended for MOB determination as it is less affected by changes in perfusion under NIRS probe (Grassi et al., 2003; Wang et al., 2006). Two patterns in Δdeoxy[heme] dynamics have been revealed to represent MOB in the current results in line with the literature (Wang et al., 2006). First, the onset of a plateau in deoxy[heme] may reflect microvascular O_2 extraction reaching a ceiling (Keir et al., 2015; Boone et al., 2016a) or simply that short periods of finger flexor reperfusion during hand release from the hold are not sufficient to provide sufficient blood flow at higher intensities and then O_2 delivery into the muscle. Only 9 climbers in this study showed plateau of deoxy[heme], and the other 18 climbers demonstrated faster increase in Δdeoxy[heme] at MOB. According to our data (**Figure 4**), both forms of inflection reflected similar intensities around the CP. This discrepancy in the oxygen dynamics between climbers may be due to many interrelated factors such as relative deepness of muscle analyzed under optodes (climbers had various forearm circumference), the muscles involved in the contraction (muscle fiber architecture), muscle fiber types assessed, and/or blood perfusion during the test (Chin et al., 2011; Murias et al., 2013; Okushima et al., 2015). For instance, it has been demonstrated that the deeper layers of rectus femoris have the potential to maintain a higher O_2 delivery to O_2 utilization ratio compared with superficial layers during incremental cycling (Okushima et al., 2015). The less activated rectus femoris provides right-shifted dynamics of deoxy[heme] with respect to a more involved vastus lateralis and vastus medialis during ramp exercise (Chin et al., 2011). It is likely that other finger flexors such as the superficial flexors may have been largely involved during intermittent contractions and mitigated the activity of deeper flexors.

In this study, good agreement between MOB and CA as the maximum steady-state intensity was found. Moreover, all climbers exercising 2° under CA were able to sustain 20 min of climbing rating the intensity from light to somewhat hard on Borg scale of perceived exertion, while they were exhausted 2° above CA after ∼ 16 ± 3 min rating the intensity from hard to extremely hard. This supports our hypothesis that MOB during isometric contractions reflects metabolic changes in the muscle from steady- to nonsteady-state conditions, rather than other intensity boundaries. However, it should be acknowledged that NIRS-derived thresholds may be only mechanistically linked to CP threshold as discussed recently (Boone et al., 2016b; Broxterman et al., 2018; Poole et al., 2021).

There was a significant but practically weak relationship between CA and climbing ability (R^2 = 0.16) which is in contrast to moderately strong association (R^2 = 0.66) from similarly determined MOB in our previous study (Baláš et al., 2021). The discrepancy may be due to selection of climbers who were mixed in sex, and discipline preference. This is supported by generally lower relationship between peak angle and climbing ability in this study when compared to previous research (España-Romero et al., 2009; Baláš et al., 2021). However, the significant relationship between CA and lead climbing ability supports the importance of oxidative capacity for achieving a high level of performance in lead climbing. On the other hand, a weak nonsignificant association (R^2 = 0.08) with bouldering ability shows that other factors are decisive for the performance of powerful whole-body movements in bouldering. For instance, the ability to climb at intensities (angles) above CA (W′) has been shown to be a more important metabolic determinant for bouldering (R^2 = 0.48) than for lead climbing (R^2 = 0.33). With respect to this study, it has to be highlighted that climbing performance depends on many other technical and tactical factors and the association between CA and climbing ability will always be lower than typical endurance sports such as running or cycling (Poole et al., 2021). Nevertheless, endurance of the finger flexors is a key sport-specific determinant of performance and lead climbers demonstrate specific adaptations (Ferguson and Brown, 1997; Thompson et al., 2014). It has been suggested that using CP and W′ may be extremely valuable in constructing individually optimized interval training programmes in a range of athletes and sport disciplines (Vanhatalo et al., 2011); therefore, coaches may use CA as the threshold intensity to train forearm muscles endurance under sport-specific conditions.

Limitations of the study include the assumptions associated with the use of continuous-wave NIRS measurement during exercise such as adipose tissue thickness, subcutaneous blood flow, or the use of physiological calibration (Barstow, 2019). However, adipose tissue under the optodes should not have affected the results as skinfold thickness in climbers' forearms has been found to be very low (Baláš et al., 2018; Fryer et al., 2018). In addition, the use of spatial resolved spectroscopy, as used in this study, appears to be unaffected by heating-induced changes in cutaneous circulation (Barstow, 2019), and as such there was no need for the physiological calibration of the NIRS output as changes in TSI and deoxy[heme], rather than absolute values, were evaluated (Barstow, 2019). It should also be noted that the findings of this study are based on a technically simple climbing route at one speed with handholds of a relatively similar size, which may differ from technical rock-climbing ascents.

CONCLUSION

Our data show that multiple tests to exhaustion with differing climbing angles allow for the estimation of CA. Climbers, coaches, and researchers may use a predefined route or circuit at three to five angles to estimate CA as a parallel of metabolic transition from steady to nonsteady states (heavy to severe exercise intensity domains). Climbing 2° below CA is tolerable for extended periods of time and perceived as light to somewhat hard, while climbing 2° above CA leads to finite time to failure. Moreover, an exhaustive climbing test with progressive increases in angle using the MOB appears to provide a valid estimation of CA.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of Charles University, Faculty of Physical Education and Sport. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JB developed the theoretical framework, conceived the study, collected the data, analyzed the data, and wrote the article. JG developed the theoretical framework, conceived the study, and analyzed the data. SF and DG provided critical feedback on drafts and edited the final manuscript for submission. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: DG is employed by Lattice Training Ltd., who provides climbing coaching and assessment services. JB is currently affiliated with Climbro, a private company who provides hangboards with integrated force sensors and mobile application for climbing specific training.

The remaining 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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Climbing-Specific Exercise Tests: Energy System Contributions and Relationships With Sport Performance

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Purpose: The aim of the study was to evaluate distinct performance indicators and energy system contributions in 3 different, new sport-specific finger flexor muscle exercise tests.

Methods: The tests included the maximal strength test, the all-out test (30 s) as well as the continuous and intermittent muscle endurance test at an intensity equaling 60% of maximal force, which were performed until target force could not be maintained. Gas exchange and blood lactate were measured in 13 experienced climbers during, as well as pre and post the test. The energy contribution (anaerobic alactic, anaerobic lactic, and aerobic) was determined for each test.

Results: The contribution of aerobic metabolism was highest during the intermittent test (59.9 ± 12.0%). During continuous exercise, this was 28.1 ± 15.6%, and in the all-out test, this was 19.4 ± 8.1%. The contribution of anaerobic alactic energy was 27.2 ± 10.0% (intermittent), 54.2 ± 18.3% (continuous), and 62.4 ± 11.3% (all-out), while anaerobic lactic contribution equaled 12.9 ± 6.4, 17.7 ± 8.9, and 18.2 ± 9.9%, respectively.

Conclusion: The combined analysis of performance predictors and metabolic profiles of the climbing test battery indicated that not only maximal grip force, but also all-out isometric contractions are equally decisive physical performance indices of climbing performance. Maximal grip force reflects maximal anaerobic power, while all-out average force and force time integral of constant isometric contraction at 60% of maximal force are functional measures of anaerobic capacity. Aerobic energy demand for the intermittent exercise is dominated aerobic re-phosphorylation of high-energy phosphates. The force-time integral from the intermittent test was not decisive for climbing performance.

Keywords: climbing, aerobic, anaerobic, physical fitness, performance, exercise testing

INTRODUCTION

Sport climbing was included in the 2020 Olympic program due to the great increase in its popularity. In addition, the highest climbing achievements performed on rocks and not during competitions have increased asymptotically in the last three decades (Michailov, 2014). Both facts indicate that climbing has reached an advanced stage of development. This places higher demands upon climbers' preparation and requires monitoring as well as evaluating climbing-specific fitness to optimize training and further increase climbing performance. It has been shown that traditionally used exercise tests are not useful in the assessment of climbers' training state (Watts, 2004). In order to select appropriate exercise tests for climbers, one should be well-acquainted with specific load characteristics, performance limiting factors, and physiological aspects in climbing.

There are many climbing disciplines, differing in duration and exercise intensity. During competitions, the time limit of lead climbing is 6 min. Otherwise, the ascents on sport climbing routes (leading) are usually 1–4 min (red-point—after working out the route) and 3–10 min long (on-sight—first attempt). Bouldering ascents usually last 30–50 s (Michailov, 2014). During a bouldering competition, the climbers may attempt a boulder problem as often as they want, and can do so in 4 or 5 min. After that, they rest for 4 or 5 min and then start working on the next boulder problem. The actual 15-m speed climbing men's record is 5.21 s. Consequently, climbing is not equivalent to permanent maximal effort but it is a mix of distinct patterns muscular efforts determined by contraction intensity related to maximal force, duration of contraction phases, and their relation to relaxation phases. Typical for all climbing disciplines is that they demand strenuous intermittent isometric muscle contractions (Sheel, 2004). The contraction time of the finger flexor muscles is much longer than their relaxation time. The contraction to relaxation ratio is blood-flow restricting. It can be 4:1 in sport climbing and 13:1 in bouldering (Schadle-Schardt, 1998; White and Olsen, 2010).

The structure of climbing performance comprises a large set of motor abilities and skills, including physiological and psychological factors, anthropometric characteristics, and flexibility (Sheel, 2004; Watts, 2004; Giles et al., 2006; Michailov, 2014). The physical variables, which largely explain the variance in climbing performance, are trainable factors such as finger-arm strength and endurance, whereas anthropometric characteristics and flexibility have comparably small effects (Mermier et al., 2000; Baláš et al., 2012; Laffaye et al., 2016). Physical, technical, and mental characteristics explain the structure of climbing performance in a similar way, which may serve as evidence that climbers need to conduct harmonious development training (Magiera et al., 2013).

From a physiological point of view, climbing is an interesting discipline because it requires: (a) a satisfactory level of aerobic power and general endurance, and (b) specific muscular strength and endurance supplied by aerobic, phosphagen [adenosine triphosphate (ATP) and phosphocreatine (PCr)], and anaerobic lactic energy systems (Sheel, 2004; Watts, 2004; Giles et al., 2006; Bertuzzi et al., 2007). Previous studies were focused on the physiological response during climbing (Watts and Drobish, 1998), finger flexor strength, and endurance (MacLeod et al., 2007; Baláš et al., 2012; Philippe et al., 2012), as well as aerobic power (Billat et al., 1995). During climbing, cardiopulmonary measures of approximately 75% maximal oxygen consumption (VO_2max) and 83% maximal heart rate or lactate concentrations (Lac) exceeding 4.5 mmol·L^{-1} suggest substantial contribution of both, aerobic and anaerobic glycolytic energy (Booth et al., 1999; Giles et al., 2006). Moreover, highly trained climbers can perform repetitive isometric contractions of the forearm without fatigue, whilst tolerating high levels of acidosis indicating high anaerobic power, buffer capacity, and lactate removal (Giles et al., 2006; Michailov et al., 2015, 2017). Although repetitive isometric contractions in climbing are of anaerobic nature, ATP-PCr recovery and lactate removal require efficient aerobic metabolism. Thus, oxygen consumption remains elevated into the post-climb recovery period (Watts, 2004). Billat et al. (1995) noted that during climbing, heart rate is high for a relatively low oxygen uptake level. They concluded that oxidative metabolism may play a secondary role in rock climbing. Similarly, Sheel et al. (2003) observed a disproportional rise in heart rate compared to oxygen uptake during climbing. However, they concluded that climbing requires not only anaerobic but also aerobic metabolism. Only Bertuzzi et al. (2007) evaluated the energy contributions during real climbing and indicated that climbing predominantly involves the aerobic and anaerobic alactic systems.

Sport-specific exercise testing is a difficult task in climbing. There is a lack of research equipment specific to this discipline, and for that reason, standard biomechanical measurements (handgrip dynamometers) or physiological measurements were performed *via* VO_2max measurements on a treadmill/cycle ergometer or by comparing physiological responses during real climbing to the results of these standard tests (Sheel et al., 2003). However, traditional ergometer tests reflect general fitness level. They are not specific to climbing. Corresponding test results did not correlate with climbing performance (Michailov et al., 2015). Unlike maximal treadmill or cycle ergometer tests, the pattern of physiological responses during climbing tests do not allow to determine submaximal performance markers comparable to lactate or ventilatory thresholds. Therefore, the interpretation of data obtained in these tests is limited when used to establish relative intensities for training through climbing (Watts, 2004; Schöffl et al., 2006). This is most likely due to isometric muscle contractions and holding one's breath during climbing, as well as the fact that climbing test results depend on muscle strength, aerobic, and anaerobic metabolism (Watts et al., 2000; Michailov et al., 2017).

Exercise tests for climbers should reflect load characteristics, sport technique, and fatigue in climbing. However, testing should not completely mimic actual climbing because the intensity and duration should be assigned according to the ability the tests are intended to assess. Therefore, many researchers have focused on testing climbers' finger strength and endurance (MacLeod et al., 2007; Philippe et al., 2012; Baláš et al., 2016; Michailov et al., 2018; Fryer et al., 2021) using different test protocols and climbing-specific dynamometers, while expressing the intensity as a percentage of maximal voluntary contraction (MVC). These types of assessments distinguished climbing groups of different ability levels and appear more informative because they are likely to induce similar patterns of muscle fiber-type activation, metabolism, and fatigue compared to real climbing situations. Moreover, some authors have used a combination of different muscle endurance tests (continuous, intermittent, and all-out) in an attempt to assess climbers' aerobic or anaerobic capacity at peripheral levels (Baláš et al., 2016; Michailov et al., 2018). Most of the parameters for these endurance tests were highly reliable (ICC between 0.845 and 0.921) and valid for climbing performance (Michailov et al., 2018). Nonetheless, no energy system contribution has been assessed so far (anaerobic alactic, anaerobic lactic, and aerobic) during a laboratory test and using a validated device dedicated to climbers' physical fitness examination. Determination of the energy contribution during climbing-specific finger muscle endurance tests shall allow to identify how informative these tests are, with respect to local aerobic or anaerobic capacity assessment and relative energy contribution, compared to real climbing.

Therefore, the aim of this study was to evaluate distinct performance indicators and energy system contributions in 4 different finger flexor muscle exercise tests, performed using an apparatus developed for comprehensive assessment of physical fitness in climbers.

MATERIALS AND METHODS

Study Design

The test battery included (a) a maximal finger strength test followed by 3 different finger flexor muscle endurance tests, (b) an all-out test (30 s), (c) a continuous, and (d) an intermittent endurance test. Tests (b) to (d) were conducted in random order. The maximal finger strength assessment served to set the relative intensity of tests (c) and (d). Before, during, and after the muscle endurance tests, gas exchange data were collected. The tests were performed with the climber's preferred hand. Blood was drawn from the fingers of the opposite hand. Pre- and post-test blood lactate levels were measured. Energy contribution (anaerobic alactic, anaerobic lactic, and aerobic) was determined for each muscle endurance test. All tests were performed on 1 day at temperatures between 20 and 22°C, and the interval between tests was approximately 1 h. Participants were asked to avoid intense physical efforts in the 2 days before testing.

Participants

Thirteen healthy, experienced male climbers volunteered for this study. Their current climbing ability level ranged from intermediate to higher elite according to the grading comparative table of the International Rock Climbing Research Association (IRCRA) (Draper et al., 2015). The participants' current, mean climbing grade (French grading system) in the red-point style (highest difficulty of a route, which a climber can climb after the route has been previously rehearsed) was 8a + (range 7a–9a French/sport grade). To enable statistical analysis, these grades were converted using the metric IRCA scale (Draper et al., 2015) and then presented along with other detailed characteristics of the participants in **Table 1**. The criteria for inclusion in the study were: practicing sport (lead) climbing, possessing a minimum current climbing level of 7a (French/sport grade), being an active climber performing at least two climbing specific-training sessions per week, and no injury in the 6 months preceding the study. Seven of our participants combined sport climbing and bouldering, although they were training to manage harder outdoor sport climbing routes. The other 6 participants regularly practiced sport climbing and specialized in alpine ascents.

Anthropometry

The body height was measured to the nearest 0.1 cm with a stadiometer (Seca, Germany). Body mass and composition (method of bioelectrical impedance) were determined using the Jawon scale (Korea). Arm span was measured in a standing position with the arms abducted horizontally at the height of the shoulders. Arm, thigh, and calf circumferences were measured at the site of the largest circumference and with the muscles relaxed.

Apparatus, Testing Position, and Warm-Up

Finger strength and endurance tests were performed on the 3DSAC, which is an advanced climbing-specific apparatus developed for comprehensive performance evaluation in climbers, as described in detail by Michailov et al. (2018). 3DSAC is composed of: (a) a 3D force measuring module (measuring range ± 2 kN, comprehensive accuracy 0.5%, 12 bit accuracy of the analog-to-digital converter, 125 Hz sample rate), calibrated for a wooden 23-mm deep climbing hold; (b) real-time feedback guidance module enabling the participants to control the intensity and duration of muscle contractions and the rest intervals; (c) construction for adjusting the position of

TABLE 1 | Participants' characteristics.

Variables	Mean ± SD
Age	29.4 ± 7.88
BH (cm)	178.2 ± 4.9
BM (kg)	69.5 ± 7.6
BMI	21.8 ± 1.8
FAT (%)	12.6 ± 2.9
FM (kg)	8.8 ± 2.2
LBM (kg)	60.7 ± 7.1
AS (cm)	184.6 ± 5.9
Circumferences (cm)	
Arm	27.6 ± 3.2
Thigh	47.2 ± 7.0
Calf	33.4 ± 3.6
Climbing experience (years)	14.54 ± 5.50
Current red-point (IRCRA scale)	23.69 ± 3.92
Current on-sight (IRCRA scale)	20.85 ± 3.13
Current boulder grade (IRCRA scale)	23.56 ± 2.19

BH, body height; BM, body mass; BMI, body mass index; FM, fat mass; LBM, lean body mass; AS, arm span.

the climbing hold according to the participants' height and arm length; and (d) a software package allowing to create different test protocols and to precisely calculate mechanical parameters.

A familiarization session was held before the study began. The participants were instructed on how to perform the tests (goal of the test and related actions, body position, and grip) and then familiarized with the device as well as technique of performing the tests. During the familiarization session, body position was corrected by the test supervisors. After confirming proper test technique, the climber was allowed to perform the test. During the warm-up and all of the tests, the participants stood facing the 3DSAC, and they used an open finger grip position on the 23-mm hold, which was mounted on the force measuring module (Michailov et al., 2018). Their shoulders were flexed at a 180-degree angle, with their elbows fully extended. Maintaining the grip, the participants flexed their knees to load the hold with their body weight (**Figure 1**). During testing, the feet were on the floor. In order not to allow climbers with high levels of strength to hang with their feet off the ground, they wore a weight vest during the maximal strength and all-out tests.

The warm-up procedure was identical to the one used by Baláš et al. (2016) and Michailov et al. (2018): 5 min of stair walking and 2 sets of eight, 5-s muscle contractions on the 3DSAC, applying a force of 30% body mass, alternated by 5-s rest intervals.

Maximal Strength Test

The maximal strength tests included 3 maximal voluntary finger flexor contractions separated by 1-min rest intervals. The maximal strength was determined as the highest force value from the 3 trials. The participants, for whom maximal force (F_{max}) was more than their body mass, were wearing weight vests, which did not allow them to hang on the hold. F_{max} and F_{max} related to body mass ($relF_{max}$) were registered during the maximal strength test. The first muscle endurance test was performed 10 min after the maximal strength test.

FIGURE 1 | Climber's position during exercise test.

All–Out, Continuous, and Intermittent Tests

In the all-out test, climbers had to quickly develop maximal force and maintain the maximal effort for 30 s. In the all-out test, peak force (F_{peak}), average force (F_{avg}), and fatigue index (FI) were used. FI was calculated *via* the following equation:

$$FI = (F_{peak} - F_{end-of-test}) \div F_{peak} \times 100$$

During the continuous test, the participants had to develop a force corresponding to 60% of F_{max} and maintain the force in a target zone totaling ± 10% of the target force for as long as possible. In the intermittent test, the intensity and target zone were the same as in the continuous test. During the intermittent test, the participants alternated contraction and relaxation intervals of 8 and 2 s, respectively. The intermittent test was also performed until the climbers were not able to maintain force in the target zone. Both the continuous and intermittent tests were automatically stopped when the force dropped below the target zone for more than 1 s.

In the continuous and intermittent tests, time in the target zone (T_{tz}), force-time integral (FTI), and FTI related to body mass were analyzed. In the intermittent test, the number of muscle contractions was also considered.

Calculation of Aerobic, Lactic, and Alactic Energy Contribution

Before (5 min), during and after the exercise tests (10 min), oxygen uptake (VO_2), and respiratory exchange ratio (RER) were measured continuously (breath-by-breath method) using an ergospirometer (Cortex MetaLyzer, Germany). The device was calibrated before each test according to the manufacturer guidelines.

The blood samples were collected by pricking the finger at rest and in the 1st, 2nd, and 3rd min post-test for the determination of lactate concentration. Plasma lactate concentration was measured *via* enzymatic colorimetry using the Lactate PAP (bioMerieux, France). Assay sensitivity amounted to 0.07 mmol·L^{-1}. The assay was linear up to 10 mmol·L^{-1}. The absorbance was measured at 505 nm using the Thermo Scientific Evolution 201 UV/VIS spectrophotometer (United States). The post-exercise increase in lactate concentration (ΔLac) was also calculated.

The energy contribution for each test was determined as previously described (Beneke et al., 2002, 2004; Bertuzzi et al., 2007; Artioli et al., 2012). In brief, aerobic contribution (net) (VO_{2Ex}) was calculated from oxygen uptake above rest during the exercise test and the energy equivalent of O_2 being assumed from 19.6 to 21.1 kJ·L^{-1} (depending on RER). To estimate the anaerobic lactic contribution, the value of 1 mmol·L^{-1} ΔLac was considered equivalent to 3 mLO_2·kg^{-1}, e.g., 63 kJ·kg^{-1} (di Prampero and Ferretti, 1999). The contribution of the anaerobic alactic system was estimated using the fast component of excess post-exercise oxygen consumption (VO_{2EPOC}) (Beneke et al., 2004; Bertuzzi et al., 2007). Total energy contribution was calculated as the sum of the 3 energy systems. In addition, the contributions of these 3 systems were also expressed as percentages in relation to total energy contribution.

Statistical Analysis

All calculations were carried out using Microsoft Excel and the IBM Statistical Package for Social Sciences (SPSS) for Windows (Version 22, Chicago, IL). Data are reported as means and SDs. Differences between the types of energy contribution from the muscle endurance tests were analyzed through ANOVA. The *post hoc* analysis was performed using Bonferroni's test. Effect sizes were presented as partial eta squared ($\eta_p{}^2$). Pearson's correlation coefficients were calculated to estimate correlations between the mechanical parameters and climbing ability. Statistical significance was set at $p \leq 0.05$.

RESULTS

The average force in the all-out test was 404 ± 46 N and FI was 38.0 ± 14.4%. The time in the target zone for the intermittent test was 2.5-fold longer (p = 0.018) than in the continuous test. The relative force-time integral in the intermittent test was significantly (p = 0.049) higher than in the continuous test. There were significant correlations between climbing ability and $relF_{max}$ in the maximal strength test (r = 0.812, p = 0.001), $relF_{avg}$ in the all-out test (r = 0.816, p = 0.001), and relFTI in the continuous test (r = 0.719, p = 0.008) (**Table 2**).

The highest ΔLac was noted after the intermittent test (2.17 ± 1.14 mmol·L^{-1}), which was greater (p = 0.002) than that observed following the continuous test (0.89 ± 0.6 mmol·L^{-1}). After the continuous test, VO_{2EPOC} was lower than that post the all-out test (p = 0.02) and that following the intermittent test (p = 0.049). VO_{2Ex}during exercise was similar (p > 0.05) for the all-out and the continuous tests. In the intermittent test, VO_{2Ex} was considerably higher than during the all-out (p < 0.001) and continuous tests (p < 0.001) (**Table 3**).

The total energy requirement for the intermittent test was approximately 3.4 times that demanded for the continuous (p = 0.002), and twice as high as for the all-out test (p = 0.033), which required more energy than the continuous test (p = 0.003) (**Table 3**). The contribution of aerobic metabolism was 59.9 ± 12.0% in the intermittent test, 28.1 ± 15.6% in continuous exercise, and 19.4 ± 8.1% in the all-out test. The corresponding contributions of anaerobic alactic energy were 27.2 ± 10.0, 54.2 ± 18.3, and 62.4 ± 11.3% (all-out test), while relative anaerobic lactic energy was 12.9 ± 6.4, 17.7 ± 8.9, and 18.2 ± 9.9%, respectively (**Figure 2**). There were no significant differences (p = 0.296) between the tests in relative anaerobic lactic contributions. However, the relative aerobic energy contribution of the intermittent test was higher than in the continuous (p = 0.004) and all-out test (p < 0.001). The continuous and all-out tests did not differ with respect to aerobic energy (p = 0.108). The relative alactic energy contribution in the intermittent test was significantly smaller than in the continuous (p = 0.006) and all-out (p < 0.001) tests. The alactic energy contribution in the continuous and all-out tests did not differ (p = 0.136).

TABLE 2 | Results of exercise tests (mean ± SD for all climbers).

Variables	Result	Correlation with climbing
Maximal strength test		
F_{max} (N·kg^{-1})	8.57 ± 1.24	0.812 (p = 0.001)
30 s all-out test		
F_{peak} (N·kg^{-1})	7.73 ± 1.27	0.349 (p = 0. 243)
F_{avg} (N·kg^{-1})	5.81 ± 0.66	0.816 (p = 0.001)
FI (%)	38.00 ± 14.42	−0.266 (p = 0.404)
Intermittent test		
# Reps	23.62 ± 17.93	0.230 (p = 0.449)
T_{tz} (s)	151.31 ± 111.5	0.230 (p = 0.449)
FTI (N.s·kg^{-1})	735.44 ± 542.76	0.407 (p = 0.167)
Continuous test		
T_{tz} (s)	60.05 ± 53.30	0.195 (p = 0.544)
FTI (N.s·kg^{-1})	301.90 ± 75.19	0.719 (p = 0.008)

F_{max}, maximal force; F_{peak}, peak force; F_{avg}, average force; FI, fatigue index; T_{tz}, time in target zone; FTI, force-time integral; p-level of significance.

DISCUSSION

In rock climbing, the gravity force is countered by grip fixation and active hanging position using the upper limbs as a fix point comparable to a relative calm pendulum or with leg-support, ideally comparable to a horizontally attached uneven tripod. Consequently, climbing specific-grip performance imposes a trainable physical factor, mostly contributing to variance of climbing performance (Mermier et al., 2000; Baláš et al., 2012; Laffaye et al., 2016).

For the first time, a test battery combining 4 distinct tests was designed to identify grip performance indicators in terms of a standardized diagnostic tool. This was achieved by measuring F_{max} *via* the MVC test and the relating the 30-s all-out grip performance, 60% of F_{max} continuous performance until failure to sustain the 60% target, and 60% of F_{max} intermittent performance until failure to repeat the 60% target to F_{max}. This test battery combines objectively determined performance indicators, clearly defined by endpoints of a duration set as 30 s all-out or sustainability of a given level of performance within set limits of tolerance. Additionally, the test battery should mimic the pattern of overcoming gravity forces in rock climbing with an analysis of corresponding aspects of metabolic demands in elite climbers.

The present approach extends the previously described high correlation between F_{max} and climbing ability, identifying comparable explanations of variance for climbing performance, further explained by F_{avg} in the 30-s all-out test and

TABLE 3 | Total energy contribution and energy system contribution in particular tests (mean ± SD for all climbers).

Energy system contribution	All-out test	Intermittent test	Continuous test	*p*-value	($\eta_p{}^2$)
Total energy contribution					
($J \cdot kg^{-1}$)	499.4 ± 186.8	1057.6 ± 436.6	314.8 ± 108.6	0.002	0.655
Anaerobic lactic					
($J \cdot kg^{-1}$)	90.6 ± 45,9	136.4 ± 71.9	55.7 ± 37.5	0.007	0.397
ΔLac($mmol \cdot L^{-1}$)	1.44 ± 0.73	2.17 ± 1.14	0.89 ± 0.6	0.007	0.399
Anaerobic alactic					
($J \cdot kg^{-1}$)	311.7 ± 131.8	287.7 ± 95.1	170.6 ± 109.5	0.007	0.466
VO_{2EPOC}($mL \cdot kg^{-1}$)	15.14 ± 6.37	14.02 ± 4.66	8.37 ± 5.53	0.007	0.462
Aerobic					
($J \cdot kg^{-1}$)	97.1 ± 55.4	633.5 ± 390.3	88.5 ± 43.9	$p < 0.001$	0.657
VO_{2Ex}($mL \cdot kg^{-1}$)	4.80 ± 2.81	30.89 ± 18.51	4.33 ± 2.18	$p < 0.001$	0.669

ΔLac–difference between peak blood lactate and lactate at rest, VO_{2EPOC}–oxygen uptake (net) during fast component of excess post-exercise oxygen consumption, VO_{2Ex}-oxygen uptake (net) during exercise.

force-time integral in the continuous 60% F_{max} test. This strong interrelationship was neither seen in net contraction time (during both continuous and intermittent tests) nor in the overall duration or force-time integral of the intermittent test. At first glance, the latter finding appears surprising, as the intermittent 60% F_{max} test also measures the sustainability of a given F_{max} fraction. The intended contraction (8 s) to relaxation (2 s) ratio of 4:1 increased the sustainability regarding the 60% of F_{max} intermittent performance test to the overall duration (total contraction plus relaxation time) of ~234 s. The real net contraction time (the time when the force was applied below the target zone added to the time when the force was within the target zone) detected *via* the force time curve of every single contraction was 171 s shifting the contraction (7.3 s) to relaxation (2.7 s) ratio toward relaxation by ~32%. The overall duration of 234 s reflects an extremely long-lasting red-point or very short on-sight, first-try sport climbing conditions. In hindsight, this test-specific pattern of intensity and duration appeared potentially suboptimal with respect to the tested climbers. Six of them were alpinists who primarily focused on practicing the on-sight type, with their first attempt in sport climbing usually lasting longer than 4 min. The remaining 7 participants combined bouldering with sport climbing lasting between 30 and 50 s and longer than 4 min, respectively. Thus, there is a fair possibility that the settings of the intermittent test resulted in a sustainability profile that was rather unspecific with respect to the specialization of the tested athletes. The great variability in the intermittent test performance may serve as a support for the idea of limited specification of the 60% intermittent test, with special respect to performance limits of the climbing events preferred by the tested athletes.

The average force of the all-out test was ~75% F_{peak}, combined with a FI of ~40%. This fits well into the pattern of performance and fatigue seen in the Wingate Anaerobic Test (WAnT) if the participant remains seated on the ergometer saddle throughout the test (Inbar et al., 1996). Remaining seated throughout the WAnT, active stabilization of the body on the ergometer during test using the arm and trunk muscles as counterbalance and the requirement for an effective transfer of leg-power onto the pedals, makes the WAnT a highly anaerobic whole-body exercise. The relative anaerobic metabolic cost of the WAnT reflects ~80% of the total metabolic energy shared as ~50% anaerobic glycolytic and ~30% anaerobic alactic energy (Beneke et al., 2002). In a typical WAnT, failure to produce 60% of peak power comes along with ΔLac in the size of ~14 $mmol \cdot L^{-1}$. Under the assumption that the distribution space of lactate reflects approximately 45% of the body mass (di Prampero, 1981; Mader and Heck, 1986; Beneke, 2003) and muscle mass was ~40% of the body mass, the latter lactate response is equivalent to an increase of ~10.5 $mmol \cdot kg^{-1}$ body mass or 26 $mmol \cdot kg^{-1}$ wet muscle in 30 s. The increase in muscle lactate substantially limits glycolytic rate, as demonstrated in all-out cycling tests lasting from 15 to 60 s. The corresponding decrease in PCr was ~20 $mmol \cdot kg^{-1}$ wet muscle, combined with an average net VO_2 from ~35 to 40 $mL \cdot kg^{-1}$ wet muscle over 30 s (Beneke et al., 2002, 2005, 2007; Wittekind et al., 2011, 2012; Leithäuser et al., 2015).

Also, the present 30-s all-out test has an overall relative anaerobic energy demand of ~80% (**Figure 2**). However, with ~18% anaerobic glycolytic and ~62% anaerobic alactic energy

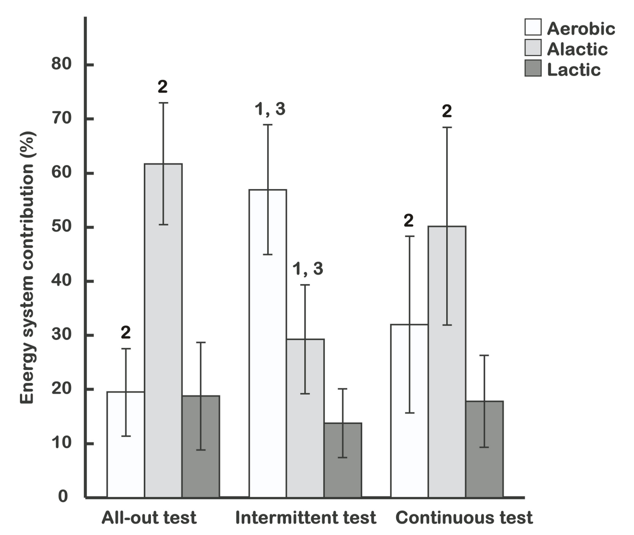

FIGURE 2 | Aerobic, alactic, and lactic relative energy contributions (mean ± SD) in 3 exercise tests proposed for climbers. 2—when significantly different ($p < 0.05$) from the intermittent test; 1, 3—when significantly different ($p < 0.05$) from the all-out and continuous test, respectively.

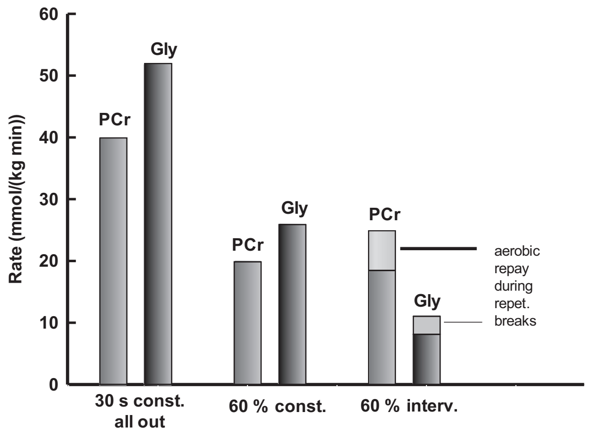

FIGURE 3 | Anaerobic [phosphocreatine (PCr) and glycolytic (Gly)] system contributions of dominantly stressed muscles in exercise tests.

(**Table 2**), the distribution between sources of anaerobic energy is pretty much the opposite of that seen in the WAnT. In highly trained athletes, isometric contractions of ~50% F_{max} led to complete vascular occlusion (Barnes, 1980). Therefore, the above differences, between energetics of WAnT and present in the 30-s all-out test, likely reflect the substantially smaller mass of the muscle dominantly stressed during isometric force development and vascular occlusion in the single-handed hanging task, as supported by our metabolic results. With reference to the above-assumptions concerning lactate water space and muscle mass, ΔLac of 1.44 mmol·L^{-1} measured as the maximum blood lactate increases shortly after test termination, and reflects 1.1 mmol·kg^{-1} body mass or 2.8 mmol·kg^{-1} muscle mass in 30 s. If this net lactate level results mainly from an increased glycolytic rate in performance limiting muscles with corresponding limited glycolytic rate due to a ~26 mmol·kg^{-1} increase in muscle lactate, then, ~11% of the total muscle mass appears to be the dominantly stressed muscle fiber mass in this specific test. The anaerobic alactic energy equals a decrease in PCr of ~4.7 mmol·kg^{-1} body mass or ~11.8 mmol·kg^{-1} total muscle mass. Furthermore, ~2.2 mmol·kg^{-1}total muscle mass would reflect a performance limiting decrease of ~20 mmol·kg^{-1} if the dominantly stressed muscle is ~11% of the total muscle mass. This is well within the range of limits for the dynamics of cellular ATP breakdown and re-phosphorylation rates of mixed skeletal muscle at maximum isometric contraction measured using magnetic resonance spectroscopy or histochemical methods (Francescato et al., 2008; Barclay, 2017). The corresponding decrease in 89% of the assisting tissue was ~10.7 mmol·kg^{-1} during 30 s (**Figure 3**). The net VO_2 was lower than in tests with high frequent contraction and relaxation cycles. Due to vascular occlusion in the isometrically stressed dominant muscles, the net VO_2 of 4.8 mL·kg^{-1} body mass is likely attributed to the aerobic metabolism of the assisting tissue, equivalent to ~13.5 mL·kg^{-1} assisting muscle mass.

A FI of ~40% in the 30-s all-out test and failure to produce 60% of F_{max} at test termination of the two 60% tests, respectively, suggest similar levels of fatigue concerning the performance-limiting muscle mass. The 60% F_{max} continuous test lasted ~60 s. It generated a ΔLac of 0.89 mmol·L^{-1} quickly released from the dominantly stressed muscles after test termination *via* maximized reperfusion and quick distribution to blood and body water. This is equivalent to 0.7 mmol·kg^{-1} body mass or 1.7 mmol·kg^{-1} muscle mass. Under the assumption that this reflects a ~26 mmol·kg^{-1} performance-limiting muscle lactate level, the dominantly stressed fiber volume totals ~7% of the total muscle mass. This is ~60% of the all-out work value, further supported by Henneman's size principle (Henneman, 1957). The anaerobic alactic energy of the constant 60% F_{max} test equaled a decrease in PCr of 2.6 mmol·kg^{-1} body mass or 6.4 mmol·kg^{-1} total muscle mass. Consequently, ~1.4 mmol·kg^{-1} total muscle mass can be attributed to a performance limiting PCr decrease of ~20 mmol·kg^{-1} dominantly stressed 7% muscle mass. This leaves a moderate decrease of ~5.4 mmol·kg^{-1} in the remaining 93% assisting muscle mass (**Figure 3**). The latter goes hand in hand with a net VO_2 of ~11.6 mL·kg^{-1} assisting muscle. Thus, the PCr and VO_2 seem to indicate that the 60% intensity reduced the strain on assisting muscles by almost 60% compared to the all-out condition, resulting in shares of ~18% glycolytic, ~54% anaerobic alactic, and ~28% aerobic energy, which appear slightly more anaerobic than the results obtained for tests of comparable duration and implementing large muscle masses (**Figure 2**).

A contraction to relaxation ratio of 2.7 increased the sustainability of the 60% F_{max} intermittent performance test to an overall duration of ~234 s, with a ~171 s net contraction time. Alternation of contraction and relaxation enables intermittent perfusion of the dominantly stressed muscles, oxygen supply, aerobic pyruvate/lactate utilization, and re-phosphorylation of high-energy phosphates. The overall net VO_2 was ~30.9 mL·kg^{-1} body mass in ~234 s. The 60% of F_{max} continuous performance test generated a net VO_2 of ~11.6 mL·kg^{-1} assisting muscle, which equals ~33.1 mL·kg^{-1} of the assisting muscle or 12.3 mL·kg^{-1} of body mass during the contraction periods of the intermittent test. The remaining 18.6 mL·kg^{-1} of body mass is used during the recovery intervals. Moreover, 1 mL of oxygen utilizes 0.015 mmol of pyruvate/lactate. This equals a pyruvate/lactate consumption of ~0.28 mmol·kg^{-1} body mass during the recovery phases throughout the test. Aerobic pyruvate/lactate utilization is regulated by pyruvate dehydrogenase (PDH). Activators of the PDH are pyruvate, CoA, and NAD^+, allosteric cofactors including Mg^{2+}, Ca^{2+}, and Mn^{2+} (Spriet and Heigenhauser, 2002; Strumilo, 2005). Consequently, the aerobic pyruvate/lactate consumption can be seen as a re-phosphorylation source of high-energy phosphates in the intermittently re-perfused dominantly stressed muscles. Additional net lactate release accumulated to 2.17 mmol·L^{-1} or ~1.6 mmol·kg^{-1} of body mass, increasing the time until a critically performance limiting intramuscular lactate concentration had been reached in the dominantly stressed muscle. The fast component of post-test VO_2 corresponds to ~4.3 mmol·kg^{-1} body mass or ~10.8 mmol·kg^{-1} muscle mass, of which 1.4 mmol·kg^{-1} do reflect the decrease of ~20 mmol·kg^{-1} in the 7% dominantly stressed muscles and the remaining 9.4 mmol·kg^{-1} of muscle mass equaled a decrease in high-energy phosphates of ~10.1 mmol·kg^{-1} assisting tissue at test termination (**Figure 4**). These decreases in high-energy phosphates came on top of ~14.6 mmol·kg^{-1} muscle mass PCr-repay generated *via* aerobic use of 18.6 mmol·kg^{-1} body mass oxygen and ~0.28 mmol·kg^{-1} body mass pyruvate/lactate during repetitive recovery intervals throughout the test. The 14.6 mmol·kg^{-1} total muscle mass PCr-repay was split according to the dominantly stressed and assisting muscles. During the initial 7.3 s of isometric contraction at 60% F_{max}, the estimated dynamic decrease in PCr was ~20% of the baseline level (Francescato et al., 2008; Barclay, 2017), and partly re-phosphorylated during the short relaxation periods without vascular occlusion (**Figure 4**). In the dominantly stressed 7% of muscle mass, this demand accumulated to ~73 mmol·kg^{-1}, combined with a PCr -payback of ~53 mmol·kg^{-1} muscle, which leads to a PCr decrease of ~20 mmol·kg^{-1} muscle mass equivalent to ~0.6 mmol·kg^{-1} of body mass. The accumulated PCr demand totaling 93% of assisting muscle mass was ~23 mmol·kg^{-1} muscle, partly compensated by a PCr payback of ~12 mmol·kg^{-1}, which further led to a decrease in PCr equaling ~10 mmol·kg^{-1} of assisting muscle mass or ~3.7 mmol·kg^{-1} body mass, leaving ~4.3 mmol·kg^{-1} body mass for post-test PCr replenishment.

Considering aerobic pyruvate/lactate utilization and aerobic re-phosporylation during the relaxation phases of the intermittent test provides a modified image as compared with the shares of ~13% glycolytic, ~27% anaerobic alactic, and ~60% aerobic energy as shown in **Figure 2**. The net lactate utilization of 0.28 mmol·kg^{-1} of body mass during subsequent recovery phases of the intermittent test recovery led to an underestimation of the glycolytic energy during accumulated contraction phases by ~18 J or ~13%, resulting in an overall underestimation of the total energy demand by ~2%. Aerobic utilization of 0.28 mmol·kg^{-1} body mass lactate requires an oxygen uptake of ~18.7 mL·kg^{-1}, equivalent to ~390 J·kg^{-1},

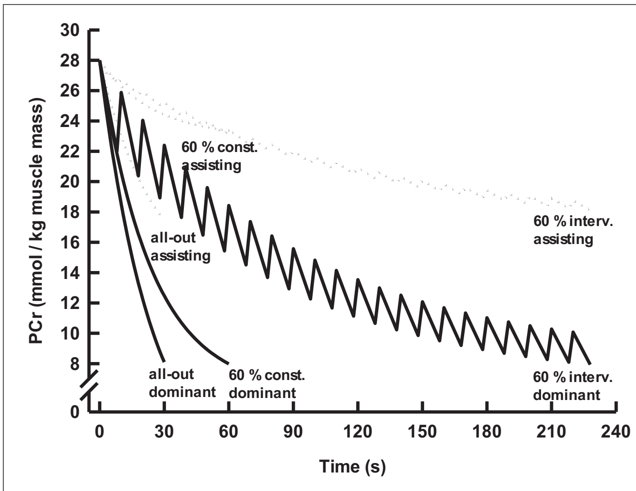

FIGURE 4 | Phosphocreatine decrease in the dominantly stressed and assisting muscles during the muscle endurance tests.

which is in the same size as ~99 J·kg^{-1} of body mass for an accumulated recovery of ~53 mmol·kg^{-1} PCr of the dominantly stressed muscles, plus ~300 J·kg^{-1} used for ~12 mmol·kg^{-1} PCr payback of the assisting muscles. The latter process does not affect the overall shares of aerobic and anaerobic alactic energy. However, it allows to indicate that ~63% of aerobic energy serves the recovery of high-energy phosphates during repetitive relaxation phases. If this fraction offers additional diagnostic value within the context of combined constant and standardized intermittent loads, then performance testing remains open for future investigation.

The combined analysis of performance and metabolic features of the present test battery, including the measurement of F_{max} *via* the MVC test and the relating 30-s all-out grip performance, 60% of F_{max} continuous performance until failure to sustain the 60% target, and 60% of F_{max} intermittent performance until failure to repeat the 60% target to F_{max}, extended the well-known interrelationship between climbing performance and F_{max} through similar correlations between climbing performance and the 30-s all-out isometric F_{avg} and isometric FTI at 60% F_{max}. Therefore, not only maximized grip force as a performance determinant in climbing but also all-out isometric contractions of a given duration or the ability to sustain a given percentage of F_{max} are equally decisive physical performance indicators. Although similar with respect to explaining the variance of climbing performance, the latter 3 tests evaluate different physiological performance limits. F_{max} allows to identify the ability of synchronized activation of relevant motor units, and thus, metabolic rate in terms of maximal anaerobic power. The observation of no interrelation between climbing performance and F_{peak} for the 30-s all-out test, which was lower than F_{max}, seems to indicate teleoanticipation and therefore, a psycho-physiological limitation of maximized activation and synchronization of motor units, as well as utilization of maximum anaerobic power at this test modality. This limitation comes with the benefit of evidence that not only F_{max} or maximal anaerobic power, but also anaerobic capacity determine climbing performance. This was indicated by the strong correlations between climbing performance and the muscles' ability to sustain submaximal anaerobic metabolic rates during all-out or submaximal, constant-intensity isometric contractions that limit blood flow or produce complete vascular occlusion. The intermittent test provides additional information on aerobic energy used for the recovery of high-energy phosphates during repetitive relaxation phases, which seems to reflect the dominant fraction of aerobic energy of this specific test modality. However, neither the latter nor any other physical or metabolic performance indicators of this specific test showed obvious links to climbing performance.

PRACTICAL IMPLICATIONS

The test battery used in this study provides comprehensive assessment of both physical qualities (i.e., strength and muscle endurance) and physiological functions (i.e., local muscle aerobic and anaerobic capacity) among rock climbers. Moreover, the present test combination can be considered a new approach in functional diagnostics that can be applied in many other sports, especially in those where peripheral factors are of great importance.

The maximal force measured *via* the MVC tests, and also F_{avg} as well as FTI determined using, for example, the isometric 30-s all-out test or constant isometric contractions at 60% of F_{max}, substantially explain the variance of climbing performance. Whether F_{max} from MVC test or F_{avg} from all-out tests with different durations is preferable, remains open for further analysis. F_{max} is likely the most decisive physical performance indicator in sport climbing. However, the specifics of lead climbing and bouldering with multiple subsequent contractions within 30 s and 10 min may support the idea that F_{avg} of the 30-s all-out test might provide the most relevant and economical testing approach. It is recommended that only F_{avg} can be analyzed from all-out isometric contraction tests because it appears likely that teleoanticipation will prevent achieving F_{max}. Although FTI at 60% of F_{max} may be equally useful, in particular for longer lasting events such as lead climbing, it appears less economical as standardization to a given intensity requires additional testing of F_{max}. However, this combined testing approach offers the possibility to directly determine anaerobic power plus anaerobic capacity. The intermittent test parameters may not correlate with climbing performance but the present results indicate that this test allows to evaluate aerobic capacity of the finger flexor muscles, which is among the abilities that should be well-developed in climbers.

LIMITATION OF THE STUDY

A limitation of the study is that our inclusion criteria restricted the pool of potential participants with sufficient climbing experience required to take part in our study. The resulting small number of included climbers requires caution when generalizing the results of the study with respect to sporting level of the climbers and specific technical aspects of the testing devices used.

CONCLUSION

The first analysis of performance predictors and metabolic profiles of a test battery combining the MVC test, 30-s all-out grip performance, and 60% of F_{max} continuous and intermittent grip performance until failure indicated that: (a) not only maximized grip force as performance determinant in climbing, but also, all-out isometric contractions of a given duration or the ability to sustain a given percentage of F_{max} are equally decisive physical performance indicators of climbing performance; (b) F_{max}, the ability of synchronized activation of relevant motor units and thus, metabolic rate in terms of maximal anaerobic power should be tested *via* single-contraction MVC tests; (c) compared to F_{max}, the F_{peak} measured during all-out tests of a 30-s duration is reduced by teleoanticipation; (d) all-out F_{avg} and FTI of constant isometric contraction at 60%F_{max} are functional measures of anaerobic capacity; (e) aerobic energy demand of the present version of an intermittent 60% F_{max} sustainability test is dominantly aerobic re-phosphorylation of high-energy phosphates during repetitive intervals, but the corresponding FTI was not decisive for climbing performance.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Bioethics Committee for Clinical Research at the Regional Medical Chamber in Kraków (opinion No. 16/KBL/OIL/2013). The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

MM and MLM designed the research, collected, analyzed, interpreted the data, drafted, edited, and revised the manuscript. MW, JS, RR, and ZS collected the data. RB interpreted the data, edited, and revised the manuscript. All authors contributed to the article and approved the submitted version.

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MINI REVIEW
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Tests and Procedures for Measuring Endurance, Strength, and Power in Climbing—A Mini-Review

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The interest in climbing is rapidly growing among professional and recreational athletes and will for the first time be included in the 2021 Tokyo Olympics. The sport has also gained increased scientific attention in the past decades. Still, recommendations for testing procedures to predict climbing performance and measure training effects are limited. Therefore, the aim of this mini-review is to provide an overview of the climbing-specific tests, procedures and outcomes used to examine climbing performance. The available literature presents a variety of tests and procedures. While the reliability of some tests has been examined, measures of validity are scarce, especially for climbing-specific endurance tests. Moreover, considering the possible combinations of climbing performance levels, disciplines, and tests, substantial gaps in the literature exist. Vague descriptions of the participants in many studies (e.g., not specifying preferred discipline, performance level, experience, and regular climbing and training volume) further limit the current knowledge and challenge comparisons across studies. Regarding contraction types, dynamic strength- and power-tests are underrepresented in the literature compared to isometric tests. Studies exploring and reporting the validity and reliability of climbing-specific tests are warranted, and researchers should strive to provide a detailed description of the study populations in future research.

Keywords: reliability, testing, performance, validity, fitness

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INTRODUCTION

In the 2021 Tokyo Olympics, climbing included three disciplines (speed-, lead-, and boulder climbing). Bouldering is performed on low walls (<6 m) with few, difficult, and often highly explosive moves (White and Olsen, 2010), whereas lead climbing is performed on higher walls (10–30 m) and consists of 20 to 50 moves with repeated sub-maximal force generation (Stien et al., 2021a). Speed climbing is performed on a slightly overhanging 15 m wall with a standardized route (Levernier et al., 2020). Success in climbing requires psychological, technical, and physical components (Vigouroux and Quaine, 2006; Baláš et al., 2012; Philippe et al., 2012). Among the physiological requirements, coaches and researchers highlight upper-body strength, power, and endurance as primary factors underpinning performance (MacLeod et al., 2007; Draper et al., 2011; Baláš et al., 2012). Despite noteworthy differences (Fanchini et al., 2013; Ozimek et al., 2017; Stien et al., 2019; Levernier et al., 2020), the three disciplines likely require partly overlapping requirements (Medernach et al., 2016). However, the tests and procedures used to measure these skills vary. Therefore, this mini-review aims to provide an overview of the climbing-specific tests, procedures and outcomes used to assess climbing performance and training effects.

METHODS

A literature search was conducted, including the search terms "Climbing," "Test," "Assessment," "Endurance," "Strength," "Force," "Intermittent," "Forearm" and "Finger." Twenty-five relevant studies including climbers and describing at least one experimental testing procedure used to assess the physical characteristics of the study population were included in this mini-review. Please see **Supplementary Materials 1**, **2** for a more detailed description of the search strategy and screening process.

CLIMBING-SPECIFIC ENDURANCE TESTS

Climbing is characterized by intermittent contractions of the finger flexors. This leads to oxidative and non-oxidative metabolic demands which have been associated with climbing performance (Fryer et al., 2018; Michailov et al., 2018; Giles et al., 2021). The most common endurance tests used to examine these capacities include intermittent or sustained contractions of the finger flexors using climbing-holds (Philippe et al., 2012; Fryer et al., 2015; Michailov et al., 2018; Stien et al., 2019) or handheld dynamometers (Mermier, 2000; Limonta et al., 2015). In addition to finger-specific tasks, number of pull-ups using different holds (Vigouroux et al., 2018), and trunk muscle tests (Saeterbakken et al., 2018; Draper et al., 2021) have been used to examine climbing-related endurance. Recently, testing procedures mimicking climbing have been examined, including motorized climbing ergometers (treadwalls), bouldering, campus board, and lead climbing (Medernach et al., 2015b; Hermans et al., 2017; Baláš et al., 2021; Stien et al., 2021b). Additionally, oxygen-uptake and -saturation have recently been measured as local aerobic capacity of the finger flexors (Baláš et al., 2021). Finally, the critical-force model has recently been introduced to assess the break point of isometric finger flexor work and time to exhaustion (Giles et al., 2021).

Isometric Sustained Tests

The most frequently applied sustained endurance tests include the bent-arm hang test, finger hang (or dead-hang), and handgrip dynamometers using 40–80% of maximal voluntary contraction (MVC). Of note, only three studies have reported the intraclass correlations (ICC) and coefficients of variation (CV) of endurance tests (Bergua et al., 2018; Fryer et al., 2018; Draper et al., 2021). The reported ICCs and CVs have ranged from 0.881–1.0 and 0.5–18%, likely depending on the climbers' performance level. Bent-arm hang measures time to fatigue hanging from a gym bar with a 90° elbow flexion while keeping the chin above the bar for as long as possible. During the finger hang test, however, the elbows are fully extended, and hold depth varies. Typically, elite climbers have used 10 mm deep rungs, whereas 14–30 mm rungs have been used for intermediate and advanced climbers. Finally, different grip positions used in climbing (slope, pinch, half- and full-crimp) have been examined in the finger hang test with the half crimp being the most frequently used grip (Baláš et al., 2012; Medernach et al., 2015b).

Intermittent Tests

In the intermittent endurance tests, the arms and/or finger flexors have been examined using handheld or custom-built dynamometers with integrated or connected force cells. The work time has varied from 5 to 10 s with relaxation times between 2 and 5 s, whereas the force threshold has ranged between 40 and 80% of MVC (Vigouroux and Quaine, 2006; MacLeod et al., 2007; Philippe et al., 2012; Michailov et al., 2018; Giles et al., 2021; Rokowski et al., 2021). Furthermore, the testing procedures include uni- and bilateral contraction in addition to extended (180°) (Medernach et al., 2015b) and flexed (90°) elbows (Vigouroux and Quaine, 2006). Of note, both climbing-specific holds with different depths (20–30 mm) and less climbing-specific handheld dynamometers have been used. The only ICC reported was 0.887 using a 23 mm-deep hold with an 8:2 work relaxation ratio using 60% of MVC among advanced climbers (Michailov et al., 2018).

Climbing and Other Tests

The most specific endurance tests in climbing are climbing to failure tests. Since the route is difficult to standardize (hold size, steepness, distance between holds), re-producible settings have been used. For example, Medernach et al. (2015b) used a 4.1 m high wall with different sized rungs (20–45mm) where the climbers had to maintain a position (4–10 s) before progressing to the next hold. More recently, climbing to failure using a treadwall was introduced and proved suitable for assessing climbing-specific endurance (Baláš et al., 2021). In addition, Stien et al. (2021b) used moves to failure on an overhanging campus board (13 cm separating the 20 mm deep rungs). Importantly, the campus board test only targets the fingers and pulling apparatus, and not the whole body (Stien et al., 2021b). Finally, number of pull-ups has been used as a measure of upper-body endurance and/or strength capacity using 10–80 mm deep holds. Depending on the performance level, decreasing hold depths may target the strength capacity more than deeper holds (Vigouroux et al., 2018).

CLIMBING-SPECIFIC STRENGTH AND POWER TESTS

The current consensus states that maximal and explosive strength in the fingers and upper-body are crucial factors for climbing performance (Horst, 2016; Sanchez et al., 2019; Saul et al., 2019). However, there is no agreement on how strength in the fingers and upper-body should be assessed. The applied methods vary in hold types, contraction form, body positioning, measuring techniques [e.g., time periods for calculating rate of force development (RFD)], execution (e.g., verbal instructions and duration), and joint angle and number of included joints.

Dynamometer Tests

Finger strength has been assessed using handheld dynamometers (Baláš et al., 2012; Ozimek et al., 2016). Despite providing a simple and accessible testing method, handheld dynamometer measurements may not reflect climbing performance (Ozimek et al., 2016; Marcolin et al., 2020). Still, handheld dynamometers have been reliable (Baláš et al., 2012; Medernach et al., 2015a), and able to discriminate between climbers and non-climbers (Quaine et al., 2003; Macdonald and Callender, 2011; Limonta et al., 2015; Assmann et al., 2020). Recently, tests that closely mimic the hold types and arm positions in climbing have been implemented (Levernier and Laffaye, 2019; Baláš et al., 2021; Rokowski et al., 2021; Stien et al., 2021a). Using climbing-specific test set-ups rather than handheld dynamometers could be especially important when assessing training effects and comparing different performance levels.

Isolated Forearm Tests

Typically, finger strength tests include fixating the elbow to potentially exclude force production from the arm- and back muscles (Grant et al., 1996; MacLeod et al., 2007; Marcolin et al., 2020; Stien et al., 2021a). This is usually achieved by positioning the elbow against a surface to restrict any movement, whereas the distance from the surface to the hold is adjusted to allow the finger flexors to exert force in the desired position. The fingers are typically positioned in a half-crimp grip on a climbing hold, likely providing a more sport-specific condition compared to handheld dynamometers (Ozimek et al., 2016; Marcolin et al., 2020). This and similar set-ups have displayed (1) ability to discriminate between performance levels (Grant et al., 1996; MacLeod et al., 2007), and (2) changes in finger strength following a training period (Stien et al., 2021a). Researchers have suggested that climbing-specific maximal strength and RFD tests performed standing on the ground with fixed elbows produced more reliable results (ICC = 0.94) compared to performing the tests with fully extended elbows (ICC = 0.88) (Michailov et al., 2018). However, the results following the extended elbow tests were more strongly associated with climbing performance.

Isometric Pulling Tests

Recently, researchers have explored tests measuring the force generated by the upper-body pulling apparatus (arms- and back-muscles) (Levernier and Laffaye, 2019; Stien et al., 2021b,c). Such test set-ups might provide a higher climbing-specificity, but at the expense of reliability as the inclusion of more joints could entail a larger variation in results (Stien et al., 2021c). Using an unconstrained, 90° elbow angle, Levernier and Laffaye (2019) demonstrated that maximal strength (CV = 2.9–10.0%) and RFD (CV = 7.8–28.3%) assessed standing and with an open-hand grip were reliable and able to discriminate between novice, skilled, and international climbers. Moreover, the authors assessed different absolute [milliseconds (ms) from the onset of force] and relative calculations of RFD [percentage from the onset (0%) to the peak force output (100%)]. The study concluded that RFD calculated using the first 200 ms (CV = 7.8–16.1%) and 95% of the force curve (CV = 12.6–28.4%) were the most reliable and discriminatory calculations of RFD. In contrast to Levernier and Laffaye (2019) and Stien et al. (2021c) included a bilateral hanging test with a half-crimp grip on a 23 mm rung with a 90° elbow angle. In agreement with Levernier and Laffaye (2019), RFD calculated using longer time scales (≥75% from the onset) were the most reliable and discriminatory measurements and the authors demonstrated CV-values between 10.0 and 31.3% for RFD among advanced-to-elite climbers. Importantly, due to a lack of differences between intermediate and advanced climbers and the high CV values observed for these groups (CV = 20.0–31.3%), Stien et al. (2021c) speculated that the possible difference in RFD was diminished by the very demanding nature of the test. Finally, the findings by Levernier and Laffaye (2019) and Stien et al. (2021c) agree, suggesting that maximal strength could be a more reliable measure than RFD.

Isometric Dead-Hang Strength Tests

In two studies, López-Rivera and González-Badillo (2012, 2019) measured maximal finger-strength as the highest extra-weight the participants could maintain for five seconds on a 15 mm hold with extended elbows. López-Rivera and González-Badillo (2012) reported that the test was sufficiently reliable, but they were unable to detect intra- or inter-group differences following eight weeks of fingerboard training. Later, the authors demonstrated significant pre-to-post changes in maximal strength, but no between-groups differences (López-Rivera and González-Badillo, 2019). A high reliability was also reported by Torr et al. (2020) who examined unilateral maximal hangs from a 20 mm rung while using an external unloading of the body mass. The total load (body mass – unloading) that participants could maintain for five seconds displayed excellent reliability between laboratory visits (ICC = 0.91–0.98) and a moderate correlation to climbing performance level (r = 0.42–0.50). Albeit unable to provide additional data (e.g., RFD), the test proposed by Torr et al. (2020) presents a sensitive and low-cost method that can be used to monitor intervention effects or to prescribe training loads.

Dynamic Strength and Power Tests

Finally, dynamic tests focusing more on the upper-body strength than the fingers have been applied (Draper et al., 2011; Laffaye et al., 2014; Ozimek et al., 2016; Levernier et al., 2020; Stien et al., 2021b). For example, Levernier et al. (2020) measured force and velocity during dynamic pull-ups on a gym bar with external loads (0–70% of body mass) and concluded that the test was reliable (CV = 1.0–6.6%) and could differentiate between disciplines in higher-elite athletes. Examining 1-RM pull-up on a gym bar, Ozimek et al. (2016) also demonstrated acceptable reliability (CV = 7.7%), but noted that the test may lack specificity to climbing. Furthermore, Laffaye et al. (2014) analyzed power output during an arm-jump test from deep jug holds. This test displayed high reliability (CV = 4.89%) and could differentiate between intermediate-to-elite climbers. Furthermore, Stien et al. (2021b) measured maximal campus board reach. Albeit able to detect within- and between-groups differences, the authors did not report the reliability of the test. In comparison, Draper et al. (2011) used a power-slap test from large jug holds and measured the maximal reach. This test was reliable (ICC = 0.95–0.98) and related to climbing ability ($r = 0.69–0.73$).

DISCUSSION

Climbing performance is measured using graded boulders or routes which categorize the performance levels (Draper et al., 2016). However, concurrent improvements in climbing-tests and -performance are poorly described in the literature (Hermans et al., 2017), whereas the association between climbing-specific tests and climbing performance has been examined (Baláš et al., 2012; Fryer et al., 2015; Laffaye et al., 2016). Several climbing-specific tests and procedures have not been validated and reliability measurements of the tests are rarely reported. Furthermore, the current findings indicate that reliability data are more frequently reported than validity data. This presents a gap in the knowledge which should be addressed in future research. In addition, and despite the differences in climbing-style and physiological requirements (Fanchini et al., 2013; Fryer et al., 2017; Stien et al., 2019), specific tests for individual disciplines do not exist.

The available literature is challenged by the vast variety of applied endurance-, strength-, and power tests (Ozimek et al., 2016; Michailov et al., 2018; Levernier and Laffaye, 2019; Torr et al., 2020; Stien et al., 2021c). For example, this review revealed 13 trials that had implemented the intermittent forearm endurance test, and these provided nine different combinations of work-to-rest ratios and force thresholds (**Table 1**). Moreover, the study populations in various investigations range from non-climbers to higher-elite athletes. Hence, a very small portion of the possible climbers-and-tests combinations have been thoroughly examined. It is paramount that researchers strive to provide detailed descriptions of the included population and validity, reliability, and sensitivity measures of the tests applied in future research.

Although researchers may argue that some test set-ups are superior to others regarding reliability or specificity to climbing, the current available evidence could be too fragmented to support either position. Moreover, it is possible that choosing to optimize conditions for either specificity or validity will come at the cost of the other. For example, complex tests may provide conditions that mimic climbing more closely but could also increase the difficulty of reproducing similar results. Importantly, the complex nature of climbing renders it challenging to argue which test set-up is more climbing-specific. More descriptive studies such as biomechanical- (Cha et al., 2015), motion- (White and Olsen, 2010), and workload-analyses (Michailov, 2014) in climbing are needed to provide a basis for test recommendations.

Currently, reliability data has only been reported for a handful of protocols. Isometric endurance tests with sustained force generation (e.g., finger-hang or bent-arm hang) may be easy to conduct, but do not mimic the locomotion in climbing. Isometric intermittent tests to failure have a greater ecological validity, but there is no consensus in work-relaxation ratio, force threshold, hold size, or grip position. In addition to the varying work-to-rest ratios and force thresholds, different hold depths (10–30 mm), hold types (jug, gym bar), and grip positions (half-crimp or open-hand) have been used. The more promising tests are climbing to fatigue tests using reproducible routes or standardized walls (Medernach et al., 2015b; Baláš et al., 2021; Stien et al., 2021b). However, these tests suffer from limited research and the findings may not be generalizable to other disciplines or performance levels.

Based on the previously reported reliability data, one could speculate that hold size greatly influences the reliability of a test, regardless of task complexity and contraction form. For example, some of the smallest CV-values reported for power and isometric strength (1.0–6.6%) have been collected from tests that used either jug holds (Laffaye et al., 2014; Stien et al., 2021b) or a gym bar (Levernier et al., 2020). For maximal strength, Stien et al. (2021b) reported a 1.1% CV using jug holds, compared to 4.7% using a 23 mm rung. Shallower holds (∼10–20 mm) have displayed CV-values between 7.8 and 31.3% (López-Rivera and González-Badillo, 2012; Ozimek et al., 2016; Stien et al., 2021c). Indeed, the fingers are likely the weakest link in the pulling apparatus and hold depth influences the biomechanical arm action during pulling movements (Vigouroux et al., 2018). Future studies should identify whether the climbing-specificity of a test is compromised by using large holds, or if large holds can maintain validity while increasing reliability.

Finally, dynamic tests are underrepresented in the literature (**Table 2**). Although climbing is characterized by isometric contractions of the finger flexors, the movements in the elbows and shoulders are often dynamic to produce vertical propulsion. Hence, one could argue that future research should focus more on dynamic strength in the upper-limbs of climbers, in addition to isometric strength in the finger flexors. Indeed, investigations using dynamic tests have demonstrated that such test set-ups are (1) reliable, (2) able to differentiate between performance levels and disciplines, and (3) sensitive enough to detect within- and between-groups differences following a training intervention (Laffaye et al., 2014; Ozimek et al., 2016; Levernier et al., 2020; Stien et al., 2021b).

Some recommendations can be made based on the finding of this mini-review. Importantly, the scarcity of relevant studies should be considered when interpreting the results, as well as the conflicting findings between studies. For isolated endurance tests, the force-time integral might be more useful compared to simply reporting the total work time (Rokowski et al., 2021). Moreover, the time to fatigue during sustained endurance tests has displayed moderate-to-strong correlations with red-point climbing performance, whereas the few studies that examined intermittent tests reported weak correlations with climbing performance (Baláš et al., 2021; Rokowski et al., 2021). For strength, more reliable results might be achieved by using isometric dynamometer tests (CV $\leq$ 10%) compared to fingerboard tests (CV $\leq$ 22.9%). The validity will likely differ depending on the test set-up (e.g., elbow angle, body positioning, and grip type) and study population (e.g., performance level or preferred discipline), but in general the seated, 90° constrained elbow set-up displayed the highest correlations with climbing performance ($r = 0.60–0.84$) (Philippe et al., 2012; Marcolin et al., 2020). Dynamic upper-body strength tests (e.g., pull-up)

TABLE 1 | Climbing-specific endurance applied in the available literature.

References	Subjects	Performance level	Test procedures	Outcomes	Reliability	Correlation with performance
Isometric tests with sustained/continuous force generation						
Mermier (2000)	44 •	Lower-grade to elite	Bent-arm hang: The subjects hang with a 90° elbow angle using the biggest holds on a climbing fingerboard. Grip endurance: dominant hand was used to measure the time maintaining 50% of MVC using a handheld dynamometer.	Time to fatigue	•	$r = 0.798$
Baláš et al. (2012)	205 •	Lower-grade to higher-elite	Bent-arm hang: The subjects hang with overhand grip (shoulder width) in a bar (2.5 cm wide) in a pull-up position with chin above the bar. Bilateral finger-hang with fully extended elbows and with four fingers open or crimp grip on a 2.5 cm ledge.	Time to fatigue	•	Bent-arm hang: $r^2 = 0.49–0.64$ Finger-hang: $r^2 = 0.66–0.76$
Limonta et al. (2015)	11 •	Elite and higher-elite	A handgrip ergometer was used to measure time to fatigue using 80% of MVC (± 5%).	Time to fatigue	•	•
Medernach et al. (2015a)	23 BC	Advanced	Bi-lateral finger-hangs using: (1) half crimp grip on a 19 mm deep edge, (2) pinch grip, (3) slope grip and (4) 30 mm-deep ledge crimp grip (Alien Fingerboard).	Time to fatigue	•	•
Ozimek et al. (2016)	14 •	Advanced and elite	Finger hang were the subjects hang from a 4 cm ledge with a half-crimp grip.	Time to fatigue	•	•
Bergua et al. (2018)	40 LC	Advanced and elite	Finger hang tests using open- and half crimp were conducted on 1) a 14 mm ledge and 2) the minimum ledge depth the subjects could hang for 40 s.	1) Time to fatigue 2) Ledge dept.	1) ICC = 0.91-0.99 2) ICC = 0.89-1.00	•
López-Rivera and González-Badillo (2019)	26 LC	Elite	Finger hang from an 11 mm deep ledge using a half crimp grip.	Time to fatigue	•	$r = 0.62$
Fryer et al. (2018)	29 LC 9 NC	Intermediate to elite	Duration of sustained arm flexors contraction at 40% of MVC using a fingerboard with an open crimp grip.	Duration and force time integral [0.4 MVC x contraction (s) x force (N)]	MVC: CV = 0.5%	•
Draper et al. (2021)	132 •	Lower-grade to elite	Bent-arm hang: The subjects hang with overhand grip (shoulder width) on a bar (2.5 cm wide) in a pull-up position with chin above the bar. Finger-hang; the subjects hang with an open crimp hold using a 30 mm deep rung	Time to fatigue	Bent-arm hang: ICC = 0.894, CV: 18% (12-32) Finger-hang: ICC = 0.881, CV: 15% (11-24)	•
Philippe et al. (2012)	12 • 12 NC	Elite and higher elite	Unilateral sustained finger flexors test to failure using 40% of MVC on a 22 mm deep wooden hold.	Time to fatigue, force integral	•	•
Baláš et al. (2021)	22 LC	Intermediate and advanced	Unilateral sustained finger flexors test using 60% of MVC on a 23 mm deep wooden hold.	Time to fatigue	•	$r = 0.560$
Rokowski et al. (2021)	14 LC	Advanced to higher elite	Unilateral sustained force production (60% of MVC) to failure on a 23 mm deep wooden hold. Performed standing with a near full elbow extension.	Time to fatigue and force-time integral relative to BM	•	Time to fatigue: $r = -0.261$ Integral: $r = 0.54$

(Continued)

TABLE 1 | Continued

References	Subjects	Performance level	Test procedures	Outcomes	Reliability	Correlation with performance
Isometric, intermittent force generation to failure						
Michailov et al. (2018)	22 •	Intermediate and advanced	Unilateral intermittent finger flexor endurance using a 23 mm deep climbing hold with an open-finger grip position (thumb as disengaged). The work relaxation ratio was 8:2 using 60% of MVC	Time to fatigue	ICC = 0.887 $n = 9$ included in reliability test	•
MacLeod et al. (2007)	11 LC	Intermediate and advanced	Unilateral intermittent finger flexor test using an open crimp grip with a 90° angle of the elbow and shoulder using 40% of MVC with an 8:2 work relaxation ratio	Time to fatigue	•	•
Medernach et al. (2015a)	24 BC	Advanced	Bi-lateral intermittent isometric test with a 30- mm deep crimp grip (Alien Fingerboard) fixed at 120° beyond vertical. The work relaxation ratio was 8:4 hanging (i.e., body-mass).	Time to fatigue	•	•
Giles et al. (2021)	11 LC	Advanced to higher-elite	Bi-lateral intermittent finger hang test on a 20 mm-deep edge (Lattice training rung) using half-crimp hold. The work relaxation ratio was 7:3 using 80%, 60%, and 45% of MVC.	Time to fatigue and time to critical force	•	•
Stien et al. (2019)	16 BC 15 LC	Advanced	Bi-lateral intermittent finger flexor test in a seated position with shoulder fully adducted and with a 90° elbow flexion. A 23 mm-deep edge was used with an open crimp grip and 70% of MVC in a 7:3 work relaxation ratio.	Time to fatigue	•	•
Vigouroux and Quaine (2006)	9 LC	Elite and higher-elite	Unilateral intermittent finger flexor test in a seated position with 45° shoulder abduction and 90° elbow flexion. The work relaxation ratio was 5:5 using 80% of MVC.	Time to fatigue	•	•
Baláš et al. (2021)	22•	Intermediate to advanced	Unilateral intermittent finger flexors test using 60% of MVC with fully extended elbow on a wooden hold with 23 mm dept. The work relaxation ratio was 8:2.	Time to fatigue, oxygen saturation.	•	•
Philippe et al. (2012)	12 • 12 NC	Elite and higher elite	Unilateral intermittent finger flexors test using 40% of MVC on a 22 mm deep wooden hold. The work relaxation ratio was 10:3.	Time to fatigue, force integral	•	•
Quaine et al. (2003)	20 LC	Novice and elite	Unilateral intermittent finger flexor test on a 20 mm deep hold performed in a seated position with 45° shoulder abduction and 90° elbow flexion. Tested at 80% of MVC with a work relaxation ratio of 5:5.	Time to fatigue	•	•
Baláš et al. (2021)	22 LC	Intermediate and advanced	Unilateral intermittent finger flexors test using 60% of MVC on a 23 mm deep wooden hold. The work relaxation ratio was 8:2.	Time to fatigue	•	$r = 0.486$
Rokowski et al. (2021)	14 LC	Advanced to higher elite	Unilateral intermittent force production (60% of MVC) to failure on a 23 mm deep wooden hold. Performed standing with a near full elbow extension. The work relaxation ratio was 8:2.	Time to fatigue Force-time integral relative to BM	•	Time to fatigue: $r = -0.268$ Integral: $r = 0.191$

(Continued)

TABLE 1 | Continued

References	Subjects	Performance level	Test procedures	Outcomes	Reliability	Correlation with performance
Climbing tests						
Medernach et al. (2015b)	24 BC	Advanced	Climbing to failure on a 4.1 m high wall (120° overhang) with four grips (20, 30, 45, and 45 mm-deep ledges. Climbers had to maintain an isometric position for 4, 6, 8, and 10 sec) before moving to the next ledge.	Inability to continue climbing	•	•
Hermans et al. (2017)	30 •	Lower-grade and intermediate	An 18 m route with progressively increasing difficulty was used. The route included 43 holds and points were given for each handhold passed. Top rope was used during testing	Numbers of handholds passed	•	•
Baláš et al. (2021)	22 •	Intermediate and advanced	Climbing to failure on 3.8 m treadwall with 14 hand moves graded 8 on the IRCRA scale with a speed of 9 m/min with increasing steepness (-5°) every minute. A sustained test to fatigue	Time to fatigue, heart rate, VO_2peak, ventilation x min^{-1}	•	•
Stien et al. (2021b)	16 •	Advanced and elite	Numbers of moves on a campus board with single arm moves up- and downwards. The board was overhanging (15°) and 13 cm separated the 20 mm-deep ledges.	Numbers of moves to fatigue	•	•
Schöffl et al. (2006)	28 LC	Elite	Climbing to failure on a treadwall.	Climbing time to failure	Between-sessions correlation: $r = 0.99$	•
Limonta et al. (2018)	13 LV	Advanced and elite	Climbing to failure on a treadwall.	Oxygen uptake and workload	•	•
Other tests						
Vigouroux et al. (2018)	10 •	Advanced to higher-elite	Numbers of pull-ups using 10, 14, 18, 22, 80 mm deep holds and a 2.5cm gym bar. The climbers were instructed to conduct the repetitions with maximal effort.	Number of pull-ups	•	•
Saeterbakken et al. (2018)	19 •	Advanced	Hanging vertically from a 6 cm beam and placed one foot on a chip 185 cm above the ground and the participant's body length in the horizontal direction. Maintained position for one second before lowering the body.	Numbers of completed repetitions	•	•
Draper et al. (2021)	132 •	Lower-grade to elite	Prone plank with the elbows bent at 90° and placed directly beneath the shoulders. The body had to form a straight line from head to feet.	Time to fatigue	•	•

IRCRA, International Rock Climbing Research Association; BC, Boulder climbers; LC, lead climbers; MVC, maximal voluntary contraction; CV, coefficient of variation; ICC, intraclass correlation; r, correlation coefficient; •, not reported. Performance level calculated using the grouping proposed by Draper et al. (2016).

TABLE 2 | Strength and power tests applied in the available literature.

References	Subjects	Performance level	Test procedures	Outcomes	Reliability	Correlation with performance
Isometric dynamometer tests						
Baláš et al. (2012)	205 LC	Advanced and elite	Handheld dynamometer with 180° elbow angle. At least 2 s hold	MVC	•	$r^2 = 0.10–0.11$
Ozimek et al. (2016)	14 •	Advanced to higher-elite	Handheld dynamometer with a 180° elbow angle.	MVC	CV = 9.7–10.0	•
Grant et al. (1996)	10 NC 20 LC	Recreational and elite	Table-mounted dynamometer with 90° elbow angle and a half-crimp grip. Force measured during 2 s maximal effort.	MVC	•	•
Marcolin et al. (2020)	34 LC 15 NC	Intermediate to higher-elite	Table-mounted dynamometer with 90° elbow angle and a half-crimp grip on a 22 mm ledge. Force measured during 2 s maximal effort.	MVC	•	$r = 0.60$
MacLeod et al. (2007)	11 LC 9 NC	Intermediate and advanced	Table-mounted dynamometer with 90° elbow angle and a half-crimp grip. Force measured during 2 s maximal effort.	MVC	•	$r = 0.706$
Fanchini et al. (2013)	10 LC 10 BC 10 NC	Advanced and elite	Seated, using a custom-built dynamometer during 3 s hold with a 180° elbow angle.	MVC RFD_{peak}	ICC > 0.90	•
Michailov et al. (2018)	22 •	Intermediate and advanced	Standing, using a wall-mounted dynamometer. Force measured during with 90° and 180° elbow angles.	MVC	90° elbow: ICC = 0.941 180° elbow: ICC = 0.878	90° elbow: $r = 0.45–0.46$ 180° elbow: $r = 0.61–0.74$
Stien et al. (2021a)	14 •	Intermediate and advanced	Table-mounted dynamometer using half-crimp on a 23 mm rung. Elbow constrained in 90°.	MVC	•	•
Philippe et al. (2012)	12 • 12 NC	Elite and higher elite	Table-mounted dynamometer with 90° elbow angle and a half-crimp grip on a 22 mm ledge. Maximal force reached in five seconds.	MVC	•	$r = 0.839$
Baláš et al. (2021)	22 LC	Intermediate and advanced	Unilateral hangs on 23 mm ledge with built-in force sensor. Had to hold for 5 s.	MVC	•	$r = 0.552$
Levernier and Laffaye (2019)	22 BC 9 NC	Advanced to higher elite	Wall-mounted dynamometer with unconstrained 90° elbow angle using open hand and half crimp grips on a 10 mm hold. RFD collected at 50, 100, and 200 ms from onset of force, as well as at 95% of peak force.	RFD MVC	RFD: ICC = 0.58–0.98 CV = 7.8–28.4% MVC: ICC = 0.94–0.99 CV = 2.6–5.9%	•
Rokowski et al. (2021)	14 LC	Advanced to higher elite	Unilateral maximal force production on a 23 mm deep wooden hold. Performed standing with a near full elbow extension. Five seconds time window available for force production.	Peak force	•	$r = 0.241$

(Continued)

TABLE 2 | Continued

References	Subjects	Performance level	Test procedures	Outcomes	Reliability	Correlation with performance
Isometric fingerboard tests						
López-Rivera and González-Badillo (2012)	9 LC	Elite and higher-elite	Dead-hang using 15 mm ledge with straight arms and half-crimp grip. Had to hold for 5 s.	Maximal extra-load (kg)	CV = 7.8% ICC = 0.96	•
Torr et al. (2020)	229 •	Intermediate-to-higher elite	Unilateral hangs on 20mm ledge with de-load. Had to hold for 5s.	Maximal total load	ICC = 0.91–0.98	r = 0.42–0.50
Ozimek et al. (2016)	14 •	Advanced to higher-elite	Dead-hang using 25 mm ledge and a half-crimp grip. Had to hold for 3 s.	Maximal total-load	CV = 22.9%	•
Stien et al. (2021c)	57 LC	Intermediate to elite	Isometric pull-up on 23 mm ledge using a half-crimp and 90° elbow angle	MVC RFD	CV = 9–20% ICC = 0.88–0.99	•
Dynamic tests						
Levernier et al. (2020)	11 BC 8 LC 5 SC	Higher-elite	Two pull-ups with 0, 30, 45, 60, and 70% BM extra-load in random order. Vertical velocity measured with accelerometer attached to the waist belt.	Force Velocity	CV = 1.0–6.6%, ICC = 0.84–0.99	•
Laffaye et al. (2014)	34 •	Intermediate to elite	Arm-jump board test from jug hold. Power output measured with accelerometer.	Power	CV = 4.89%, ICC = 0.976	•
Ozimek et al. (2016)	14 •	Advanced to higher-elite	1RM pull-up with extra-load performed on a gym bar.	Maximal total load	CV = 7.7%	•
Stien et al. (2021b)	17 LC	Advanced and elite	Maximal reach with one hand performed on a 15° overhanging campus board using 20 mm rungs. 13 cm between ledges.	Number of rungs reached	•	•
Draper et al. (2011)	38 LC	Novice to elite	Maximal reach (powerslap) with one hand performed on a custom board using jug holds.	Reach (cm)	ICC = 0.95–0.98	r = 0.69–0.73

IRCRA, International Rock Climbing Research Association; BC, Boulder climbers; LC, Lead climbers; SC, speed climbers; NC, non-climbers; RFD, rate of force development; RFD_{peak}, RFD calculated using the steepest portion of the force curve; MVC, maximal voluntary contraction; s, seconds; BM, body mass; CV, coefficient of variation; ICC, intraclass correlation; r, correlation coefficient; •, not reported.
Performance level calculated using the grouping proposed by Draper et al. (2016).

also revealed a high reliability (CV ≤ 7.7%), but such tests could potentially lack specificity to climbing compared to tests focusing on the finger flexors (Ozimek et al., 2016). Finally, high intensity, upper-body tests (i.e., powerslap and campus board reach) were investigated in two studies (Draper et al., 2011; Stien et al., 2021b) and displayed a strong relationship with climbing performance ($r = 0.69–0.73$).

Establishing reliable and valid testing procedures is essential for the field of climbing research. Today, no consensus exists regarding preferred sport-specific performance assessments. This study provides a brief overview of the applied endurance-, strength-, and power-tests, and highlights gaps in the literature. The findings of this mini-review revealed that numerous approaches to measuring climbing-related performance have been applied, but few have reported the reliability and validity of the tests. Hence, the current knowledge is fragmented as very few findings have been re-tested in subsequent studies with similar methodology. Moreover, poor descriptions of populations challenge performance level- and discipline-specific testing recommendations. Importantly, the pioneer work by Draper et al. (2016) needs to be acknowledged for first providing a numerical scale, making it possible to compare climbing performance across continents, and more recently attempting to establish a test battery (Draper et al., 2021). Hopefully, this mini-review will provide a useful overview of the scientific literature and inspire researchers to work toward agreeing upon common tests and procedures.

AUTHOR CONTRIBUTIONS

NS and AS wrote the first draft of the article and extracted the relevant data from the included studies. VA reviewed the data extraction and settled any disagreements between NS and AS. All authors contributed to the conceptualization and methodology. All authors provided critical reviews of the paper.

SUPPLEMENTARY MATERIAL

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CASE REPORT
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Case Report: Using Telehealth to Treat Triceps Tendinopathy in a Rock Climber

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This case study presents a 38-year-old, female rock climber with posterior elbow pain who was evaluated and treated using Telehealth. The use of telehealth for a clinical exam requires a larger emphasis be placed on posture observation and movement analysis since hands on assessment techniques cannot be used. During the patient exam, movement analyses identified scapulohumeral positional faults and dyskinesis, while self-palpation and self-midline resistance testing helped identify that the triceps tendon was the pathological tissue. A comprehensive rehabilitation program was developed based on concepts of regional interdependence to treat contributing factors in the scapular region and source tissues in the brachial region. After 10 weeks, the climber's pain decreased from 4/10 to 0/10. She made a full recovery back to her previous grade of V8 bouldering and was able to complete a V10 longstanding boulder project pain-free. This is the first case study of its kind to identify unilateral scapular dyskinesia in a patient with suspected triceps tendinopathy and to demonstrate a positive treatment effect by combining scapular strength exercises with eccentric exercises addressing the affected tissue.

Keywords: physical therapy, elbow pain, regional interdependence, telehealth, rock climbing

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INTRODUCTION

Since COVID-19 emerged in the first months of 2020, social distancing and stay-at-home orders moved telehealth from a convenient option to an essential tool (Lee, 2020). As a result of nation and local mandates, many medical providers had to adjust their practice models to include telehealth care. Telehealth is performed in the field of physical therapy mostly through utilizing two-way synchronous audio and video. It has several strengths when compared to the in-person setting. Telehealth has the benefit of improved access to care (Branford et al., 2016; Seto et al., 2019), reduced travel time (Seto et al., 2019), improved convenience (Powell et al., 2017), improved patient engagement (Guo and Albright, 2017), reduced costs (Powell et al., 2017; Jiang et al., 2019; Seto et al., 2019), and improved session attendance (Kairy et al., 2009; Morris et al., 2011). Telehealth objective exam measures have been shown to be valid and reliable (Russell et al., 2010; Somerville et al., 2017) and interventions have been shown to improve pain and physical function (Cottrell et al., 2016). Telehealth has comparable patient satisfaction levels when compared to in-person rehabilitation (Moffet et al., 2017).

Although Telehealth presents some advantages when compared to in-person sessions it also has drawbacks. These include technology barriers (Lin et al., 2018; Seto et al., 2019), increased difficulty with exam measures (Powell et al., 2017), patient/provider preferences (Kruse et al., 2016), security, privacy, and confidentiality challenges (Hall and Mcgraw, 2014; Powell et al., 2017). However, most notably, since manual assessments cannot be performed by the clinician, the objective exam has a greater emphasis on movement analysis (Malliaras et al., 2021). Although this can be a potential barrier, it can also be viewed a benefit. By not being able to manual assess a patient, the clinician needs to rely more heavily on analyzing a climber's movement. This may allow them to look past the affected pain region and integrate concepts on regional interdependence (Wainner et al., 2007) into their diagnostic procedures. Regional interdependence is a concept that unrelated impairments in a remote anatomical region may contribute to or be associated with the patient's primary complaint. By using this concept remotely, clinicians may be able to uncover impairments that may have been missed in an in-person clinical exam that was solely focused on the painful region. Additionally, since it has been shown that telehealth improves patient self-efficacy (Guo and Albright, 2017), it can be utilized for improved patient engagement by placing a greater emphasis on the self-performance of corrective exercises and optimizing movement patterns.

This article focuses on a rock climber who was evaluated and treated using telehealth with suspected triceps tendinopathy. There are three heads of the triceps muscle: the medial, lateral, and long head. The three heads share a central tendon that inserts into the olecranon process of the elbow. Triceps tendinopathy, like other tendinopathies, occurs when repetitive use of the tendon leads to activation and proliferation, matrix changes including disorganization of collagen and neovascularization. In a prospective single-institution study that evaluated the demographics of 911 independent climbing injuries (Shöffl et al., 2015), the most 149 common body regions injured were the finger (52%), shoulder (17.2%), hand (13.1%), and the forearm and elbow (9.1%). Most of the elbow injuries in the study (5.5%) were identified as epicondylitis. Triceps tendinopathy is not only a rare condition in climbers but also in the general population with some studies citing a 3.8% prevalence of elbow injuries when assessed with MRI (Koplas et al., 2011). However, although prevalence is low, the methods used in this case study to assess the injury in the remote setting can be generalized to all body regions.

METHODS

A 38-year-old, female rock climber was evaluated *via* Telehealth for elbow pain. She had 20 years of bouldering experience with a maximum grade of V11 and a pre-injury grade of V8. The evaluation was performed remotely utilizing Telehealth and the patient had no previous plan of care developed for her elbow pain. She presented 4-months post-partum with right sided posterior elbow pain superior to the olecranon. She reported a chronic history of mild elbow pain lasting over 1 year with a severity of 1 out of 10 on the VAS scale with 0 being "no pain" and 10 being "pain as bad as it could possibly be." She continued to train for climbing during her pregnancy until the final 4 weeks and took 1 month off from training after her baby was born. In 3 months prior to the evaluation, after having her baby, she reported that she had increased the volume and intensity of her climbing training and her elbow pain had increased to 4/10 during specific movements such as push-ups, bench-press, and wiping counters. She reported hard bouldering moves such as lock-offs and gastons increased her symptoms. She also reported a minor right ring finger injury 6 weeks prior to the evaluation and an acute left ankle sprain from a bouldering fall 4 weeks prior to the evaluation. Secondary to pain she was limited climbing the grade of V6. She denied any numbness or tingling. The remote clinical examination included a posture analysis (**Figure 1A**) and a movement analysis of shoulder abduction (**Figure 1B**), shoulder flexion with elbow flexion (**Figure 1C**), offset pushups (**Figure 1D**), climbing movement (**Figure 1E**), and self-assessment of palpation and midline resistance testing. Posture and movement analysis demonstrated asymmetric scapulohumeral positional faults and dyskinesis including excessive scapular winging, inadequate scapular elevation/upward rotation, and excessive humeral internal rotation with shoulder flexion. Self-palpation reproduced symptoms with moderate pressure and midline resistance testing of elbow extension was provocative for symptoms at 90 degrees of shoulder flexion (4/10) and 0 degrees of shoulder flexion (2/10).

Based on the subjective reports and objective data gathered remotely, the patient was given a home exercise program based on a rehabilitation framework to unload the affected tissues, improve mobility, increase muscle performance, and retrain climbing movement. Each intervention was specially linked to a hypothesis driven movement impairment remotely tested during the session. Interventions consisted of patient education to carry her baby with her left arm and avoid leaning on the elbow. Her mobility exercises consisted of posterior rotator cuff and latissimus dorsi soft tissue mobilization followed by latissimus dorsi stretching. Each exercise was prescribed for 3 sets of 30 s daily. Her muscle performance exercises consisted of push-up plus airplane, wall taps, and triceps eccentrics performed at 0, 90 and 180 degrees of humeral flexion. Each exercise was prescribed for 3 sets of 8 repetitions to failure and performed 3 times per week. Adherence was assessed using a subjective report questionnaire. The patient was encouraged to return to her regular climbing schedule of 4 sessions per week (**Figures 2**, **3**). The patient's goal for therapy was a single session remote evaluation with a self-administered home program. Exercises were reviewed during the initial evaluation with video and verbal feedback and correct exercise performance was confirmed. Detailed videos and written descriptions of the exercises were provided to the patient.

RESULTS

As a result of the remote environment, a large emphasis in the evaluation of the patient relied on subjective information and

FIGURE 1 | **(A)** Winging of the inferior angle of the scapula right greater than left indicating serratus anterior weakness. **(B)** Increased right sided humeral creasing with shoulder abduction indicating possible humeral hypermobility and inadequate scapular upward rotation and elevation. **(C)** Right humeral internal rotation with shoulder/elbow flexion indicating a latissimus dorsi mobility deficit. **(D)** Right sided scapular winging with offset pushup indicating serratus anterior muscle weakness. **(E)** Scapular winging with climbing movement on overhung wall indicating serratus anterior muscle weakness.

movement analysis. During movement analysis, it was discovered that the patient demonstrated scapulohumeral positional faults and dyskinesis including excessive scapular winging, inadequate scapular elevation/upward rotation, and excessive humeral internal rotation with shoulder flexion (**Figure 1**). The patient performed her home exercise program independently as prescribed for 10 weeks.

At 10-week follow-up the patient reported that her triceps pain was 0 out of 10 and she had returned to training and climbing pain-free at her previous grade of V8 without restriction. Additionally, she reported that 8 weeks after the evaluation she was able to complete a long-standing boulder project; a V10 problem called Sunshine which consists of challenging sloper and gaston moves (**Table 1**).

DISCUSSION

There were benefits and drawbacks to evaluating this patient remotely. Since the patient worked full time and was caring for her child, the benefits of the session included reduced travel time and improved convenience. Since the session occurred during the early stages of the pandemic, the patient was able to minimize in-person contact risk by attending the session from the safety of her own home. Additionally, an added benefit was that the patient had a home climbing wall, and the clinician was able to observe climbing and exercises in the patient's home environment. The primary drawback of the Telehealth session was that many of the mobility and muscle performance deficits from the observed movement faults were built off hypothesis that

TABLE 1 | Pain levels and bouldering grade from evaluation to discharge.

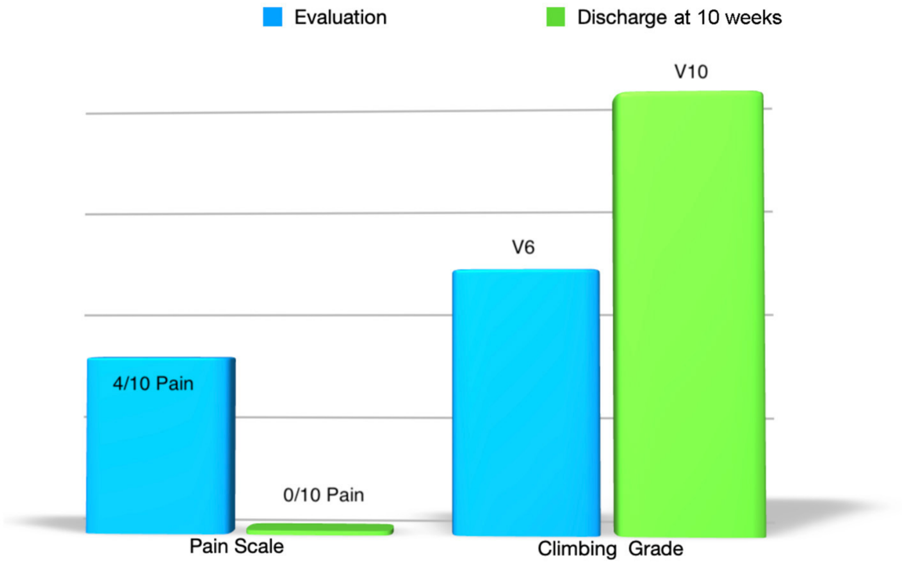

FIGURE 2 | (From top left to bottom right) Tennis ball on posterior rotator cuff, latissimus dorsi soft tissue with foam roll, latissimus dorsi/triceps stretch with dowel, pushup-up plus airplane, wall taps, triceps eccentrics 0 degrees humeral flexion, triceps eccentrics 90 degrees humeral flexion, triceps eccentrics 180 degrees humeral flexion.

could not be tested in the Telehealth setting. However, by not being able to perform manual tests and measures, it did allow for a greater emphasis to be paced on movement assessment. The emphasis on movement assessment uncovered some meaningful movement impairments that may have been missed during an in-person session.

The unloading techniques for the elbow included both carrying her baby with her opposite arm and not leaning on the elbow. The proposed theory for changing her carrying arm was to decrease the co-contraction of the triceps muscle needed to stabilize her baby while carrying. The theory behind not leaning on her elbow was to decrease potential irritation to the olecranon bursa (Reilly and Kamineni, 2016) which could further exacerbate the patient's triceps tendinopathy.

The rationale behind the mobility techniques targeting the periscapular musculature were directly related to the patient's observed impairments. Posterior rotator cuff mobility was prescribed with the hypothesis that a co-contracted infraspinatus and teres minor could lead to a lack of glenohumeral dissociation and contribute to scapular winging (**Figure 1E**). Latissimus Dorsi mobility was prescribed based on the movement observation excessive humeral internal rotation with shoulder flexion and elbow flexion (**Figure 1C**). The humeral internal rotation movement with end range shoulder flexion can lead to increased

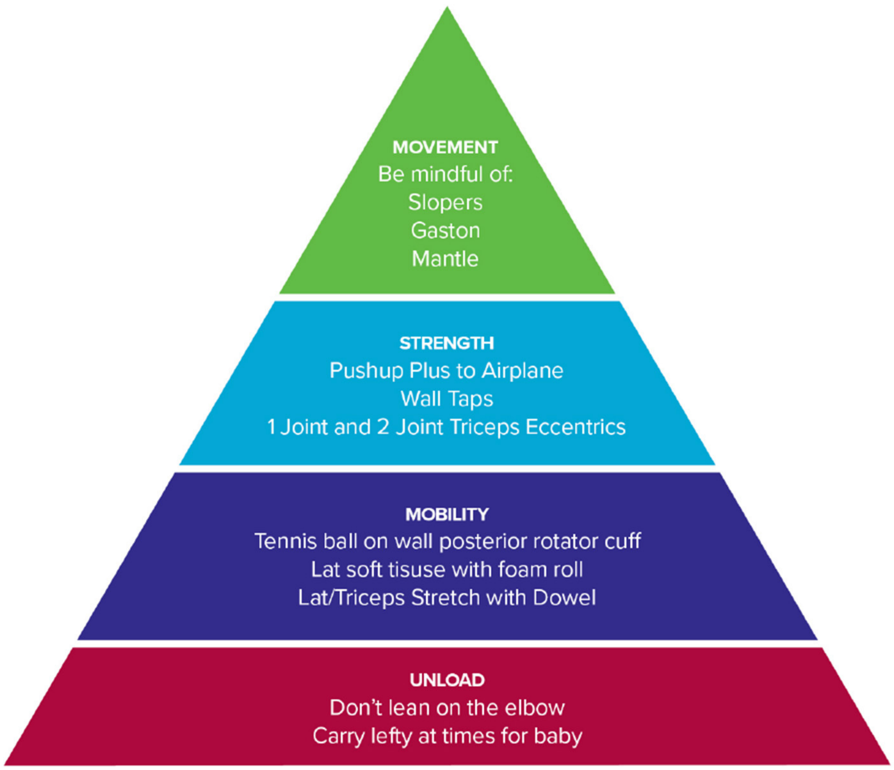

FIGURE 3 | Organization of rehabilitation into a framework.

triceps contraction while climbing secondary to the altered elbow position.

It has been shown in research that scapular positioning and dyskinesis affect the elbow and when addressed can resolve elbow pain (Bhatt et al., 2013). Based on the concept of regional interdependence, scapular positioning and strengthening exercises were selected to treat the patient's elbow pain. And since it has also been shown that the push-up plus exercise elicits high levels of electro-myographic activity from the serratus anterior (Decker et al., 1999), a push-up plus variation was included in the treatment program. It has also been shown that eccentric exercises can have positive effects on pain and muscle strength in patients with lateral elbow tendinopathy (Yoon et al., 2021), and even more recently it has been shown that eccentric-concentric training combined with isometric contractions is an effective treatment for lateral elbow tendinopathy (Stasinopoulos and Stasinopoulos, 2017). The patient was prescribed eccentrics based on patient preference and supporting research.

The movement exercises were identified to decrease the overuse of the triceps and minimize scapular dyskinesia while climbing. The excessive use of gastons and mantles places a high degree of stress on the triceps musculature and the use of slopers exaggerated the climber's scapular winging, so a recommendation was made to avoid routes with the excessive use of slopers, gastons, and mantles.

Limitations of this case report include the lack of a standardized subjective report questionnaire at initial evaluation and follow-up, and the inability to achieve in-person objective tests and measures secondary to the remote environment.

CONCLUSION

The use of telehealth to conduct a clinical exam requires that a larger emphasis be placed on posture observation and movement analysis since hands on assessment techniques cannot be used. Since rock climbing is a sport that requires precise movement performance, Telehealth can serve as a valuable tool to assess climbers with injuries especially when barriers exist to performing examinations in-person. Even in rare and difficult to diagnose conditions such as triceps tendinopathy, Telehealth can be an effective tool for clinical assessment and can be used to a return a climber back to optimal function.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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ORIGINAL RESEARCH
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The Load Structure in International Competitive Climbing

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The analysis of the load structure in competitions is essential to develop performance structure models from which sport-specific testing and training protocols can be derived. The aim of this study was to characterize the external load structure of competitive climbing at an international level in the disciplines of speed, bouldering, lead, and Olympic combined based on video recordings of top athletes. In speed, the route was completed by women with a median of 11 moves and by men with 9 moves that required 0.73 and 0.60 s per move, respectively. Bouldering competitions are characterized by various bouts of activity with resting periods in between. Athletes attempted a boulder problem, a median of 3 times in the qualification and semi-final rounds and 4 times in the final round with an average attempt duration of 27.0 s. In lead, the load structure is characterized by an average climbing time of 4:09 min and 4:18 min, 31.6 and 30.0 actions, contact times of 6.4 s and 6.2 s, and reach times of 1.4 s and 1.6 s for women and men, respectively. Olympic combined competitions combine all 3 single disciplines starting with speed followed by bouldering and lead and are characterized by high competition loads, long durations of almost 3 h, and relatively short resting periods in between.

Keywords: competition analysis, elite climbing, bouldering, lead climbing, speed climbing, world cup

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INTRODUCTION

International climbing competitions were first held in 1989 and since then, the research interest of sport and exercise scientists has steadily increased. One of their main concerns is to optimize athlete performance by, for instance, developing performance structure models. Sport-specific requirements, which underlie these models, are derived from competition load structures. In terms of direct applications, this knowledge enables researchers to develop specific testing protocols which imitate competition load structure and permit the design of sport-specific training and conditioning programs that enhance the effectiveness of training for sports performance (Rhea et al., 2006).

Competition load structure can be characterized by internal (individual psychological and physiological response) and external (general characteristics of the competition) measured parameters. Regarding the first, there are numerous studies in sport climbing, which have examined the load structure in simulated competition situations based on such parameters as VO_2 max (Billat et al., 1995; Mermier and Robergs, 1997; Watts et al., 2000; Sheel et al., 2003; Bertuzzi et al., 2007), lactate concentration (Bertuzzi et al., 2007; Gajewski et al., 2009; Gáspari et al., 2015), and heart rate (Billat et al., 1995; Watts et al., 2000; Sheel et al., 2003; Gajewski et al., 2009; Fuss et al., 2020). External parameters can, in contrast to the internal ones, be assessed free of repercussion on the athlete's performance and obtained from real competitions. This feature notwithstanding, studies investigating the load structure based on external parameters are uncommon in comparison to those that investigate internal parameters.

Today's present competition climbing disciplines are speed, lead, bouldering, and Olympic combined (International Federation of Sport Climbing, 2020).

No studies exist regarding the load structures of speed or Olympic combined climbing competitions. For bouldering, White and Olsen (White and Olsen, 2010) analyzed the load structure of a national bouldering competition in the United Kingdom in 2010. Six elite-level male climbers were analyzed on two selected boulder problems. The structure of the competition was similar to the one nowadays used in the qualification and semi-final rounds of the bouldering World Cups with alternating climbing and resting times of equal durations. While climbing, athletes attempted the boulder problems on average 2.8 times with one attempt lasting 29.8 s. Before starting the initial attempt, athletes spent an average of 75.3 s viewing the boulders and rested 114.5 s between attempts. This meant a 1:3.8 exercise to recovery ratio between climbing and resting intervals. During attempts, the athletes spent more time in dynamic than in static positions and had longer hand contact time than reach times (7.9 s vs. 0.6 s). A similar approach was taken by Medernach et al. (2016), who analyzed the 20 best competitors of each gender on 3 selected boulder problems during the qualification round of a bouldering World Cup in 2013. Women did on average 5.1 attempts per boulder with a duration of 15.2 s and a resting time between attempts of 33.4 s whereas men did 4.3 attempts with a duration of 23.8 s and resting time between attempts of 27.2 s. Another approach was taken by Augste et al. (2021), who classified the boulder problems in so-called boulder types according to their predominant characteristics and analyzed their frequencies and the athlete's success rates. Dynamic moves occurred most frequently and represented the types with which athletes most struggled. However, the studies from White and Olsen (2010) and Medernach et al. (2016) are either limited to male athletes (White and Olsen, 2010), to certain modus (White and Olsen, 2010; Medernach et al., 2016), or to a relatively small number of analyzed climbing performances (White and Olsen, 2010; Medernach et al., 2016). Furthermore, as is to be expected, the evolution of the sport and changes in rules, such as time allowance per boulder, and route setting styles result in a different load structure than back in 2010 or 2013. For lead, Schädle-Schardt (1998) determined the load structure during three national or international championships between 1989 and 1993. Twenty-three athletes (11 women and 12 men) were studied during the final round of each competition. The single attempts consisted of an average of 36.4 moves for women and 42.3 moves for men. This corresponds to an average total climbing time of 4.04 min for women and 4.25 min for men, respectively. The average overall hand contact time was 9.0 s and the average total reach time was 2.4 s with no significant differences between subgroups. Years later, Arbulu et al. (2015) studied 8 women and 8 men at the lead final of the World Climbing Championships in 2012. The total climbing time was almost 6 min for women and less than 4 min for men. Significant differences between women and men were found in frequency and the duration of hand contact, chalking, and resting. For example, the hand contact times were 8.5 s for women and 7.0 s for men. However, in international lead climbing competitions, various rule changes and changes in climbing and route setting styles have occurred in recent years, meaning that the cited previous findings are no longer necessarily valid. Furthermore, the flash modus, which is applied nowadays during the qualification round, has not yet been studied (Schädle-Schardt, 1998; Arbulu et al., 2015).

To summarize, representative values of external measured parameters from current competitive climbing on an international level are still missing. The aim of our study was therefore to analyze the external load structure to determine the general characteristics of competitive climbing at an international level in today's present competition climbing disciplines.

MATERIALS AND METHODS

Procedure

For the analysis of the discipline-specific load structure, video recordings of international climbing competitions were used. For bouldering and lead, we selected a 2018 World Cup and the 2018 World Championship. For speed, one 2018 World Cup was analyzed; for the Olympic combined discipline, the 2018 World Championship was selected. The discrepancies regarding the number of analyzed competitions are rooted in the standardization of the route in speed climbing and the rarity of Olympic combined as an international competition format. The analyzed videos were either obtained from the International Federation of Sport Climbing (IFSC) YouTube channel or were the respective competition's own recordings (Casio EXILIM EX-F1 Cameras, sample rate 30 Hz, speed: 300 Hz). Videos were analyzed using Kinovea (Version 0.8.15) software.

Variables

The variables analyzed were those considered relevant to describing the load structure in each respective discipline.

Speed: Speed climbing is carried out as a race of two competitors belayed by auto belay systems on two identical, standardized routes. The load structure of each run is characterized by the *start time*, the *number of actions*, *contact times,* and *reach times*. The *number of actions*, *contact times*, and *reach times* were assessed for upper and lower limbs independently. The *start time* was calculated as the time difference between the starting signal and the visible beginning of the motor action of the hips in the rightward direction. Athletes have to start at the end of the acoustic countdown which can be anticipated (International Federation of Sport Climbing, 2018). If the athlete reacts to the start signal in less than 0.01s, this is considered as a false start. However, the measurement device is a so-called starting pad for one foot, which means that it is possible for motor action of the hips to commence before the start signal (negative values) without being considered as false start as long as the foot maintains contact with the starting pad for the required time. Due to the high temporal resolution of the camera (300 Hz), it was possible to accurately capture the beginning of the movement. For the purpose of measuring the *number of actions*, an action was determined to be a visible displacement of the limb across the phase of the loss and regaining of contact between holds. *Contact times* were calculated as the time span between the first contact with the climbing holds or the climbing wall and its complete loss of contact. *Reach times*, meanwhile, were calculated as the difference between the loss of contact and the start of the next contact.

Bouldering: In bouldering, short climbs (boulders) at jumping height were protected by landing mats have to be climbed in as few attempts as possible. Bouldering competitions consist of 3 rounds with different modes. In the qualification and semi-final round, a course of boulders has to be climbed in the prescribed order within a fixed time period of 5 min for each boulder, which equals the resting time between boulders. In contrast, in the final round, each boulder is attempted by all competitors before they move on to the next boulder as a group. The climbing time is limited to 4 min. A collective observation period of 2 min per boulder precedes the final but not the qualification or semi-final round. Because the qualification and semi-final round share the same mode, they were considered together and contrasted with the final round. To determine the load structure, the following parameters were quantified in accordance with the IFSC Rules 2018 (International Federation of Sport Climbing, 2018): the *number of attempts per boulder*, *observation time* as the time between the start of the climbing period and the beginning of the first attempt, *attempt duration* differentiated between successful and not successful attempts and average attempt duration, *climbing time per boulder* as the sum of attempt durations per boulder, *resting time between attempts* and *resting time between boulders*, *resting time per boulder* as the observation time plus the sum of resting times between attempts, and the *ratio of climbing and resting time per boulder*.

Lead: In lead climbing, the competitors attempt routes on walls a minimum of 15 m high while having to clip the rope into protection points for safety reasons. Progression up the wall is the main scoring criteria. Two different modes are applied during lead climbing competitions, namely, "flash" (used in the qualification round) and "onsight" (used in the semi-final and final round). These modes differ in the amount of route information available to the athletes before they climb. Accordingly, the qualification round was contrasted with the semi-final and final rounds, which were considered together due to sharing the same mode. To determine the load structure, *contact times* and *reach times*, the *number of actions*, and the *total climbing time* were analyzed. *Contact times* and *reach times,* and the *number of actions* were measured in the same way as in speed climbing. Additionally, bodyside and finger grip position (open hand grip vs. crimp grip) were noted. The *reach times* of the upper limbs were further subdivided according to whether the athletes were chalking to reduce sweat, clipping the rope into the protection points, shaking their arms for recovering, or just aiming to grab the next hold ("grabbing only"). Combinations of these movements were also considered. *Total climbing time* was measured according to the IFSC Rules (International Federation of Sport Climbing, 2018) as the time span between the start of the attempt and the moment where either the final quickdraw of the route was clipped or a fall occurred and the contact with all extremities to the holds or the climbing wall was lost.

Olympic combined: In the Olympic combined event, athletes compete against each other in the abovementioned single disciplines. During the final round, athletes compete in all three single disciplines within one competition, starting with speed, bouldering, and then lead. In speed, the athletes have to do either 1 or 3 runs depending on whether they advance to the next stage or not. Both, the bouldering and lead parts follow the final round format of standard competitions in the disciplines described above. Observation time in each discipline takes place during the resting time between events. The final ranking is determined based on multiplying the athlete's result in each respective discipline. Where load structure is concerned, the analysis of the overall duration of the competition and the resting times between the single disciplines was prioritized because it was assumed that the load structure of the single disciplines is similar to the load structure of the single disciplines carried out within the Olympic combined competition. The *overall duration of the competition* was measured as the time span between the beginning of the first attempt of the first speed run and the end of the lead attempt. The *resting time between runs in speed* was measured as the time span between the end and the start of the consecutive speed run, the *resting time between speed and bouldering* as the time span between the end of the last speed attempt and the beginning of the first climbing period in bouldering and, lastly, the *resting time between bouldering and lead*, as the end of the last attempt in bouldering and the beginning of the lead attempt. Further details are described in the respective section of the single disciplines.

Sample

Subjects were elite athletes competing at international climbing competitions in 2018 and represent the best climbers of the respective competition:

Speed: The 20 fastest runs with available video recordings were analyzed while considering only the 2 fastest runs per athlete. In cases where an athlete completed more than 2 of the 20 fastest runs, runs from the next fastest athlete were selected to enhance variability. The selected runs were scored from 12 women and 14 men athletes, respectively. The runs were analyzed regardless of the round of competition.

Bouldering: Four competition rounds, the qualification, semi-final, and final round from the World Cup and the final round of the World Championship, were included. In both, the qualification and semi-final round, the courses of the semi-finalists (each round: 20 per gender), and in the final rounds, the courses of the finalists (each final round: 6 per gender) were analyzed. As some athletes participated in the selected rounds of both competitions, video recordings of 20 different female athletes and 24 different male athletes were analyzed.

Lead: In total, 37 attempts from female and 43 attempts from male athletes were analyzed. These data represent 8 attempts per gender in both the semi-final and final rounds of the World Cup (16 attempts in total per gender), 6 attempts per gender from the finals of the World Championship, and those 10 attempts by women and 16 attempts by men in which the route was topped in the qualification round. Just as in bouldering, some athletes participated in both competitions, which means that the attempts were obtained from 12 different female and 25 different male athletes.

Olympic combined: Only the final round of the World Championship was analyzed as the qualification round is already covered by studies of the single disciplines, which means that the load structure was obtained from the 6 female and the 6 male finalists.

Reliability

Two independent raters assessed inter-rater reliability on 5% of the data. The intraclass correlation coefficient (ICC) according to the schema developed by Koo and Li (2016) was used as the reliability coefficient and calculated for each analyzed variable separately. In the case of disagreements regarding the consideration of movements as separate actions where contact and reach times were concerned, data were compared up until the point of disagreement respectively from thereon. Inter-rater reliability of all variables is presented in **Table 1**.

The inter-rater reliability was very high across all disciplines for almost all of the analyzed parameters. This conclusion can be drawn from the fact that the relative reliability coefficients (ICC) exceeded the 0.81 benchmark in almost all cases, which according to Hopkins (Hopkins, 2000) indicates high reliability. Exceptions occurred in lead climbing only, where the ICC for the number of actions of the lower extremities was 0.38. This may be due to the fact that the two raters disagreed as to whether short contacts with the wall are a sufficient criterion to rate them as separate actions. However, the difference was rather small ($M = 1.25$, standard deviation [SD] $= 2.12$) and the ICC could be largely influenced by the small number of observations ($n = 8$).

A general high reliability is in line with existing studies in this field (Schädle-Schardt, 1998; White and Olsen, 2010; Arbulu et al., 2015). This further confirms time-motion analysis as a reliable tool to analyze kinematic parameters in the context of load structure determination.

Statistical Analyses

IBM® SPSS® Statistics (RRID:SCR_019096, Version 26) was used for all statistical analyses.

For speed, the climbing route is highly standardized, and therefore statistical tests for analyzing group differences were applied: *t*-tests to calculate group differences between genders for the assessed independent variables start time, number of actions upper and lower limbs, and contact and reach times for upper and lower limbs. Statistical significance was accepted at $p < 0.05$ level. For bouldering, lead, and Olympic combined, in contrast, only descriptive data are provided. Due to the dependency of the load structure on route characteristics and climbing style of the athletes, which differ between rounds and genders, no inferential statistics were calculated.

RESULTS

Speed

The load structure in speed climbing is determined by two attempts in the qualification round and one attempt in each stage of the final round. Each attempt is characterized by the start time, the number of actions, and the contact and the reach times of the upper and lower limbs. Statistics from those variables are presented in **Table 2**.

TABLE 1 | Inter-rater reliability of the analyzed dependent variables used for load structure determination.

	Variables	ICC	95% CI LL	95% CI UL
Speed	Start time	0.90*	−0.01	1.00
	Number of actions upper limbs	1.00***	1.00	1.00
	Number of actions lower limbs	1.00***	1.00	1.00
	Contact time upper limbs	0.98***	0.88	0.99
	Contact time lower limbs	0.93***	0.72	0.97
	Reach time upper limbs	0.89***	0.70	0.95
	Reach time lower limbs	0.92***	0.66	0.97
Bouldering	Number of attempts per boulder	1.00***	1.00	1.00
	Successful attempt duration	1.00***	1.00	1.00
	Non-successful attempt duration	1.00***	1.00	1.00
	Climbing time per boulder	1.00***	1.00	1.00
	Average attempt duration per boulder	1.00***	1.00	1.00
	Observation time	0.99***	0.91	1.00
	Resting time between attempts	1.00***	1.00	1.00
	Resting time per boulder	1.00***	0.99	1.00
	Resting time between boulders	1.00***	1.00	1.00
	Ratio between climbing and resting time	1.00***	0.99	1.00
Lead	Total climbing time	0.99***	0.92	1.00
	Number of actions upper limbs	0.97***	0.85	0.99
	Number of actions lower limbs	0.38	−1.00	0.86
	Contact time upper limbs	0.99***	0.99	1.00
	Contact time lower limbs	1.00***	1.00	1.00
	Reach time upper limbs	0.99***	0.99	1.00
	Reach time upper limbs grapping only	0.97***	0.96	0.98
	Reach time lower limbs	0.98***	0.98	0.97
Olympic combined	Resting times between runs in speed	1.00***	1.00	1.00
	Resting time between speed and bouldering	1.00***	1.00	1.00
	Resting time between bouldering and lead	1.00**	1.00	1.00
	Total competition duration	1.00***	1.00	1.00

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.*

Group comparison showed significant differences between the load characteristics of women and men for all of the analyzed parameters. Consistently, longer durations were found in the women's than in the men's category.

Bouldering

The structure of bouldering competitions consists of a course of boulders (5 in the qualification round and 4 in the semi-final and final round) which have to be climbed within a fixed time period. Within each climbing period, the athletes attempted a boulder problem 3 times in the qualification-/semi-final round and 4 times in the final round at a median with an average attempt

TABLE 2 | Statistics of international speed climbing competitions.

		Start time	Number of actions upper limbs	Number of actions lower limbs	Contact time upper limbs	Contact time lower limbs	Reach time upper limbs	Reach time lower limbs
Women	*N*	20	40	40	421	427	439	466
	M	0.10 s	11.2	11.7	0.25 s	0.39 s	0.49 s	0.33 s
	SD	0.08 s	0.5	1.1	0.08 s	0.14 s	13.24 s	11.03 s
	Median	0.07 s	11.0	12.0	0.23 s	0.40 s	0.36 s	0.28 s
Men	*N*	20	40	40	365	366	385	406
	M	−0.08 s	9.7	10.2	0.24 s	0.36 s	0.38 s	0.23 s
	SD	0.09 s	0.8	1.0	0.08 s	0.11 s	0.11 s	0.10 s
	Median	−0.07 s	9.0	10.0	0.19 s	0.32 s	0.35 s	0.33 s
Women vs. men	*T*	5.977	10.505	6.471	2.283	3.179	11.712	11.982
	P	<0.001	<0.001	<0.001	0.023	0.002	<0.001	<0.001
	Mean difference	0.18	1.5	1.6	0.01	0.03	0.12	0.10
	95% CI LL	0.12	1.2	1.1	0.00	0.01	0.10	0.08
	95% CI UL	0.24	1.8	2.0	0.02	0.05	0.14	0.11

Sample: 20 runs from 12 female and 14 male athletes, respectively. N, sample size; M, mean; SD, standard deviation; T, t-value; P, p-value; CI LL, confidence interval, lower limit; CI UL, confidence interval, upper limit.

TABLE 3 | Statistics of international bouldering competitions.

		Number of attempts per boulder	Successful attempt duration	Non-successful attempt duration	Climbing time per boulder	Average attempt duration per boulder	Observation time	Resting time between attempts	Resting time per boulder	Resting time between boulders	Ratio between climbing and resting time
Qualification and semifinal round women	*N*	177	91	485	176	173	175	397	173	70	173
	M	3.2	39 s	21 s	76 s	28 s	47 s	35 s	125 s	498 s	0.72
	SD	2.0	14 s	14 s	42 s	13 s	11 s	21 s	66 s	167 s	0.42
	Median	3	36 s	18 s	68 s	25 s	48 s	33 s	119 s	421 s	0.60
Qualification and semifinal round men	*N*	180	111	548	175	175	172	420	135	67	134
	M	3.4	32 s	13 s	62 s	27 s	51 s	34 s	113 s	430 s	0.68
	SD	2.7	13 s	13 s	33 s	18 s	13 s	22 s	73 s	84 s	0.49
	Median	3	29 s	8 s	54 s	24 s	50 s	31 s	90 s	394 s	0.56
Final round women	*N*	48	25	202	48	48	48	173	47	36	47
	M	4.4	39 s	12 s	70 s	27 s	16 s	22 s	96 s	1308 s	1.72
	SD	4.0	19 s	14 s	34 s	24 s	8 s	14 s	68 s	366 s	2.39
	Median	4	35 s	6 s	70 s	24 s	15 s	19 s	91 s	1468 s	0.94
Final round men	*N*	52	26	182	52	52	52	142	52	39	52
	M	3.7	31 s	16 s	73 s	24 s	20 s	32 s	109 s	1416 s	1.10
	SD	1.8	12 s	13 s	33 s	15 s	10 s	21 s	57 s	165 s	1.18
	Median	4	28 s	12 s	66 s	21 s	19 s	28 s	112 s	1419 s	0.69

Sample: 52 courses from 20 female and 24 male athletes, respectively. N, sample size; M, mean; SD, standard deviation.

duration of 27.0 s and an average resting time between attempts of 32.2 s. Due to the different modes applied, the resting time between boulders was around 8 min in the qualification-/semi-final round and 22 min in the final round.

Details about the load structure in bouldering are presented in **Table 3**.

Lead

The load structure in lead climbing is characterized by two attempts in the qualification round with a minimum resting time of 50 min in-between and by a single attempt in the semi-final and final rounds. Every attempt is characterized by an average climbing time of 4:09 and 4:18 min, 31.6 and 30.0 actions, contact times of 6.4 and 6.2 s, and reach times of 1.4 and 1.6 s in the women's and men's category, respectively. Statistics analyzing the climbing, contact and reach times, and the number of actions in a more detailed way are presented in **Table 4**.

The average durations of contact and reach times were equal between the left and the right bodyside for both the upper and lower limbs. Reach times of the upper limbs were further

TABLE 4 | Statistics of climbing, contact and reach time, and the number of actions at international lead climbing competitions.

		Total climbing time	Number of actions upper limbs	Number of actions lower limbs	Contact time upper limbs	Contact time lower limbs	Reach time upper limbs	Reach time upper limbs grapping only	Reach time lower limbs
Qualification round women	*N*	10	20	20	584	705	564	275	682
	M	3:39 min:s	29.4	35.5	8.01 s	6.98 s	2.17 s	0.69 s	1.21 s
	SD	0:48 min:s	4.8	5.2	4.81 s	7.04 s	2.23 s	1.14 s	1.56 s
	Median	3:40 min:s	28.5	35.5	7.60 s	4.87 s	1.36 s	0.43 s	0.73 s
Qualification round men	*N*	16	32	32	874	1,000	831	473	958
	M	4:55 min:s	27.3	31.3	6.61 s	6.18 s	2.07 s	0.65 s	1.38 s
	SD	0:49 min:s	3.5	4.2	3.64 s	8.05 s	2.21 s	0.71 s	1.94 s
	Median	4:40 min:s	27.5	32.0	6.10 s	3.87 s	0.77 s	0.47 s	0.77 s
Semifinal and final round women	*N*	26	52	52	1,393	1,602	1,356	728	1,587
	M	4:21 min:s	27.9	34.6	5.63 s	6.13 s	1.50 s	0.62 s	1.20 s
	SD	0:56 min:s	7.2	4.2	4.95 s	6.32 s	2.49 s	2.39 s	1.57 s
	Median	4:11 min:s	27.5	34.5	5.25 s	4.17 s	0.53 s	0.43 s	0.8 s
Semifinal and final round men	*N*	26	52	52	1,432	1,535	1,398	792	1,519
	M	3:55 min:s	28.8	32	6.30 s	5.98 s	1.86 s	0.69 s	1.34 s
	SD	1:08 min:s	8.1	9.2	4.04 s	7.43 s	1.97 s	1.00 s	2.13 s
	Median	3:52 min:s	28.0	30.5	5.95 s	3.73 s	0.77 s	0.47 s	0.73 s

Sample: 37 attempts from 12 female athletes and 43 attempts from 25 male athletes. N, sample size; M, mean; SD, standard deviation.

subdivided: reaching directly (grabbing only) for the next hold occurred most frequently (54.9%) and lasted up to 1 s in 90.8% of the cases. In 81.9% of cases, reaching directly for the next hold occurred either alone or in combination with the other categories. Athletes shook their hand, clipped, or chalked in 4.0, 3.4, and 2.3% of the actions, though when combined with grabbing, these percentages were increased to 4.3, 4.4, and 8.1%, respectively. Shaking alone or in combination with other categories ("shaking any") were occurred in 24.5% of the actions, "clipping any" in 21.3% and "chalking any" in 19.5%. For those, a different frequency distribution pattern of the durations had been found in comparison to "grabbing only" with the majority of the reach times lasting longer than 3 s for "shaking any," longer than 2 s for "clipping any," and longer than 5 s for "chalking any."

Regarding finger grip positions: In the women's category, the crimp grip was applied in 66.5% of the cases and the open hand grip in 33.5% whereas, in the men's category, the crimp and open hand crimp were applied in 36.7 and 63.3% of the cases, respectively.

Olympic Combined

The load structure of the final round of Olympic combined is considered apart from that of the single disciplines and is characterized by the resting time between the runs in speed, the resting time between speed and bouldering and between bouldering and lead, and the total duration of the competition. Statistics are presented in **Table 5**.

DISCUSSION

Speed

The median number of actions was varied between 9 and 12 for the upper and the lower limbs, respectively, with men carrying out fewer actions than women. These gender-related differences are caused by the fact that men tend to skip hold 7 referring to numbering all holds that include footholds in an ascending order from the ground. This is well known as the so-called "Tomoa Skip." Higher up, women used hold 18 with their right hand whereas men directly went from hold 14 to 19 skipping hold 18. However, very low SDs show that the movement sequences of the top athletes are very standardized.

Movement speed can be derived from the sum of contact and reach times resulting in an average movement time for the upper and lower limbs of 0.74 and 0.72 s in the women's and 0.62 and 0.59 s for the men's category, respectively. Not considering the differentiation between the upper and lower limbs, the average movement time was 0.73 s in the women's and 0.60 s in the men's category. Men carried out fewer actions than women and therefore had to cover a greater distance per action and nonetheless also had significantly shorter contact and reach times. However, this is hardly surprising given that men and women compete on an identical route despite having different constitutions.

Notably, contact times recorded are shorter than those found by Fuss and Niegl (2006). On the one hand, this could be due to the fact that their study was conducted on a non-standardized route; on the other, it could be due to the fact that athletes have become significantly faster in recent years. For example, between 2009 and 2018, the fastest time at the World Championships was improved from 9.3 to 7.65 s for women and from 6.64 to 5.63 s for men (International Federation of Sport Climbing, 2021). The differences between women and men might be related to sex-related strength differences (Sandbakk et al., 2018).

Another interesting finding is that the starting time was on average 0.01 s in the women's and −0.08 s in the men's category. Due to the fact that the start signal can be anticipated

TABLE 5 | Statistics of international Olympic combined climbing competitions.

		Resting times between runs in speed	Resting time between speed and bouldering	Resting time between bouldering and lead	Total competition duration
Final round women	*N*	8	6	6	6
	M	6:41 min:s	31:11 min:s	41:55 min:s	2:52 min:s
	SD	1:20 min:s	4:32 min:s	9:17 min:s	0:12 min:s
	Min	4:14 min:s	24:52 min:s	35:10 min:s	2:35 min:s
	Max	8:34 min:s	37:22 min:s	59:07 min:s	3:07 min:s
Final round men	*N*	8	6	6	6
	M	6:08 min:s	30:41 min:s	34:31 min:s	2:29 min:s
	SD	1:41 min:s	3:21 min:s	8:47 min:s	0:11 min:s
	Min	3:19 min:s	26:28 min:s	24:02 min:s	2:14 min:s
	Max	8:20 min:s	36:26 min:s	45:43 min:s	2:44 min:s

Sample: 6 competition courses from 6 athletes per category. N, sample size; M, mean; SD, standard deviation; Min, minimum; Max, maximum.

(International Federation of Sport Climbing, 2020), athletes partly started the movement before the last beep of the countdown. Such short or even negative starting times seem likely with years of practice taking into account the findings from Borysiuk and Sadowski (2007), who observed a significant reduction in latent reaction time due to time anticipation within a single experiment. The ability to precisely anticipate and appropriately coordinate the movement start may imply a high-performance benefit.

In terms of practical application, the recommended number of repetitions for sport-specific testing and training protocols should reflect the median number of actions, which varies from 9 and 12. Furthermore, the movement speed of around 0.73 and 0.6 s for women and men, respectively, serves as an additional training parameter and biometric feedback tool for training control (Weakley et al., 2021). Additionally and as already mentioned, minimizing starting times holds the potential to significantly reduce speed running times.

Bouldering

The load structure in bouldering is characterized by bouts of activity punctuated with resting periods. Therefore, the ability to recover seems crucial. Well-trained recovery ability enables competitors to shorten the resting times between attempts, therefore, permitting them to make more attempts within each climbing period and through the course of the entire competition. The importance of endurance for bouldering performance is supported by the findings of numerous studies (Fryer et al., 2017; Michailov et al., 2018; Stien et al., 2019). Other factors contributing to success in bouldering are high bouldering skills and excellent onsight/flash climbing abilities. Furthermore, another key component was found to be the discovery of new creative solutions after an unsuccessful attempt (Künzell et al., 2021).

The current study updates and expands existing knowledge due to its relatively large sample size and its analysis of all rounds of current competition bouldering when compared to the study of a national competition by White and Olsen (2010) and to the study of World Cups 5 years earlier by Medernach et al. (2016). The comparison of concrete results with the study of Medernach et al. (2016), who analyzed a competition that was held in the same format, shows that in our study women executed fewer attempts ($M = 3.2$ vs. $M = 5.1$) but with longer durations ($M = 28$ s vs. $M = 15$ s). Men executed fewer attempts as well ($M = 3.4$ vs. $M = 4.3$) and rested longer in between them ($M = 34$ s vs. $M = 27$ s). This indicates a trend toward executing fewer but more well-planned attempts while focusing on recovery between them in order to increase success. This underlines the necessity of up-to-date competition analyses in order to map the load structure correctly and help athletes to be prepared in the best way possible.

In terms of practical application: In bouldering, the load structure is determined by alternating climbing and resting periods. Therefore, in order to simulate the load structure of bouldering competitions, it is recommended to train multiple (Billat et al., 1995; Mermier and Robergs, 1997) high-intensity efforts (equaling the number of attempts) with durations of around 30–40 s (equaling average and successful attempt durations) followed by resting periods of around 20–30 s (equaling the resting time between attempts) and to perform 4–5 sets (equaling the number of boulders) with serial rests of either 8 or 22 min between sets (equaling the resting time between boulders).

As recovery ability is paramount in bouldering, recovery strategies targeting the different resting times found in bouldering competitions should be developed and practiced.

Lead

The current study provides valuable insights into the current load structure in competitive lead climbing.

As already stated, various rule changes and changes in climbing and route setting styles have occurred in recent years, which could explain the differences between studies. In detail, the trend toward a more dynamic and faster climbing style is reflected in the contact and reach times, which were consistently lower in this study compared to the previous ones [contact time upper limbs women: $M = 5.63$ s vs. $M = 10.3$ s (Schädle-Schardt, 1998) vs. $M = 8.5$ s (Arbulu et al., 2015), contact time upper limbs men: $M = 5.63$ s vs. $M = 9.1$ s (Schädle-Schardt, 1998) vs. $M = 7.0$ s (Arbulu et al., 2015), reach time upper limbs women: $M = 1.50$ s vs. $M = 2.4$ s (Schädle-Schardt, 1998), and reach time upper limbs men: $M = 1.86$ s vs. $M = 2.5$ s (Schädle-Schardt, 1998)].

Since reaching directly for the next hold ("grabbing only") accounts for only 54.9% of the cases, contact and reach times are highly influenced by the frequencies and durations of shaking, clipping, and chalking of the athletes, which might contribute to the much shorter durations reported above in comparison to the findings of Schädle-Schardt (Schädle-Schardt, 1998) and Arbulu et al. (2015).

Short contact and reach times and high climbing speed might positively influence the climbing economy if the route requirements tend to exceed the athlete's critical force (Giles et al., 2021) and maintaining a stronger pace throughout the attempt has been shown to be beneficial for competition climbing success (Arbulu et al., 2015; Kotchenko, 2017). According to routesetters, women had to face difficulties of around 8b in the qualification round and 8b+/8c in the final rounds whereas men faced difficulties of 8b+/8c in the qualification and 8c+ in the final rounds.

A practical implication, which can be derived from the load structure in lead climbing for performance analysis, for example, is the assessment of climbing-specific intermittent finger endurance. Different test protocols have been used but the ones that are representative of the load structure of current competition climbing should be prioritized (Michailov et al., 2018). Based on the results, this would mean a 6 s work to 2 s rest ratio representing the overall averages of contact and reach times.

Olympic Combined

The combination of all 3 single disciplines within the final round of Olympic combined climbing competitions results in a higher competition load as compared to the single disciplines.

The average resting time between the runs in speed climbing was 6:24 min (SD = 1:29). Minimal and maximal resting times were 3:19 and 8:34 min, respectively. This relatively large deviation could be explained by the competition format.

The same accounts for the resting times between speed and bouldering and between bouldering and lead. Due to the starting order of the subsequent disciplines being in reverse order with respect to ranking up until this point in the competition, the differences between the minimal and maximal resting times were roughly 13 and 10 min between speed and bouldering and 24 and 21 min between bouldering and lead in the women's and men's category, respectively.

Given the high competition loads and the relatively short resting times between disciplines, a practical application of this study's result may be that athletes should not only train in a way to maximize performance in the single disciplines but to also handle the required high load, long duration, and short resting times of the combined format.

Crucial aspects for targeting this are tailored fueling (Michael et al., 2019) and recovery strategies. The latter must be highly effective and at the same time require a very limited amount of time. The reason for this is that in practice, the resting times can only partially be used for recovery due to fact that the observation period of the following discipline (4 times 2 min for bouldering and 6 min for lead), immediate climbing preparation, and other activities take place during this period.

Evidence indicates that a few minutes of active recovery either by walking or easy climbing (Draper et al., 2006; Valenzuela et al., 2015) lead to improved recovery and therefore are considered a tailored recovery strategy. For cold water immersion, in contrast, only durations of 20 min have been evaluated (Heyman et al., 2009) while the benefit of shorter periods remains unclear.

LIMITATIONS

The main limitation of the current study is the dependency of load structure on route characteristics. These vary greatly from competition to competition and even from boulder/route to boulder/route and therefore it is generally difficult to derive a universally valid load structure. Single influences were reduced by a broader data basis, which was derived from the selection of different routes and courses of competitions from different competitions. Nevertheless, the current study is limited in regard to the chosen sample and by virtue of not considering a wider range of competitions.

Furthermore, load structure is dependent on an athlete's climbing style. By analyzing the world's best climbers in each discipline, the presented load structure tends to be more valid for high-level athletes who compete at international climbing competitions than for lower level climbers who have different climbing abilities and might not be able to use the same methods (e.g., the so-called Tomoa skip in speed climbing). These athletes should therefore use load structures that represent the requirements of their own climbs and climbing abilities.

Another limitation arises from the constant development of climbing and route setting styles, which means that the presented load structure based on 2018 competitions does not necessarily represent the requirements of current competitions. This is especially true of the Olympic combined where a new format will be applied in the 2024 Olympic Games. Generally speaking, a retrospective approach is an inherent problem of this research area.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Commitee for Ethics University of Augsburg. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

All authors conceived of and designed the analysis, collected the data, discussed the results, and contributed to the final manuscript. MW performed the data and statistical analysis and took lead in writing and editing the manuscript. By providing critical feedback and revising the initial manuscript, CA and SK helped shaped the final manuscript. CA supervised the project. All authors contributed to the article and approved the submitted version.

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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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Effects of Different Hangboard Training Intensities on Finger Grip Strength, *Stamina*, and *Endurance*

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Climbing-specific training programs on hangboards are often based on dead-hang repetitions, but little is known about the real intensity applied during such effort. The aim of this study was to quantify and compare the effects of different training intensities (maximal, high submaximal, and low submaximal intensities) on the fingers' physiological capabilities using a hangboard fitted with force sensors. In total, 54 experienced climbers (13 women and 41 men) were randomly divided into four groups, with each group following different training intensity programs: maximal strength program performed at 100% of the maximal finger strength (MFS; F100), intermittent repetitions at 80% MFS (F80), intermittent repetitions at 60% MFS (F60), and no specific training (control group). Participants trained on a 12 mm-deep hold, twice a week for 4 weeks. The MFS, *stamina*, and *endurance* levels were evaluated using force data before and after training. Results showed similar values in the control group between pre- and post-tests. A significantly improved MFS was observed in the F100 and F80 groups but not in the F60 group. Significantly higher *stamina* and *endurance* measurements were observed in the F80 and F60 groups but not in the F100 group. These results showed that a 4-week hangboard training enabled increasing MFS, *stamina* and *endurance*, and that different improvements occurred according to the level of training intensity. Interestingly, the different intensities allow improvements in the targeted capacity (e.g., *stamina* for the F80 group) but also in the adjacent physiological capabilities (e.g., MFS for the F80 group).

Keywords: climbing, training, force intensity, finger strength, fatigue, stamina, endurance

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INTRODUCTION

The introduction of sport climbing at the recent 2021 Olympic Games in Tokyo is the result of a considerable increase in the number of recreational and competitive practitioners and climbing structures. Climbing performance requires a complex combination of physiological, psychological, technical, and tactical resources for successfully climbing a particular route or mastering a boulder problem (Saul et al., 2019). Among such resources, a key factor for performance is the ability to generate finger strength and the ability to limit forearm muscle fatigue (Watts et al., 1996). Climbing indeed generates intense and intermittent isometric contractions of the muscles actioning the hand and the fingers, especially those located in the forearm (Ferguson and Brown, 1997).

During climbing, three physiological forearm parameters have been identified: (i) the capability to exert maximal finger force on holds (Schweizer and Furrer, 2007), (ii) the time to exhaustion (called *stamina* here) which is the capacity to maintain a certain level of high-force intensity before fatigue, i.e., before loss of strength occurs over time (Quaine et al., 2003), and (iii) the level of force intensity that the climber is still able to sustain once he/she is in a state of exhaustion (Vigouroux and Quaine, 2006), i.e., after having experienced the onset of fatigue [known as critical force (Giles et al., 2019) or *endurance* here]. These physiological parameters are peculiar to climbing and are the results of specific physiological phenomena acting at the forearm level. Specifically, forearm ischemia occurs at 45–75% of maximal finger grip force (Barnes, 1980; Macleod et al., 2007) which implies that climbers should develop muscle force capabilities and local anaerobic and aerobic capabilities and also capabilities to limit the effect of the local ischemia on muscle physiology. These determinants make climbing a unique activity in that it involves training principles in fingers, hands, and forearms that are not found in other sports.

To maximize the climbers' physiological capabilities, climbing alone is a good strategy for novices, but not sufficient for more experienced climbers (Hörst, 2008). This is the reason as to why climbing-specific training tools such as hangboards have been developed and are widely used both by the trainers and by the climbers (Hörst, 2008). Hangboards are equipped with holds of various shapes, sizes, widths, and depths. To improve the maximal finger strength, some training techniques propose to work at the maximum intensity by hanging for a short time (e.g., 3 s) with maximal added weight or on the minimum depth edge and repeat it several times (e.g., 3 repetitions with 60 s rest time; López-Rivera and González-Badillo, 2012; Levernier and Laffaye, 2019; Mundry et al., 2021). To enhance *stamina*, some training sessions propose hanging intermittently (e.g., López-Rivera and González-Badillo, 2019; alternating 10 s hanging and 5 s resting), generally with the full body weight, on a hold less than one phalange deep (López-Rivera and González-Badillo, 2019), for a required number of repetitions (Medernach et al., 2015) usually defined to be close to failure during the last one (López-Rivera and González-Badillo, 2019). To work at the *endurance* level, training with more dead-hang repetitions is proposed, but at moderate intensity by reducing body weight using pulleys while hanging and until exhaustion (Giles et al., 2019), in order to induce fatigue and then increase the force level that can be maintained once fatigue is established.

Thus, until now, the intensity of the exercises designed for use on hangboards has been typically judiciously adjusted by modulating the three following parameters: the size of holds, the hanging and rest times and/or the number of repetitions, and adding/subtracting weight while hanging (López-Rivera and González-Badillo, 2012, 2019; Medernach et al., 2015; Levernier and Laffaye, 2019). Thus, training strategies to control intensity consist of manipulating some of these parameters while kipping others equal. For example, Medernach et al. (2015) proposed (in part) to train at body weight by modifying hanging times between 3 and 10 s and number of repetitions between 6 and 10, supervised by the coaches. Nevertheless, such methods could have some limits: first, changing the size (and even the form) of holds implies different positions and surfaces used by fingers and generates different muscle coordination such that the training exercise addresses different synergies instead of only changing the intensity. Second, modulating the time or the number of repetitions to adjust exercise intensity (e.g., hanging less time or less repetitions on the same hold with body weight to decrease the difficulty) may involve a change in the targeted physiological capacities instead of changing only the exercise intensity (e.g., from *stamina* to strength when decreasing the hanging time or the repetitions). Finally, using additional or reducing weight is not convenient as it requires use of harness, rope or loads, and it is hard to set the accurate right level of weight for each repetition.

Nowadays, newly developed instrumented hangboards or single holds provide improvement in feasibility and accuracy, and are a valid and reliable measurement of applied loads with an accuracy in the <1 N range (Anderson, 2018; Michailov et al., 2018; Vigouroux et al., 2018; Feldmann et al., 2021; Marino et al., 2021). These instrumented tools technically allow modulating training exercise intensity thanks to force visual feedback, on the same hold. Though, little is known about how this modulation should be carried out to obtain the best improvements in the various physiological capacities. For example, with a maximal intensity exercise targeting maximal finger strength improvement, we ignore the impact on other physiological parameters (*stamina* and *endurance*). This approach is crucial to clarify as it is consistent with many training programs in other sports that modulate intensity of force exerted during exercise (Bompa and Carrera, 2005; Suchomel et al., 2021). We are also questioning what physiological adaptation processes are involved depending upon the intensity.

Thus, the aim of this study was to quantify the effects of several training intensities on the finger's physiological capabilities with an instrumented hangboard. Three training programs (maximal, high-submaximal intensity, and low-submaximal intensity) performed during 4 weeks were tested. We hypothesized that the improvements in the three physiological parameters (maximal finger strength, *stamina*, and *endurance*) are different depending on the level of force intensity required during the training exercises, i.e., high-intensity training increases maximal strength and low-intensity training increases resistance to fatigue. We also hypothesized that the amount of benefit in one physiological parameter is dependent on its baseline level (whether maximal finger strength, *stamina*, or *endurance*).

MATERIALS AND METHODS

Participants

In total, 54 climbers were tested (13 women and 41 men, 25.0 ± 6.2 years old, 173.6 ± 8.3 cm, 64.2 ± 8.7 kg). They were advanced or elite climbers according to IRCRA (International Rock Climbing Research Association) scale (Draper et al., 2015), mostly lead rock practitioners (see **Table 1** for red-point grade). They were randomized into four different training protocols, each following different training intensity programs or no specific training (control group, CT). Participants had no hand or upper extremity injuries in the 6 months prior to the test. They were

TABLE 1 | Descriptive characteristics of the participants of each group (mean ± SD).

	F60 ($n = 14$)	F80 ($n = 14$)	F100 ($n = 14$)	CT ($n = 12$)	*p*-value
Age (y)	23.8 ± 4.3	23.4 ± 5.0	23.3 ± 4.5	28.8 ± 9.4	0.08
Height (cm)	171.1 ± 8.9	174.4 ± 9.7	174.1 ± 7.0	175.0 ± 7.5	0.62
Body mass before training (kg)	62.6 ± 7.5	64.1 ± 9.2	63.7 ± 7.9	67.0 ± 10.8	0.63
Body mass after training (kg)	62.6 ± 7.9	64.3 ± 9.1	63.5 ± 7.6	67.4 ± 10.9	0.57
"On-sight" performance (au)	18.3 ± 2.7	17.6 ± 3.5	17.2 ± 2.6	18.1 ± 3.6	0.83
"Redpoint" performance (au)	21.7 ± 3.7	20.9 ± 3.3	20.5 ± 3.3	21.2 ± 3.8	0.82

"On-sight" performance means climbing a sport route at the first attempt without any information about it; "Redpoint" performance means climbing a sport route after inspecting and practicing it. Both performances represent the most difficult grade achieved in the past 6 months and are converted to the IRCRA scale. p-values represent results of the one-way ANOVA comparing the four tested groups.

informed of the risks and benefits of the research protocol and signed a consent form. Protocol has been validated by the sport science national ethics committee.

Procedures

The participants first performed some initial tests (week 1) consisting of an assessment of maximal finger strength (MFS), *stamina*, and *endurance* on a hangboard fitted with strain gauges (SmartBoard, Peypin d'Aigues, France). This hangboard (**Figure 1**) provides real-time feedback about the vertical force applied on it allowing precise modulation of the force intensity (1 N accuracy). Data concerning the force applied to the holds re recorded and analyzed using the SmartBoard app (50 Hz). r the following 4 weeks (weeks 2–5), they followed one of the three training protocols [except for the CT group ($n = 12$)] on the instrumented hangboard with 2 sessions per week, with at least 1 day rest between sessions. Participants were instructed to continue their climbing activity normally outside of the study without increasing or decreasing their current practice. Post-training tests, identical to the initial ones, were performed at week 6 in all the groups. In order to avoid fatigue effects, the participants were not allowed to climb the day before the initial and post-tests.

Test Sessions (Weeks 1 and 6)

Strength Test

After a 30 min warm-up and familiarization with the SmartBoard, consisting of muscular awakening, easy traverses and specific exercises on the SmartBoard with increasing intensities, climbers had to exert the maximum force with one hand on a 12 mm hold for 6 s (climbers were weighted when needed to perform a force intensity higher than their body weight). The type of grip (slope, half-crimp, and full crimp) was self-selected and it was required that participants used the same grip throughout the experiment. Two trials were tested on each hand, and the best was selected. The sum of the maximum forces exerted with the right and left hands was directly displayed on the interface and was considered as the participant's initial maximal finger strength (MFSi) at week 1 and post-MFS (MFSp) at week 6.

Fatigue Test

On a 12 mm-width ledge, participants exerted 80% MFSi by alternating a hanging phase of 10 s and a rest phase of 6 s during 24 repetitions. The 80% level was controlled by the visual force feedback and carefully adjusted by off-loading with feet on the ground or conversely using additional ballast. The fatigue test reproduced the one performed in Vigouroux and Quaine (2006): when the subjects were not able to maintain the required 80% MFSi, they were required to continue the exercise and exert the maximum level of force they are able. Generally, this last part was performed by off-loading at the minimum possible the body weight with feet on the ground as illustrated in **Figure 1**. The recorded fatigue kinetic (**Figure 2**) allows evaluating the percentage of *stamina* (determined as the capacity to maintain the required 80% for the overall duration of the test) and the percentage of *endurance* (determined as the level of force intensity that the climber is able to perform when he is exhausted in comparison to the initial level of force), directly displayed by the app.

Training Sessions (Weeks 2–5)

Each training protocol used the same 12 mm hold. For this study, three different training programs (F60, F80, and F100) were tested. These trainings are detailed later and were determined (i) from literature to develop maximal force intensity (F100) and (ii) to induce fatigue (F60 and F80) with different force intensities but similar overall loads.

F60 Protocol

Participants ($n = 14$) exerted efforts representing 60% MFSi by alternating a 10 s-hang phase with the two hands and a 6 s-rest phase, 24 times. The 60% level was controlled throughout the protocol by the visual force feedback and adjusted carefully by off-loading with feet on the ground or conversely using additional ballast. Once fatigue occurred, participants were required to continue the exercise and exert the maximum level of force they are able until the 24th repetition. Two sets were performed, separated by a 6-min recovery period.

F80 Protocol

Participants ($n = 14$) exerted 80% MFSi, by alternating a 10 s-hang phase with the two hands (with or without feet on the ground, weighted if 80% MFSi > body weight) and a 6 s-rest

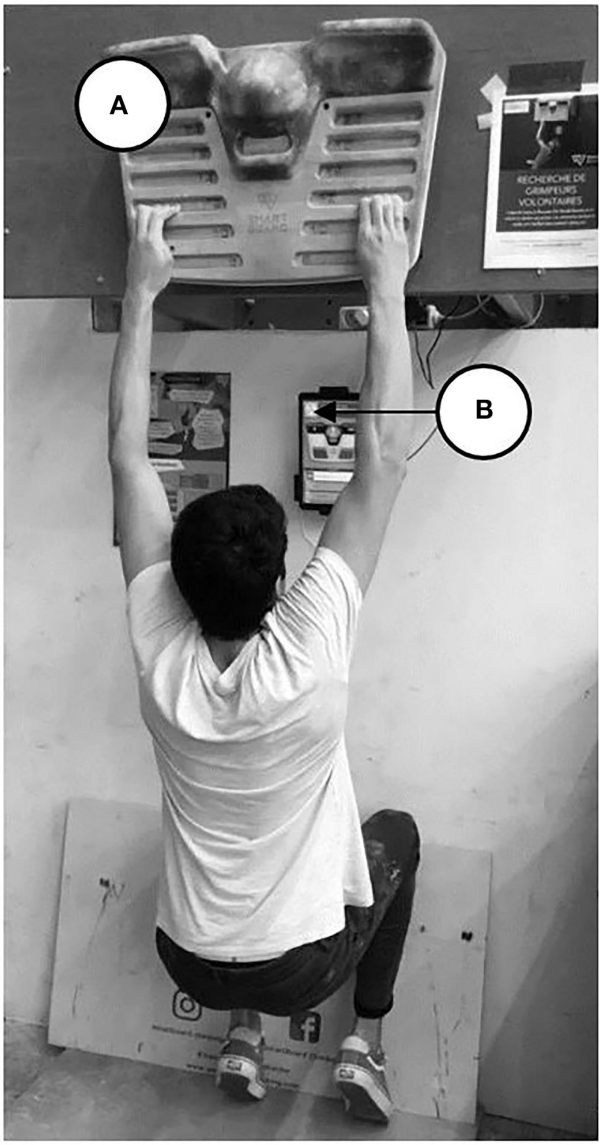

FIGURE 1 | Force-time curve during the 24 repetitions of the fatigue test of one representative participant. *Stamina* (represented by the horizontal arrow) is the capacity to maintain the 80% of maximal finger strength (MFS) threshold. *Endurance* is the percentage of force the participant is able to perform after the onset of fatigue (represented by the dotted black line). On this test, the participant performed 633 N for MFS, 45.2% for *stamina* and 70.3% for *endurance*.

phase, for a maximum of 12 times or, once participants were no longer able to exercise 70% MFSi during the hanging phase, the sets was stopped. Three sets were performed, with 8 min of recovery time between each.

F100 Protocol

This protocol is based on the Levernier and Laffaye protocol (Levernier and Laffaye, 2019). Climbers ($n = 14$) applied their maximum force with the right hand, then with the left hand,

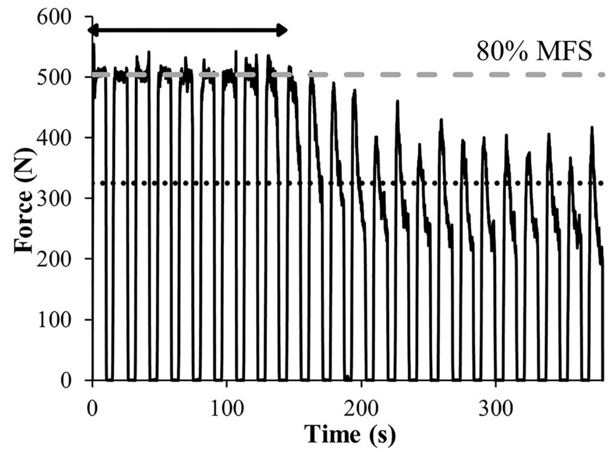

FIGURE 2 | Illustration of one participant during the fatigue test performed on the SmartBoard **(A)**, on the 12 mm hold. The feedback of the force level was displayed on the tablet **(B)** so that the participant can adjust the level of force intensity required during the test/training by using his feet on the ground.

for 6 s each, alternating grip types (slope or half-crimp). If the climbers were able to hang with one hand, they were sufficiently weighted so that they were able to exert their maximal force. Two sets of 6 hangs with each hand were performed every 3 min, with a 5 min-recovery time between sets.

Statistical Analysis

Data are reported as mean ± SD. One-way ANOVA was performed to evaluate differences of the descriptive characteristics between the groups. The effects of training intensity on MFS, *stamina,* and *endurance,* were assessed by comparing the CT, F60, F80, and F100 groups using a two-factor repeated measure ANOVA (training × group), with Tukey *post-hoc* analysis when ANOVAs were significant. In addition, effect sizes (eta squared, η^2) were calculated. To evaluate the relationship between initial levels of MFS, *stamina,* and *endurance* and their benefits after training, Pearson test correlations were assessed. Significance level was set at $p < 0.05$. Statistical tests were processed using STATISTICA software (version 6, StatSoft, Inc.).

RESULTS

The anthropometric data and climbing abilities are summarized in **Table 1**. No statistical differences between groups were observed for all characteristics ($p > 0.05$).

Maximal Finger Strength

Maximal finger strength results before and after training are presented in **Figure 3A**. Statistical analysis did not show any group effect on MFS [$F_{(3,50)} = 0.7$; $\eta^2 = 0.039$; $p = 0.56$]. A significant training effect was observed [$F_{(1,50)} = 68.9$; $\eta^2 = 0.032$; $p < 0.001$] showing that MFS was greater after training than before. Significant interaction [$F_{(3,50)} = 10.3$; $\eta^2 = 0.014$; $p < 0.001$] showed that the increase in MFS was different by group

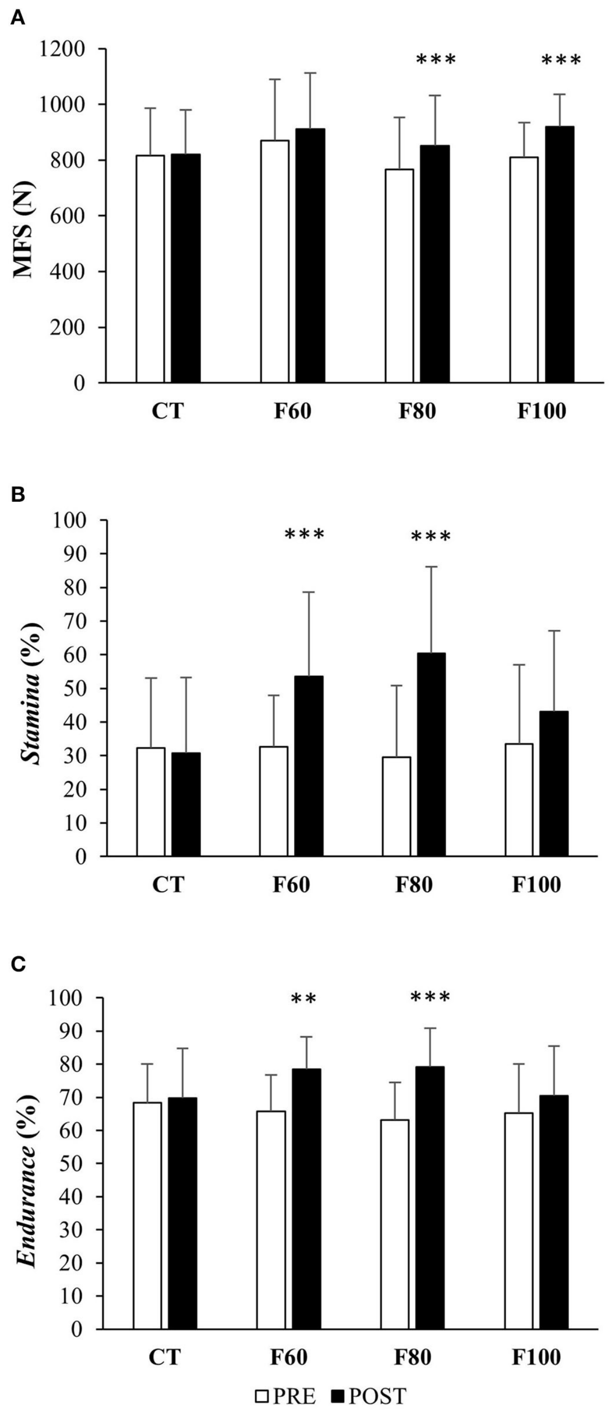

FIGURE 3 | Mean values (± standard types) of **(A)** maximal finger strength (MFS in N), **(B)** *stamina* (in %), and **(C)** *endurance* level (in %) in each group (CT, F60, F80, and F100) pre- (white bars) and post- (black bars) training. Significance differences were shown (**$p < 0.01$ and ***$p < 0.001$) relative to pre-training.

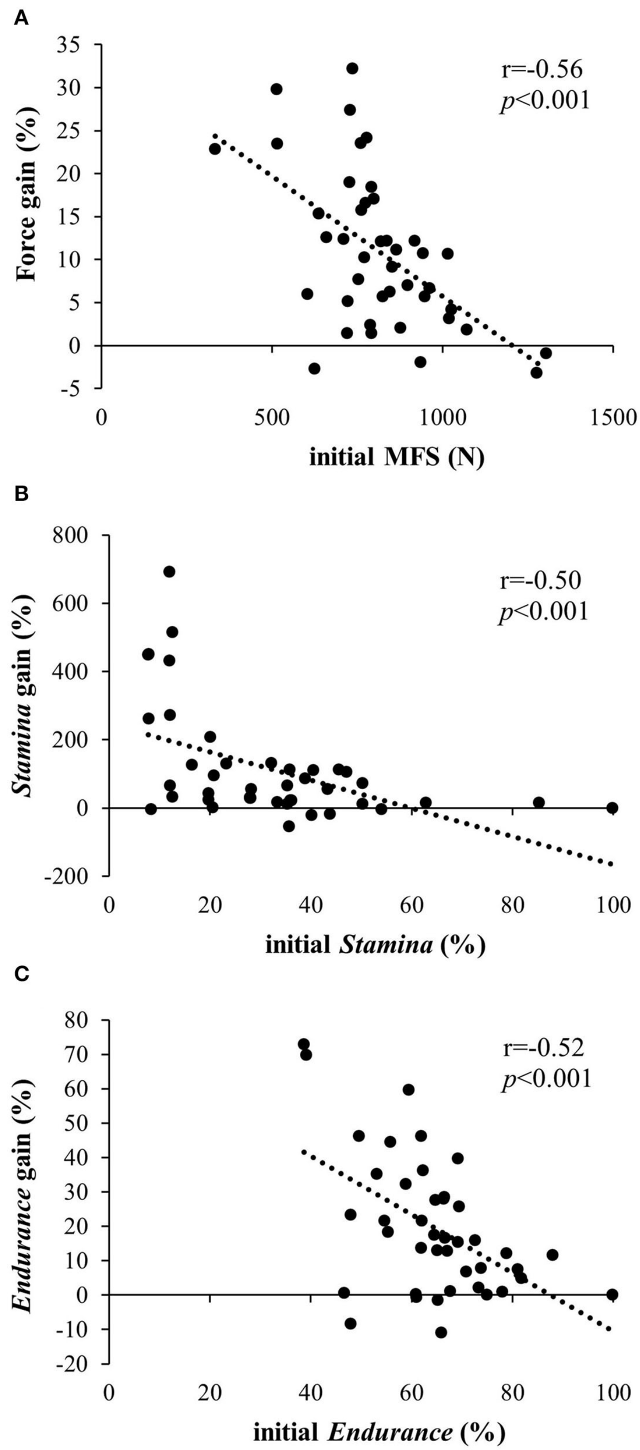

FIGURE 4 | Post-training gain (in %) according to the initial **(A)** MFS (in N), **(B)** *stamina* (in %), and **(C)** *endurance* (in %) for training group subjects (F60, F80, and F100).

(+0.7 ± 5.0%; +5.9 ± 8.2%; +12.4 ± 8.4% and +14.3 ± 8.8% for the CT, F60, F80, and F100 groups, respectively). *Post-hoc* tests revealed that MFS was significantly different in the F80 and F100 groups ($p < 0.001$) before (767 ± 186 N and 810 ± 125 N for the F80 and F100 groups, respectively) and after training (852 ± 178 N and 920 ± 116 N for the F80 and F100 groups, respectively) but not in the CT and F60 groups (before: 816 ± 170 N and 869 ± 221 N, respectively; after: 820 ± 160 N and 912 ± 201 N, respectively; $p > 0.05$).

When merging the training groups (F60, F80, and F100 groups), a significant but moderate negative correlation ($r = -0.56$; $p < 0.001$) was found between the initial MFS and the force gain during the strength test after training (**Figure 4A**; $r^2 = 0.32$).

Stamina

Stamina percentages realized before and after training are presented in **Figure 3B**. Statistical analysis did not show any group effect on *stamina* [$F_{(3,50)} = 1.1$; $\eta^2 = 0.051$; $p = 0.37$]. A significant training effect was observed [$F_{(1,50)} = 36.3$; $\eta^2 = 0.106$; $p < 0.001$] showing that *stamina* was higher after training than before. Significant interaction [$F_{(3,50)} = 7.8$; $\eta^2 = 0.071$; $p < 0.001$] showed that the increase in *stamina* was different by group. *Post-hoc* tests revealed that *stamina* was significantly different in the F60 and F80 groups ($p < 0.01$) before (32.6 ± 15.3% and 29.5 ± 21.3% for the F60 and F80 groups, respectively) and after training (53.5 ± 25.1% and 60.4 ± 25.7% for the F60 and F80 groups, respectively) but not in the CT and F100 groups (before: 32.4 ± 20.7% and 33.5 ± 23.5%, respectively; after: 30.8 ± 22.5% and 43.1 ± 24%, respectively; > 0.05).

Moreover, when merging the training groups, a significant but moderate negative correlation ($r = -0.50$; $p < 0.001$) was found between the initial *stamina* level and *stamina* benefits during the fatigue test after training (**Figure 4B**; $r^2 = 0.25$).

Endurance

Endurance levels realized that before and after training are presented in **Figure 3C**. Statistical analysis did not show any group effect on *endurance* [$F_{(3,50)} = 0.4$; $\eta^2 = 0.019$; $p = 0.77$]. A significant training effect was observed [$F_{(1,50)} = 50.2$; $\eta^2 = 0.117$; $p < 0.001$] showing that *endurance* was higher after training than before. Significant interaction [$F_{(3,50)} = 7.1$; $\eta^2 = 0.053$; $p < 0.001$] showed that increase in *endurance* was different by the group. *Post-hoc* tests revealed that *endurance* was significantly different in the F60 and F80 groups ($p < 0.001$) before (65.7 ± 11% and 63.2 ± 11.3% for the F60 and F80 groups, respectively) and after training (78.5 ± 9.6% and 79.2 ± 11.5% for the F60 and F80 groups, respectively) but not in the CT and F100 groups (before: 68.3 ± 11.7% and 65.3 ± 14.8%, respectively; after: 69.7 ± 14.9% and 70.4 ± 15%; $p > 0.05$).

Moreover, when merging the training groups, a significant but moderate negative correlation ($r = -0.52$; $p < 0.001$) was found between the initial *endurance* level and *endurance* benefits during the fatigue test after training (**Figure 4C**; $r^2 = 0.27$).

DISCUSSION

This study aimed to investigate the effects of different training programs performed at different intensities on the finger muscle capabilities (MFS, *stamina,* and *endurance*). Results suggest that a 4-week hangboard training program is a powerful method for increasing MFS, *stamina*, and *endurance* levels in the climbers, and also that improvements in the finger muscle capabilities depending on the intensity level of the training exercise. Similar values in the control group between both pre- and post-tests showed that increases observed in other training groups are not attributed to a familiarization effect with the tests nor to other concomitant activities.

The results for initial MFS levels were in the range of those measured in the previous studies (Quaine et al., 2011), although higher MFS values were observed by Medernach et al. (2015), Levernier and Laffaye (2019), and López-Rivera and González-Badillo (2019), while lower values were observed by Amca et al. (2012) and Fanchini et al. (2013). These variations may have several explanations: (i) difference in IRCRA level of climbers across studies considering MFS and IRCRA level are positively correlated (i.e., MFS is higher in elite climbers than in novices; Grant et al., 1996; Baláš et al., 2012), (ii) the "climbing style" since "boulderers" have higher initial MFS values than "lead rock practitioners" (Fanchini et al., 2013), and (iii) difference in grip depth used to perform the force test for the reason that the deeper the grip, the greater the force applied (Amca et al., 2012).

Our results showed that the MFS levels were improved with the F100 and F80 groups, being considered as high-intensity training (70–100% MFS). The increases are probably not due to hypertrophy in the forearms (Shimose et al., 2011; España-Romero and Watts, 2012) but to neural adaptation processes during the first weeks of training (López-Rivera and González-Badillo, 2012), allowing a better capacity to recruit motor units on a given movement and/or an increased discharge rate of individual motoneurons (Škarabot et al., 2021) as well as a better anaerobic capacity in the forearms, in order to generate a major muscle activation (Pitcher and Miles, 1997). MFS also increased in similar proportions for the F80 group whose training represents intermittent exercise with a submaximal load-generating fatigue. In the forearms, this exercise at these intensities generates local ischemia stimulus, through reduced blood flow and lactate accumulation (Saeterbakken et al., 2020). Thus, F80 represents a combination of high-mechanical tension and medium metabolic stress that may be effective to increase muscle strength (Duchateau et al., 2021).

On the other hand, a load of lower intensity (60% of initial MFS for the F60 group) did not seem to have sufficient force intensity to obtain large MFS improvements even if a trend is emerging (+5.9 ± 8.2%; $p = 0.07$). A longer training time and/or a higher training frequency could allow for the higher strength gain, as in the López-Rivera and González-Badillo (2012) study where MFS increased by an average of 0.5% between the 4th and 8th week of training.

Our results showed a greater increase in MFS than those observed in the previous studies (Levernier and Laffaye, 2019) where improvements ranged from +5% (Medernach et al.,

2015) to +9.6% (López-Rivera and González-Badillo, 2012). This discrepancy may be related to the lower initial MFS level of our climbers compared with those in the aforementioned studies, since a significant negative correlation ($r = -0.56$; $p < 0.001$) was observed between the MFS gain percentage (when merging the trainings) and the initial MFS (**Figure 4**), i.e., the higher a subject's initial MFS, the lower the strength gain after training. However, it should be noted that variability is high and only explains about one-third of the results ($r^2 = 0.32$). Thus, further studies should be conducted to explore the different factors conditioning strength gain.

The F60 and F80 groups significantly increased *stamina* after training, from 32.6 ± 15.3% to 53.5 ± 25.1% and from 29.5 ± 21.3% to 60.4 ± 25.7%, respectively. Thus, by adjusting the force amplitude realized during trainings at a submaximal level (80 and 60%) is an efficient way to improving resistance to fatigue. Improvements in *stamina* with intermittent type training are in agreement with the literature (Medernach et al., 2015; López-Rivera and González-Badillo, 2019), where repetition training on a hangboard showed between 25 and 34% increase in *stamina* after 4 training weeks. It is worth noting that in these articles, the training control was performed based on a time measurement and the intensity based on a grip width control. Observed increase in *stamina* in our study is probably because of an improved aerobic metabolism thanks to the increase in glycogen and phosphagen storage capacities (Bertuzzi et al., 2007). It can also be attributed to a better limitation of local ischemia effects in the forearms which improve supply, irrigation, and consumption of oxygen in the muscle, increasing oxidative capacities of the skeletal muscle (Ferguson and Brown, 1997; Fryer et al., 2016). In addition, the faster lactate shuttle and enhanced glycolytic activity allow for greater effectiveness in managing submaximal loads thanks to an improved muscle recruitment pattern.

Concerning the F80 group, an additional assumption may explain *stamina* increase. By increasing his/her MFS after training, the force applied by the participant to perform the fatigue test becomes <80% of his/her post-MFS value and therefore represents a lower intensity during this exercise, even though his/her absolute value (in Newtons) remains the same. Thus, fewer motor units need to be activated for the same load and there is a potential to recruit a greater number of non-fatigued motor units. This delays the involvement of type II fibers as well as lactate accumulation (Hickson et al., 1988; Marcinik et al., 1991), allowing for energy conservation and a longer time to exhaustion. Higher *stamina* improvement with F80 can thus be explained by the combination of improved aerobic/anaerobic metabolisms and improved MFS.

The F100 group did not show significant increase in *stamina* after 4 training weeks. This is in accordance with our hypothesis since F100 training does not generate fatigue and thus does not result in the fatigue adaptation. However, it is possible that this increase could be greater and becomes significant with longer training duration, as in the López-Rivera and González-Badillo study (López-Rivera and González-Badillo, 2019) in which *stamina*, with a purely strength-targeted method, increases insignificantly by 10% after 4 training weeks but increases significantly by 34% after 8 weeks.

Endurance level increased in the F60 and F80 groups, from 65.7 ± 11% to 78.5 ± 9.6% and from 63.2 ± 11.3% to 79.2 ± 11.5%, respectively. On the contrary, *endurance* was not improved by training in the F100 group. As for *stamina*, intermittent training (F60 and F80) generates greater fatigue accumulation than maximum intensity training (F100) and therefore reduces the ability to maintain the effort required throughout the session. Intermittent exercise thus provokes a reduction in the short-term strength of type II muscle fibers, caused by the rapid consumption of energy inputs, and type I muscle fibers as a consequence of hypoxia (Pitcher and Miles, 1997). Nevertheless, this exercise type allows for a better tolerance to fatigue than the F100 group. It also allows for the development of aerobic capacity through a faster reoxygenation in forearms (better vasodilatation) during rest phases (Ferguson and Brown, 1997) as well as a better removal of the muscular metabolites. This promotes adaptation of muscular capacities, limiting fatigue effects to maintain higher intensity strength once fatigue has set in.

Some limitations should be acknowledged. First, the 4-week training interval could be considered as short in comparison to non-climbing specific studies on force development which claim effects after 8 weeks (Morris et al., 2022). In total, 4-week duration is thus not long enough to draw conclusions about middle- and long-term training effects, and further studies are needed. Nevertheless, studies addressing to specific climbing training revealed that a 4-week plan based on finger flexor muscles were sufficient to increase strength in the elite climbers (Medernach et al., 2015; Levernier and Laffaye, 2019). Second, participants did not have the same time practice of climbing activity outside the experiment (according to their own usual practice). A part of the results variability can thus be attributed to this various time of climbing practice and mostly to mixed population (advanced to elite climbers, men, and women, etc.). Third, we chose to base the intensity training on the first session instead of testing climbers before each training session, to not influence the effect trainings. But, it is important to keep in mind that intensity (of F60 and F80 groups) may change over days/weeks because of fatigue in that moment. Finally, the effects of different intensity resistance training on angiogenesis, muscle oxygenation kinetics, and muscle oxidative capacity have not been measured in this study and remain highly speculative as to which physiological pathway-enhanced finger capabilities in the training groups. Additional studies are clearly necessary to investigate the physiological phenomenon under training processes by more measurements such as electromyography, lactatemia, or blood flow (with near infrared spectroscopy) to confirm our physiological assumptions. A last consideration is that the use of a force-cell hangboard enables to compute scores based on force-time data (MFS in Newtons; *stamina* and *endurance* in percentage). This approach is in accordance with the previous laboratory studies (Vigouroux and Quaine, 2006; Giles et al., 2019) but differs from others which focused on evaluation using hanging time (Medernach et al., 2015; López-Rivera and González-Badillo, 2019). Comparison of current results with the literature should be interpreted carefully.

Overall, this study showed that, after 4 weeks of hangboard training, maximal finger strength, *stamina*, and *endurance* increase, that different improvements occurred according to the training intensity levels, and that different training levels allow improvements in the targeted capacities (e.g., *stamina* with F80) but also in the adjacent capabilities (e.g., MFS with F80). Such trainings could be useful to quickly improve the climber's capacities, just before a competition for example. The F100 training improves MFS without reaching physiological exhaustion during the sets allowing to complete it by other works on route or boulder with minimal quality loss in comparison with the F60 and F80 trainings. The F60 training allows benefits with low-force intensity, therefore, it may be suitable for the climbers concerned about a risk of injury or wishing to return to training after a long period of inactivity (Peters, 2001). The F80 training promotes simultaneous enhancement of each physiological parameter, especially useful for a versatile climbing practice. However, these enhancements were a function of the initial level of our climbers as shown by the significant results of regressions in MFS, *stamina*, and *endurance*, i.e., the higher a subject's initial level in one of the physiological parameters, the lower the benefit after training. Presumably, the improvement will be smaller in a group of elite athletes, for example. Further research is thus needed to determine which improvements could be expected in each initial level. As well, it would have been interesting to evaluate a climbing-specific outcome parameter, as IRCRA level enhancement, in order to observe the potential consequences of hangboard training when climbing a harder route/boulder. Nevertheless, since climbing performance is multi-factorial, it remains highly difficult to investigate the relationship between the reported physiological improvements and athletes' performance during climbing (MacLeod, 2009).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Sport Science National Ethics Committee (CERSTAPS: IRB00012476-2020-19-11-69). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LV and CL concepted the work and wrote the initial draft. CL and MD carried out the experiments. MD, EB, and LV wrote the manuscript. All authors approved the final manuscript.

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Conflict of Interest: LV and CL report their involvement in the development of SmartBoard in "ScienceForClimbing (SFC)" firm, and their current position as scientific advisors. SFC was not involved in any aspect of this research.

The remaining 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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The Effects of 10 Weeks Hangboard Training on Climbing Specific Maximal Strength, Explosive Strength, and Finger Endurance

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The aim of this study was to investigate the effects of 10 weeks of hangboard training (HBT) on climbing-specific maximal strength, explosive strength, and muscular endurance. In total, 35 intermediate- to advanced-level climbers (8 women and 27 men) were randomized into a hangboard training group (HBT) or a control group (CON). The HBT program consisted of two sessions of 48 min per week using the Beastmaker 1000 series hangboard, and the following application to smartphone. Both groups continued their normal climbing training routines. Pre- and post-intervention, maximal peak force, maximal average force, and rate of force development (RFD) were measured while performing an isometric pull-up on a 23 mm deep campus rung and jug holds. In addition, finger endurance was measured by performing a sustained dead-hang test on the same rung. The HBT increased peak force and average force in 23 mm rung condition, average force in jug condition, and utilization rate øl,.- in peak force to a greater extent than CON ($p = 0.001$–0.031, ES = 0.29–0.66), whereas no differences were detected between groups in RFD (jug or 23 mm), peak force in jug condition, utilization rate in RFD, average force or in dead-hang duration ($p = 0.056$–0.303). At *post-test*, the HBT group demonstrated 17, 18, 28, 10, 11, and 12% improvement in peak force, average force, RFD in 23 mm rung condition, average force in jug condition, utilization rate in peak force, and dead-hang duration, respectively [$p = 0.001$–0.006, effect size (ES) = 0.73–1.12] whereas no change was observed in CON ($p = 0.213$–0.396). In conclusion, 10 weeks of HBT in addition to regular climbing was highly effective for increasing maximal finger strength compared with continuing regular climbing training for intermediate and advanced climbers.

Keywords: grip strength, grip endurance, training, sport climbing, rate of force development (RFD)

INTRODUCTION

The popularity of rock climbing is continuing to grow among athletes, recreational climbers, and researchers. The most frequently examined factors in climbing performance are anthropometric-, physiological-, psychological- and technical factors (Watts et al., 1993; Baláš et al., 2012; Saul et al., 2019). Among the physiological determinants of climbing performance, it is generally accepted that both maximal strength and local muscular endurance in the finger flexors are the two most crucial components for predicting climbing performance (Grant et al., 1996; Watts and Jensen, 2003; Watts, 2004; MacLeod et al., 2007; Baláš et al., 2012; Saul et al., 2019), despite a variety of testing protocols (Stien et al., 2022). For example, specific finger strength and dead-hang duration have been found to explain up to 52 and 70% of the total variance of climbing ability (Baláš et al., 2012; Laffaye et al., 2016).

Although finger flexor strength and endurance are the most significant predictors of climbing performance (Cutts and Bollen, 1993; Ferguson and Brown, 1997; Grant et al., 2003; Baláš et al., 2012; Saul et al., 2019), only limited number of finger strength training studies have been conducted (López-Rivera and González-Badillo, 2012, 2019; Medernach et al., 2015b; Levernier and Laffaye, 2019a; Stien et al., 2021a). For example, López-Rivera and González-Badillo (2019) investigated 8 weeks of either maximal hangs, intermittent hangs, or a combination of both in advanced to elite level climbers. All groups demonstrated improvements in finger endurance (i.e., dead-hang duration), but no difference was observed among the three training approaches (López-Rivera and González-Badillo, 2019). Unfortunately, the study did not include any measurement of finger strength or include a control group.

To the best of our knowledge, only three studies have investigated the effects of specific finger strength training and included a control group (Medernach et al., 2015b; Levernier and Laffaye, 2019a; Stien et al., 2021a). Despite similarities, these studies are based on different training protocols, such as dynamic campus board training (Stien et al., 2021a), one arm isometric hangs on the slope and half crimp (Levernier and Laffaye, 2019a), and a combination of different isometric hangs and dynamic exercises (Medernach et al., 2015b). However, none of the three studies demonstrated finger training to be more effective than regular climbing in maximal finger strength measurements. Still, Medernach et al. (2015b), Levernier and Laffaye (2019a), and Stien et al. (2021a) demonstrated improvements in other significant finger training performance outcomes [i.e., finger endurance, campus board moves to failure, and rate of force development (RFD)]. Furthermore, Stien et al. (2021a) examined the upper body strength after the campus board training in a jug and 23 mm rung conditions and demonstrated improvements in isometric pull-up strength in the jug condition, but not in the rung condition (Stien et al., 2021a). Of note, the three studies (Medernach et al., 2015b; Levernier and Laffaye, 2019a; Stien et al., 2021a) included few participants (14–23) on a high climbing performance level (advanced to higher elite) using short intervention periods (4–5 weeks), which may explain the lack of between-group differences in maximal finger strength. Therefore, little is known of the chronic effects (>5 weeks) of finger training on climbing-specific outcomes (i.e., finger strength and endurance) using lower-level climbers (intermediate to advance). The aim of this study was to compare the effects of a longer supplemental finger training protocol while continuing climbing training as usual on climbing specific maximal strength and explosive strength in the finger flexors (primary), and muscular endurance (secondary) in intermediate to advanced recreational climbers. We hypothesized that a specific 10-week hangboard training (HBT) program in addition to regular climbing training would be more effective for increasing specific maximal strength, explosive strength (RFD), and muscular endurance than just continuing regular climbing training.

METHODS

Study Design

A randomized controlled trial was used to compare the additional effects of combining an HBT program with regular climbing training. After pre-testing, the participants were randomized, by drawing lots, into either the HBT or control (CON) groups. Both groups were encouraged to continue their normal climbing training routine, but the HBT-group completed the hangboard program two times a week. Before and after the intervention, all participants were tested for peak force (F_{peak}), average force (F_{avg}), and RFD during an isometric pull-up performed on both a 23 mm campus rung and jug holds. Finger endurance was tested during a continuous dead hang test on the same 23 mm campus rung.

Participants

A sample size calculation was conducted based on the 23 mm rung findings from Stien et al. (2021a). For an alpha level of 0.05 and power of 80%, a sample size of 32 participants appeared to be necessary to detect significant differences between the two groups. There were approximately 70 adult climbers in the climbing club, in addition to 30–40 climbers who were members of the local climbing center who all were asked to participate. To participate, the climbers had to be over 18 years old, free of injuries for the last 6 months, climbing regularly (minimum two times a week), and have a red-point performance level of at least 6a (French grade). Forty-three recreational climbers, who fulfilled the inclusion criteria, volunteered for the study. During the intervention, eight climbers dropped out for various reasons unrelated to the study. Therefore, thirty-five participants (8 women and 27 men) successfully completed the 10-week training intervention. The climbing performance was reported using the French grading system (1-9a/b/c) and converted to the numeric International Rock Climbing Research Association (IRCRA)-scale (1–32) (Draper et al., 2016). Descriptive data for the two groups are shown in **Table 1**. Before baseline testing, all participants were informed about the study, both orally and in writing, and signed an informed consent form. The study procedures were in accordance with the ethical guidelines of the Western Norway University of Applied Sciences and complied with the standards of treatment of human participants in research, as defined in the 5th Declaration of Helsinki, and were evaluated by the Norwegian Centre for Research Data (2017/56550).

Testing Procedures

All participants were instructed to refrain from any hard physical activity 48 h before testing. Before testing, the participants performed 5 min of an easy climbing traverse followed by 10 min of progressive bouldering (50–80% of their maximum). During the warm-up boulders, the participants had a minimum of 1-min rest between boulders and ∼10 min of rest before testing. The

TABLE 1 | Descriptive data.

	CON ($n = 17$) Mean ± SD	HBT ($n = 18$) Mean ± SD
Age (year)	26.8 ± 7.9	26.2 ± 6.4
Height (cm)	175.1 ± 8.8	175.3 ± 9.2
Weight (kg)	66.7 ± 9.2	70.0 ± 8.7
BMI (kg/m^2)	21.7 ± 1.8	22.8 ± 2.3
Fat mass (%)	12.4 ± 4.5	13.7 ± 4.5
Climbing experience (year)	7.2 ± 5.8	6.0 ± 6.4
Best red-point (IRCRA)	17.5 ± 4.6	15.5 ± 3.2

CON, control group; HBT, hangboard training group; BMI, body mass index; IRCRA, International Rock Climbing Research Association.

test order was standardized and started with three attempts at the isometric pull-up on the 23 mm campus rung, followed by three attempts of isometric pull-up on jug holds. Finally, finger endurance was tested in a sustained dead-hang test on the 23 mm campus rung. Only one attempt was made in the dead hang test.

Isometric Pull-Up

To measure climbing-specific maximal- and explosive strength, an isometric pull-up test was used, ranging from (i) a 23 mm deep and 43 cm wide campus rung with rounded edge (Wood grips Campus Rung size M, Metolius™, USA) and (ii) a wooden jug hold (depth: 30 mm, height: 30 mm, width: 70 mm) a Beastmaker 1000 series hangboard (Beastmaker Limited, Leicester, United Kingdom). The force (N) was measured with a force cell (Musclelab™ v13.10, 200 Hz, Ergotest Technology AS, Norway) anchored to the concrete floor. The force cell was connected to the climber with a static aramid cord that was fastened to the belay loop of a climbing harness. The climber's position was adjusted (by changing the length of the aramid cord) to 90 degrees angle in the elbow joint (measured with a goniometer) before the test was initiated (**Figure 1**) (Saeterbakken et al., 2019; Stien et al., 2019). The participants pulled themselves up to the aramid cord that was tight and elbows were in the 90 degrees angle and maintained the position for ∼1 s while waiting for the start signal from the test leader. The test leader initiated the test with an oral signal, and the climber performed an isometric pull-up as fast and hard as possible (Maffiuletti et al., 2016), and maintained maximum force for 5 s (Stien et al., 2019). The test was performed with a standardized half-crimp grip with a passive thumb on the 23 mm campus rung, and no restrictions for jug holds. Then, 3 min of rest separated each attempt, and a 5-min rest was given before the jug condition. The attempt with the highest recorded absolute force values for both conditions (rung and jug holds) was used in the analyses. For each isometric pull-up condition, peak force (F_{peak}) and average force (F_{avg}) were measured in addition to RFD. The F_{peak} was identified as the highest force output on the force-curve and F_{avg} was calculated as the highest mean force over a 2-s period, excluding the peak (Saeterbakken et al., 2019; Stien et al., 2019). For the calculation of the RFD, the change in force output and time window was between the onset of force generation and to the F_{peak}, which was found to be the most reliable in the present test (Stien et al., 2021b). The onset of force was detected manually using the commercial software (Musclelab™ v13.10, Ergotest Technology AS, Norway), in line with previous recommendations (Maffiuletti et al., 2016). The relative utilization of force on the 23 mm campus rung relative to the jug holds was calculated as follows; [(23 mm rung results/jug results) × 100] (Stien et al., 2019). Commercial software (Muscellab™ v13.10, Ergotest Technology AS, Norway) was used to analyze the stored data.

Dead-Hang Duration

The dead-hang test was performed on the same 23 mm campus rung as the isometric pull-up test after resting for 5 min. The participant was instructed to hang on the campus rung for as long as possible with passive thumbs and fully extended elbows (Watts, 2004; Baláš et al., 2012). The continuous dead-hang test is frequently used and proven to be reliable and valid using a 20–30 mm rung, and is recommended for differentiating climbing performance levels (Baláš et al., 2012; Fanchini et al., 2013; Hermans et al., 2016; Seifert et al., 2017; Stien et al., 2019; Draper et al., 2020). Before starting the test, the participants chalked up their fingers and the campus rung was brushed. To avoid swings, all participants started the test by bending their legs and loading their fingers. Timing started when the participants' legs left the ground and stopped when the feet touched the floor. All participants received motivational feedback and verbal seconding every 10th s during the test. The dead-hang times were measured by the same person using a stopwatch, which has proven to be reliable with an accuracy of 0.1 s (Radner et al., 2017).

Training Protocol

Prior to each training session, the participants were instructed to perform 15 min of easy climbing or bouldering as a warm-up. The training was conducted on the Beastmaker 1000 series hangboard (Beastmaker Limited, Leicester, United Kingdom) and the participants followed a standardized program using the Beastmaker application (2015, version 3.2.1) on a smartphone. In the Beastmaker application, the difficulty levels (5A−7C) were adjusted based on the size of handholds and the number of included fingers. All training sessions consisted of two identical sets separated by 6 min of rest. Each set includes six progressive hang-series with seven repetitions. One repetition consists of 7 s of hang time and 3 s of rest (7:3 ratio).A 2 min and 30 s rest was given between the different hang-series. To adapt to the training and lower the risk of injuries, all participants were instructed to complete the first 2 weeks on low resistance (5A−5C program). To ensure progression for the last 8 weeks of the training protocol, all participants were instructed to increase the difficulty of the training program when it could be conducted without failure. The program difficulty was increased by changing grip conditions (e.g., smaller holds or fewer fingers) and the order of hold types. The hang time, rest time, and number of repetitions and sets were constant, which made all the sessions last 48 min, regardless of program difficulty. Within the session, 10 min was hanging time on the

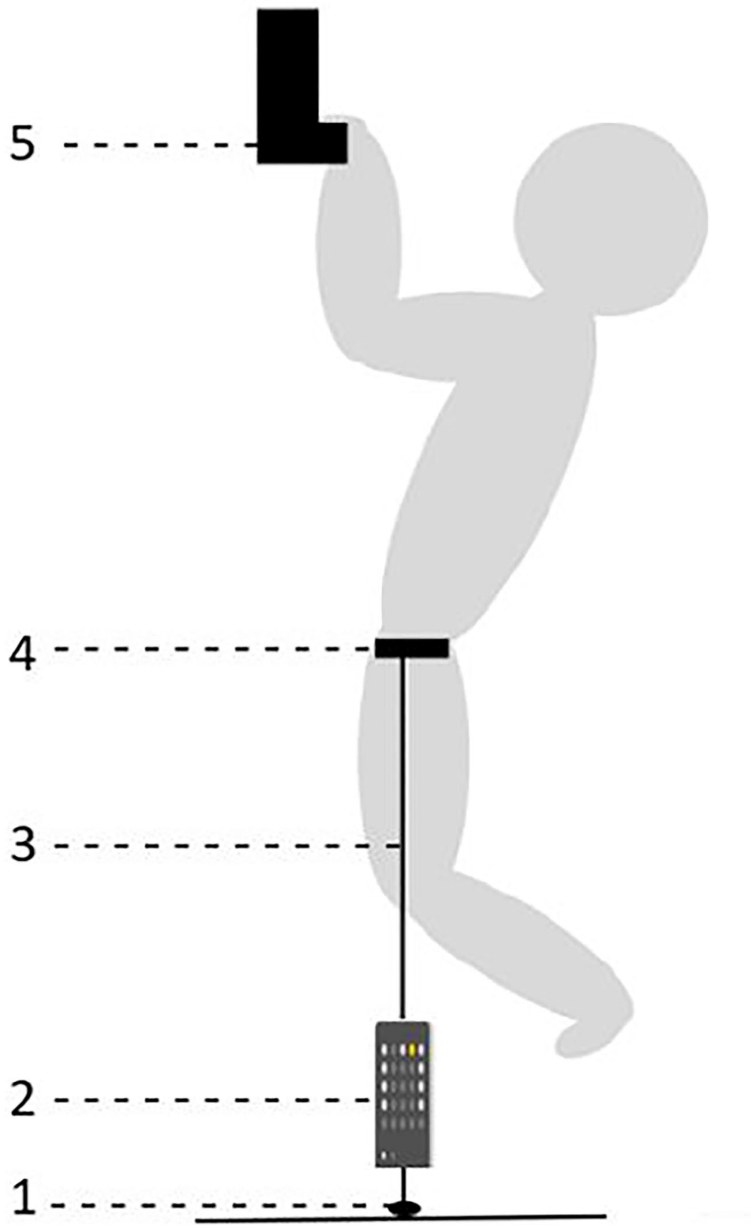

FIGURE 1 | Schematic presentation of the isometric pull-up test showing (1) expansion bolt in the concrete floor, (2) the force cell, (3) the static aramid cord, (4) the climbing harness, and (5) the 23 mm rung or jug holds.

board. All participants had to fill in a training log where they stated which program they trained for each session. To secure progression in the Beastmaker-program, participants in the HBT group had follow-up sessions on two different occasions with a researcher (week 2–3 and 6–7). The log form also included other types of training, such as climbing, bouldering, and endurance training. This was mandatory for both the training and control groups, to have an overview of total training volume during the intervention program. The participants in the HBT group completed on average ∼90% of the training sessions during the 10-week protocol.

Statistical Analyses

All analyses were performed using the commercial statistical software SPSS (IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp). Data were assessed for normality using the Shapiro–Wilk test and all data ($p = 0.304$–963) except dead-hang duration ($p = 0.010$) were normally distributed. Analysis of covariance (ANCOVA) with the pre-test scores as covariates was used to assess differences between the groups for the parametric variables, and independent-samples *t*-tests were used to check for pre-to-post changes within the groups. Differences in training volume were assessed using paired and independent *t*-tests for the within- and between-groups differences, respectively. Dead-hang duration was analyzed using the Wilcoxon signed-rank test for the within-groups comparisons and a Mann–Whitney *U*-test for the between-groups differences. The alpha level was set at <0.05 for statistical significance. All data are presented as mean [± standard deviation (SD)] and Cohen's d effect size (ES). An ES of <0.2 was considered trivial, 0.2–0.5 small, 0.5–0.8 medium, and >0.8 large (Cohen, 1988).

RESULTS

No differences were observed between groups at baseline for any of the descriptive- ($p = 0.131$–0.960) or performance parameter ($p = 0.055$–0.871).

Isometric Pull-Up on the 23 mm Campus Rung

The HBT group improved F_{peak} by 89.71N ± 80.25N ($p < 0.001$, ES = 1.12), F_{avg} by 61.19N ± 59.55N ($p < 0.001$, ES = 1.03), and RFD by 436.18Ns-1 ± 506.60Ns-1 ($p = 0.003$, ES = 0.86) from pre- to post-test, whereas none of the parameters increased in the CON group ($p = 0.213$–0.265) (**Figure 2**). When adjusting for the pre-test results, the HBT group reached a higher F_{peak} ($p = 0.008$, ES = 0.31) and F_{avg} ($p = 0.009$, ES = 0.29) at post-test than the CON group, whereas the RFD was not significantly different between the groups ($p = 0.056$, ES = 0.21) (**Table 3**).

Isometric Pull-Up on Jug Holds

The HBT group improved F_{avg} in the jug condition by 54.94N ± 63.35N ($p = 0.003$, ES = 0.87), whereas F_{peak} ($p = 0.134$) and RFD ($p = 0.128$) (**Figure 2**) were not increased from pre- to post-test. None of the parameters increased in the CON group ($p = 0.144$–0.871). When adjusting for the pre-test results, the HBT group reached a higher F_{avg} ($p = 0.031$, ES = 0.45) at post-test compared with the CON group, whereas F_{peak} ($p = 0.143$, ES = 0.38) and RFD ($p = 0.165$, ES = 0.23) were not significantly different between the groups (**Table 3**).

Utilization Rate

The utilization rate of F_{peak} in the rung condition relative to the jug condition significantly improved for the HBT group (10.67 ± 10.54%, $p < 0.001$, ES = 0.73) but not for the CON group ($p = 0.704$). No change occurred in either group for the F_{avg} ($p = 0.211$ and $p = 0.974$). The HBT group increased the utilization of RFD by 9.86 ± 18.51% ($p = 0.043$) whereas the CON group did not ($p = 0.724$). The ANCOVA revealed that the utilization of F_{peak} at post-test was higher for the HBT group than the CON group ($p < 0.001$, ES = 0.66), whereas no between-groups differences were found for the utilization of RFD ($p = 0.786$) and F_{avg} ($p = 0.593$) (**Table 3**).

Finger Endurance

A significant improvement in dead-hang duration was observed from pre- to post-test for the HBT group (6.8 ± 8.6 s, $p = 0.006$, ES = 0.79), but not for CON ($p = 0.215$) (**Figure 3**). The change was not significantly different between the groups ($p = 0.303$) and the groups were not different at post-test ($p = 0.832$) (**Table 3**).

Training Sessions

A significant difference between groups in the number of climbing training sessions during the intervention was found, with the CON group training more often than the HBT group ($p < 0.001$, ES = 1.00) (**Table 2**). Of note, for all training sessions (climbing-, strength-, and endurance training), there was no significant difference in the total number of training sessions between the groups ($p = 0.925$).

DISCUSSION

As hypothesized, the present study demonstrated a greater improvement in maximal finger strength (F_{peak} and F_{avg}) on the 23 mm campus rung for the HBT group compared with the CON group. In addition, the utilization rate in F_{peak} increased for the HBT group compared with the CON group. Furthermore, 28 and 12% significant improvements in explosive strength and finger endurance, respectively, were observed for the HBT group whereas the CON group demonstrated no improvements between the pre- and post-test. Finally, in contrast to our hypotheses, we found no differences between the groups for utilization rate in F_{avg} and RFD, RFD in jug and rung conditions, F_{peak} in a jug, or in finger endurance.

The HBT program was based on recommendations for resistance training regarding intensity, volume, and frequency (ACSM, 2009). Based on the principle of training specificity and the length of the intervention program, it was not surprising that the finger flexors became stronger which was reflected by the increased performance on the 23 mm rung. Importantly, when performing the isometric pull-up on the jug holds, the back-, shoulder-, and elbow muscles are more important than the finger flexors, as demonstrated by Stien et al. (2019). Hence the training on the hangboard seems to have a small transfer effect on the force-generating capacity of the larger muscles in the upper body, indicated by a positive change in F_{avg} in the jug condition. It could be speculated that the increased performance in F_{avg} is caused by high activation of the back- and shoulder muscles during finger hang training. Of note, the strength tests (rung and jug) were conducted with a 90-degree elbow angle whereas the HBT was conducted with fully extended elbows. Consequently, the improved performance on the 23 mm rung for the HBT group could be a result of better utilization of the force generated rather than an increased force-generating capacity, meaning that the finger strength has developed more than the pulling muscles in the back, shoulders, and elbows. This speculation is supported by greater effect sizes in 23 mm rung vs. jug condition (ES = 1.12, 1.03 vs. ES = 0.87) and the results from utilization rate showing improved utilization for the HBT group in F_{peak}.

The fact that the participants in the HBT group improved more than the CON group in all the strength tests performed on the 23 mm rung could also be explained by specificity. The participants in the CON group continued their regular training routine consisting of freely chosen indoor climbing and/or bouldering training, with no training protocols or intensity

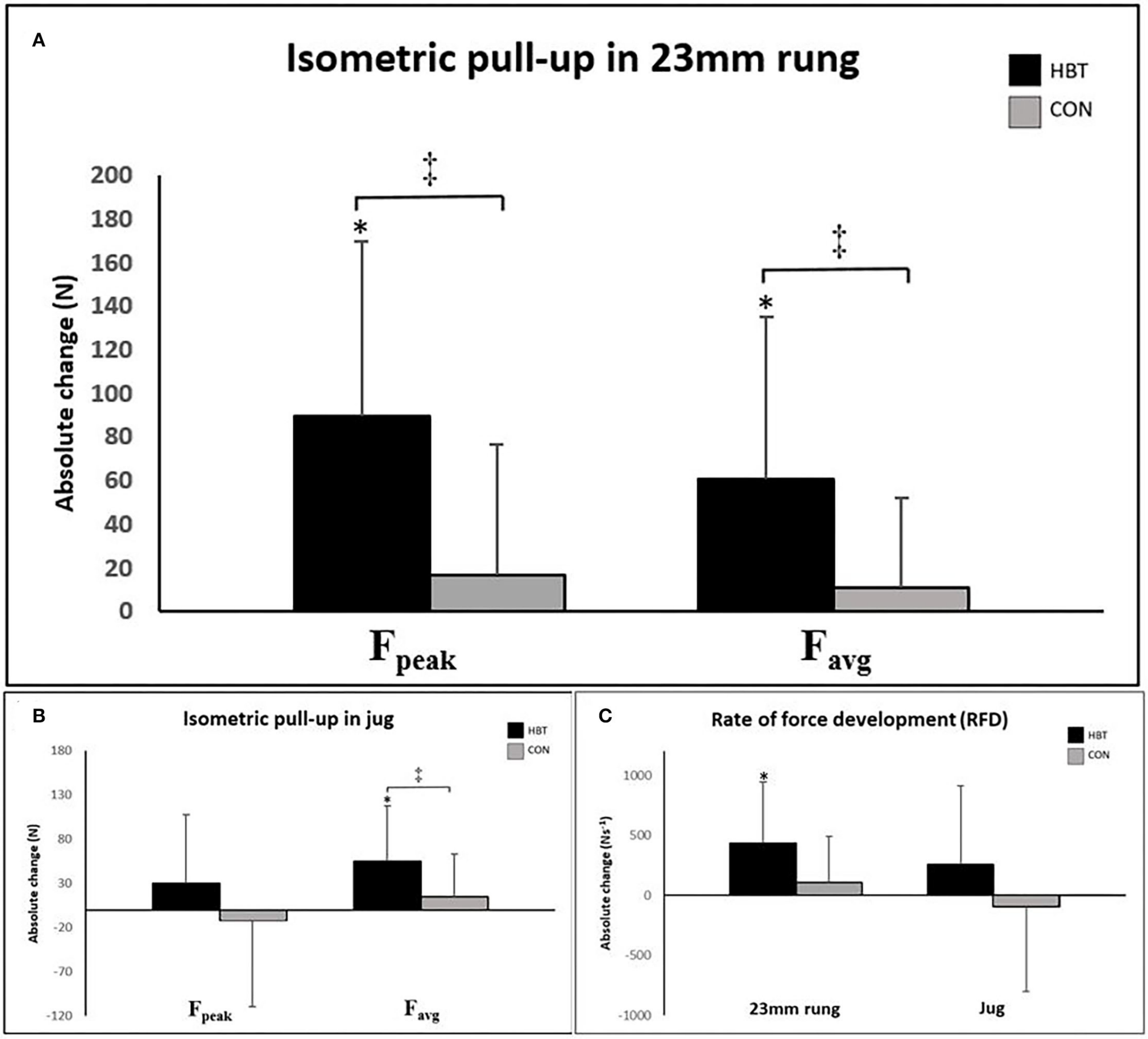

FIGURE 2 | Absolute change in isometric pull-up **(A)** F_{peak} and F_{avg} on the 23 mm campus rung, **(B)** F_{peak} and F_{avg} on the jug, and **(C)** the rate of force development (RFD) in the 23 mm rung and jug conditions. Error bars represent standard deviations (SDs). *Significant change from pre-test ($p < 0.05$). ‡Significant difference in change between groups ($p < 0.05$).

and volume regulation. Typically, when climbing, all types of handholds are used and the whole body works in varied positions depending on the route, wall angle, and the proportion of support by the legs. In contrast, training on a hangboard is closer to the isometric pull-up testing condition, mainly due to a static activation of fingers and upper body muscles, without the use of the legs. However, unstructured climbing training seems, in this and previous studies, to be an ineffective way to increase the specific strength or climbing performance over a relatively short period of time (Baláš et al., 2012; Medernach et al., 2015a; Hermans et al., 2016; Levernier and Laffaye, 2019a; Stien et al., 2021a). Therefore, it could be speculated that recreational climbing does not provide enough stress or overload to improve the finger strength for intermediate to higher elite level climbers/boulderers in such a short time frame (4–10 weeks).

The present findings, the significant difference between groups in finger strength, are partly in contrast with previous studies examining the effects of finger training (Medernach et al., 2015b; Levernier and Laffaye, 2019a; Stien et al., 2021a). Importantly, all these studies used a short intervention period (i.e., <5 weeks), included climbers with higher climbing ability, and used training exercises that stimulate the larger upper-body muscles in addition to the fingers. However, it could be speculated whether it is the duration of the intervention, the content of the training, the lower skill level of the climbers, or

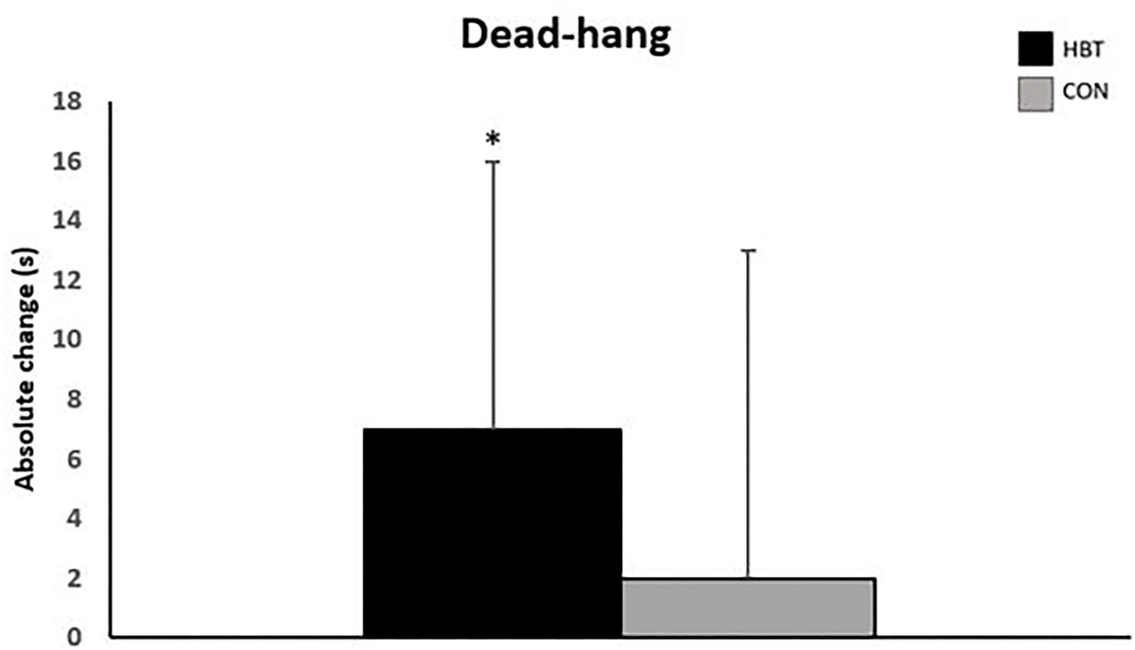

FIGURE 3 | Absolute change (in seconds) for Dead-hang test. *Significant change from pre-test ($p < 0.05$).

TABLE 2 | Number of self-reported training sessions within the 10-week intervention.

	CON ($n = 17$) Mean ± SD	HBT ($n = 18$) Mean ± SD
Climbing and/or bouldering	21.6 ± 6.5	8.8 ± 6.3≠
Other training (strength* and endurance)	27.1 ± 12.5	24.0 ± 14.7
Hangboard training program		17.7 ± 1.3
Total number of training sessions	48.7 ± 11.2	48.1 ± 18.5

CON, Control group; HBT, Hangboard training group.
≠Significantly different from control group, $p < 0.001$.
**Not finger strength training.*

a combination that has led to the difference between the groups in the present study.

In addition to maximal finger strength, RFD is a crucial factor in climbing (Fanchini et al., 2013; Levernier and Laffaye, 2019b). Further, only Levernier and Laffaye (2019a) and Stien et al. (2021a) have investigated changes in RFD after specific finger training protocols in climbers. In contrast to the hypothesis, the present study showed no significant differences in RFD between the HBT and CON groups (28 and 8%, respectively). These findings are in line with Levernier and Laffaye (2019a), who reported a 17% non-significant increase in RFD, using half crimp position following finger training. However, the present study showed a tendency for a difference between the groups for RFD in 23 mm rung condition, which indicates that a longer training intervention could be beneficial in developing RFD. In contrast, both campus training and one-arm isometric hangs are proven to be more effective than climbing/bouldering in improving the average and early phase RFD after just 4–5 weeks of training (Levernier and Laffaye, 2019a; Stien et al., 2021a). However, according to Andersen and Aagaard (2006), the RFD is strongly related to maximum voluntary contraction (MVC) in time intervals later than 90 ms from onset of the contraction. However, no finger strength increase was reported by Levernier and Laffaye (2019a) or Stien et al. (2021a), which indicates that the reported increase in RFD can mainly be explained by neural adaption to the training. Indeed, the findings by Stien et al. (2021b) indicated that the higher RFD observed in elite climbers compared with intermediate and advanced climbers were not caused by the higher maximal strength alone.

The participants in the HBT group demonstrated a 12.1% improvement in finger endurance whereas the participants in the CON group demonstrated no change. Despite this, no differences between the groups were found at post-test meaning that the HBT was not superior to regular climbing training. The test specificity to the training protocol might be an explanation for the lack of difference. For example, the different energy systems contribute differently during intermittent work (e.g., 8:2 and 7:3 ratio) and sustained work (Maciejczyk et al., 2022). Additionally, the intervention was more specific toward muscle strength and less toward muscle endurance. In contrast to the present study, López-Rivera and González-Badillo (2019) reported a 45% increase in hang time after an 8-week intermittent HBT program. Unfortunately, the study had no control group. Of note, López-Rivera and González-Badillo (2019) tested dead-hang duration on an 11 mm campus rung instead of the more common > 20 mm (Draper et al., 2020), which probably present different workload characteristics

TABLE 3 | Absolute data (pre and post) and absolute difference between pre and post for all tests.

			Hangboard training group			Control group		
			Pretest	Posttest	Change	Pretest	Posttest	Change
Isometric pull-up in 23 mm rung	F_{peak}	(N)	425.5 ± 181.5	515.3 ± 167.5*	89.7 ± 80.3≠	442.2 ± 212.2	462.2 ± 188.0	20.0 ± 73.4
	F_{avg}	(N)	282.0 ± 135.3	343.2 ± 149.5*	61.2 ± 59.6≠	289.8 ± 147.7	302.3 ± 141.2	12.5 ± 41.0
	RFD	(Ns^{-1})	1,098.2 ± 440.2	1,534.4 ± 571.5*	436.2 ± 506.6	1,275.1 ± 840.8	1,388.0 ± 829.8	112.9 ± 375.0
Isometric pull-up in jug holds	F_{peak}	(N)	662.1 ± 192.9	691.9 ± 172.2	29.8 ± 77.9	616.6 ± 295.6	612.1 ± 251.0	−4.5 ± 115.4
	F_{avg}	(N)	501.6 ± 178.7	556.5 ± 172.4*	54.9 ± 63.4≠	459.2 ± 201.5	476.4 ± 190.0	17.2 ± 47.6
	RFD	(Ns^{-1})	2,138.6 ± 864.3	2,394.6 ± 686.7	256.1 ± 657.8	2,224.2 ± 1,332.6	2,157.9 ± 1,306.1	−66.3 ± 692.2
Utilization rate (23 mm vs. jug)	F_{peak}	(%)	63.6 ± 16.8	74.3 ± 13.9*	10.7 ± 10.5≠	74.9 ± 20.6	77.9 ± 21.2	3.0 ± 18.4
	F_{avg}	(%)	57.4 ± 23.4	61.6 ± 17.7	4.2 ± 13.2	62.8 ± 16.8	62.6 ± 14.2	−0.2 ± 11.9
	RFD	(%)	54.0 ± 18.2	63.8 ± 16.2*	9.9 ± 18.5	66.9 ± 36.6	70.3 ± 26.2	3.4 ± 35.1
Dead-hang	Duration	(s)	49.4 ± 17.2	56.2 ± 16.8*	6.8 ± 8.6	55.8 ± 25.6	58.0 ± 18.5	2.2 ± 11.0

All results are presented as mean ± SD.
**Significantly different from pretest results ($p < 0.05$).*
≠Significantly different from the control group ($p < 0.05$).

and are therefore less comparable with the results in the present study.

The present study has some limitations. We found HBT to be effective in improving the performance in climbing-specific finger strength and endurance tests. Although finger strength has been claimed to be important for climbing performance (Grant et al., 1996; Watts, 2004; MacLeod et al., 2007; Baláš et al., 2012; Saul et al., 2019), we cannot conclude that the findings translate to improved climbing or bouldering performance. A climbing bouldering performance test would have strengthened the study. To test finger flexor endurance in climbers, it is currently recommended to use both an intermittent test and a sustained dead-hang test (Seifert et al., 2017). However, for practical reasons, we could only conduct one endurance test and opted out the intermittent test to avoid favoring the HBT group. It should be mentioned that the intermittent testing (7:3 or 8:2) better reflects the work-relief parameter, with a mean contact time of 8.2 s in sport climbing (Michailov, 2014). However, the dead-hang test is frequently used in climbing research and is proven to be a valid and reliable test with a strong correlation to climbing performance (Baláš et al., 2012; López-Rivera and González-Badillo, 2012, 2019; Medernach et al., 2015b; Hermans et al., 2016; Ozimek et al., 2016; Bergua et al., 2018; Draper et al., 2020).

In conclusion, 10 weeks of supplemental HBT in addition to regular climbing training is more effective for improving the specific finger strength in intermediate to advanced level climbers, compared with continuing regular climbing training. However, the HBT was not superior to regular climbing training in improving RFD or dead-hang duration.

PERSPECTIVE

This study aimed to improve the evidence-based knowledge about HBT on climbing-specific strength and endurance tests. The results indicate that a 10-week intervention with specific finger flexor training can be effective to increase a climber's specific maximal strength. Therefore, HBT can prepare a climber for further climbing performance development, using an isometric exercise loaded with only body mass. Stronger fingers can likely allow a climber to hold on to smaller holds and improve the climbing time to exhaustion by letting the climber use a lower percentage of maximal finger strength at a given handhold. These findings contribute to the climbing and research communities' understanding of the effects of a common HBT protocol and should encourage and support both trainers and athletes to include the blocks of supplemental HBT in a periodization program to improve climbing performance.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Norwegian Centre for Research Data (2017/56550). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

EH have written the original draft and EH and NS analyzed the data. EH, IN, VV, and AS completed data collection. All authors have contributed to the conceptualization, critical feedback, editing the draft and have approved the submitted version.

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Optimization of an Intermittent Finger Endurance Test for Climbers Regarding Gender and Deviation in Force and Pulling Time

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Performance diagnostics of finger strength is very relevant in climbing. The aim of our study was to find modalities for an intermittent finger flexor muscle endurance test that optimize the correlation of test performance with lead climbing performance. Twenty-seven female and 25 male climbers pulled with 60% MVC and a work-to-rest ratio of 7:2 s on a fingerboard until fatigue. The highest correlations, $R = 0.429$, were found for women when 9% deviation in the required force and 1 s deviation in the required pulling time was tolerated. For men, the optimum was reached with the same time deviation and a force deviation of 6%, $R = 0.691$. Together with maximum finger strength the repetitions explained 31.5% of the variance of climbing ability in women and 46.3% in men. Consequences from our results are to tolerate at least 7% force deviation for women and 5% for men and to terminate the finger endurance test quickly after the force falls below the threshold.

Keywords: climbing, rock climbing, lead climbing, testing, fingerboard

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INTRODUCTION

Scientific monitoring of the new Olympic sport of climbing is increasing. One focus is on performance diagnostics of maximum finger strength and finger endurance, which are very relevant in climbing (MacLeod et al., 2007; Baláš et al., 2012; Philippe et al., 2012; Saul et al., 2019). The test protocols used by individual research groups are quite different (Stien et al., 2022). Two main variations can be identified: In one variation, participants have to perform sustained isometric contractions (**Table 1**). In the other variation intermittent contractions are used, which prescribe specific rhythms of work and rest (**Table 2**). Here, the contraction-relax ratios are based on the demands of lead climbing (Michailov, 2014). The performance parameters recorded in previous studies usually refer to the time to failure (TTF), the force-time integral (FTI) or the number of repetitions completed (REP) (**Tables 1**, **2**). For both, continuous and intermittent protocols, different test devices have been used: Hand dynamometers, specially designed measuring apparatuses and the currently most common rungs or holds.

Many studies have used the above presented parameters to examine performance differences between climbers and non-climbers (MacLeod et al., 2007; Philippe et al., 2012), between climbers of different ability levels (Fryer et al., 2015a,c; Ozimek et al., 2017; Bergua et al., 2018), or between different climbing disciplines (Michailov et al., 2018; Stien et al., 2019). However, some studies also focus on how well measured finger endurance performance predicts climbing performance. Two points are striking here. First, regarding the relationship of endurance tests to climbing

TABLE 1 | Overview of measurement methods of finger flexor muscle endurance based on sustained isometric contractions.

Study	Parameter	Load	Device
Cutts and Bollen (1993)	FTI	80% MVC	Hand dynamometer
Ferguson and Brown (1997)	TTF	40% MVC	Hand-grip ergometer
MacLeod et al. (2007)	TTF, FTI	40% MVC	Special apparatus
Limonta et al. (2008)	TTF	80% MVC	Hand-grip ergometer
Philippe et al. (2012)	TTF, FTI	40% MVC	Special apparatus
Baláš et al. (2012)	TTF	Finger hang	25 mm ledge
López-Rivera and González-Badillo (2012)	TTF	Finger hang	11 mm ledge
Fryer et al. (2015c)	(TTF,) FTI	40% MVC	Special apparatus
Fryer et al. (2015a)	FTI	40% MVC	Special apparatus
Medernach et al. (2015)	TTF	Finger hang	3 Different grips
Baláš et al. (2016)	TTF, FTI	60% MVC	Special apparatus
Ozimek et al. (2016)	TTF	50% MVC	Hand dynamometer
		Finger hang	25 mm ledge
			40 mm ledge
Ozimek et al. (2017)	TTF	Finger hang	25 mm ledge
			40 mm ledge
Hermans et al. (2017)	TTF	Finger hang	25 mm ledge
Bergua et al. (2018)	TTF	Finger hang	14 mm edge
	Minimum edge depth	40's-Finger-hang	Edge
Michailov et al. (2018)	F_{avg}, $I_{fatigue}$	30's All out test	Special apparatus
López-Rivera and González-Badillo (2019)	TTF	Finger hang	11 mm edge
Baláš et al. (2021)	TTF, FTI	60% MVC	23 mm ledge
Rokowski et al. (2021)	TTZ, FTI, FTI/kg	60% ± 10% MVC	23 mm ledge

; time till task failure (s); FTI, force-time integral (Ns); F_{avg}, average force; $I_{fatigue}$, fatigue index; TTZ, time in target zone (s).

performance, there have been some studies to date on sustained contractions (López-Rivera and González-Badillo, 2012; Ozimek et al., 2016; Bergua et al., 2018; Michailov et al., 2018; Baláš et al., 2021). For intermittent tests, however, the evidence is still relatively limited. To our knowledge, only two studies consider the relationship of intermittent testing to climbing performance (Baláš et al., 2021; Rokowski et al., 2021).

Second, a closer look reveals that the termination criteria for test execution are selected quite differently. In Baláš et al. (2021), for example, the test is automatically terminated by the software if a threshold value is undershot. In other studies, the test is stopped by the participant due to volitional fatigue (MacLeod et al., 2007; Fryer et al., 2015a). Also, this threshold value varies from study to study from 5% (Limonta et al., 2008; Philippe et al., 2012; Fryer et al., 2015b) to 10% (Baláš et al., 2021), or one standard deviation (Giles et al., 2021), respectively. Further variations are found for the duration for which the value falls below the threshold. For example, some tests are terminated with a tolerance of 1 second (Baláš et al., 2021), in other studies a tolerance of 2 s is allowed (Philippe et al., 2012; Fryer et al., 2015c). It is a bit of a dilemma to decide when the repetition is not valid anymore. Because when worsening fatigue is being experienced, the value continues to fall slowly.

It seems reasonable to us to look for implementation modalities for frequently used tests that increase the validity of the tests. Therefore, the main goal of our study was to find out which test termination criteria in intermittent finger flexor muscle endurance tests optimize the correlation of test performance with climbing performance. Furthermore, we wanted to find out how well the optimized endurance test together with the athletes' maximum strength predicts lead climbing performance.

MATERIALS AND METHODS

Participants

Calls for study participation were made via social media as well as announcements in local climbing gyms. The precondition was that participants had to be at least 16 years old and climb regularly, no matter at what climbing grade. All individuals who responded within the allotted period and met the criteria were invited for the study. Further consideration was given to all those who could indicate the three highest grades of lead climbing difficulty they had climbed in redpoint mode within the last 12 months. According to Draper et al. (2011) the average of these difficulty levels represented the dependent variable climbing performance in the test and was reported on the IRCRA scale (Draper et al., 2015). Thus, a total of 52 climbers (27 female, 25 male) finally participated in the study (**Table 3**). They were on average 29.1 ± 6.6 years old and had 5.6 ± 5.2 years of climbing experience. Their climbing skill ranged from 11 to 24 on the IRCRA scale. According to the IRCRA scale classification

TABLE 2 | Overview of measurement methods of finger flexor muscle endurance using intermittent isometric contractions.

Study	Parameter	Load	Work-to-rest ratio	Device
Ferguson and Brown (1997)	TTF	40% MVC	5:2 s	Hand-grip ergometer
Vigouroux and Quaine (2006)	REP	80% MVC	5:2 s	Special apparatus
MacLeod et al. (2007)	TTF FTI	40% MVC	10:3 s	Special apparatus
Philippe et al. (2012)	TTF FTI	40% MVC	10:3 s	Special apparatus
Fryer et al. (2015a)	FTI	40% MVC	10:3 s	Special apparatus
Fryer et al. (2015b)	FTI	40% MVC	10:3 s	Fingerboard apparatus
Medernach et al. (2015)	TTF	Hang	8:4 s	Fingerboard
Baláš et al. (2016)	TTF, FTI	60% MVC	8:2 s	Special apparatus
Michailov et al. (2018)	REP, TTF, FTI	60% MVC	8:2 s	Special apparatus
Giles et al. (2019)	TTF	80, 60, 45% MVC	7:3 s	20 mm rung
Stien et al. (2019)	TTF	60% MVC	7:3 s	23 mm ledge
Baláš et al. (2021)	TTF, FTI	60% MVC	8:2 s	23 mm ledge
Giles et al. (2021)	End-test force	100% MVC	7:3 s	20 mm rung
Rokowski et al. (2021)	TTZ, FTI, FTI/kg	60 ± 10% MVC	8:2 s	23 mm ledge

TTF, time till task failure (s); FTI, force-time integral (Ns); REP, repetitions till task failure (#).

TABLE 3 | Participant characteristics.

	Women	Men	Total
N	27	25	52
Age [years]	29.4 ± 7.6	28.8 ± 5.4	29.1 ± 6.6
Climbing experience [years]	5.8 ± 3.9	5.3 ± 5.0	5.6 ± 3.6
nd climbing skill [IRCRA]	14.2 ± 2.3	16.1 ± 2.8	15.1 ± 2.7
nbing classification	15 intermediate 12 advanced	19 intermediate 5 advanced 1 elite	34 intermediate 17 advanced 1 elite
Handedness	5 left, 22 right	2 left, 23 right	7 left, 45 right
Absolute maximum force dominant hand [kg]	44.0 ± 8.2	62.4 ± 7.1	52.8 ± 12.0
Absolute maximum force non-dominant hand [kg]	42.6 ± 8.9	60.0 ± 8.2	50.1 ± 12.2
Relative maximum force dominant hand [% body weight]	70.8 ± 12.7	85.5 ± 11.2	77.5 ± 14.0
Relative maximum force non-dominant hand [% body weight]	68.3 ± 13.1	82.3 ± 13.6	74.7 ± 15.0

(Draper et al., 2015), 34 athletes were intermediate, 17 advanced and one elite. Seven were left-handed and 45 were right-handed.

The experiments were undertaken with the understanding and written consent of each participant, and the study conforms with Declaration of Helsinki. The Ethics Committee of the Augsburg University, Germany, approved our research (approval number 20/104, 03 April 21).

Procedure

In a cross-sectional study, we conducted a maximum finger flexor muscle strength test and an endurance test on a fingerboard.

The participants started with a standardized 15-min warm-up consisting of a general warm-up of the involved muscles and a specific warm-up on the fingerboard. They performed 3 series of 5 repetitions of intermittent pulling (7 s pulling, 2 s rest) with increasing load. The first two series were performed two-handed, and the last one one-handed with 50, 70 and 50% of the body weight, respectively. We took the body weight because the maximum force was not known yet. The intermittent pulling within the warm-up served at the same time for familiarization for the following endurance test. Thereafter, 2 preparatory trials for the maximum strength test were performed.

For the maximum strength test, the participants stood on an Entralpi© force plate and had to pull alternately with the right and left hand as hard as they could for 5 s on a 23 mm deep rung with 12 mm radius with a half crimp finger position. This procedure was repeated three times. There was a 10-s rest between the right- and left-hand repetitions, and a 3-min rest between each of the three trials. The maximum strength (MVC) of each hand measured with the Entralpi© app was set to the maximum of the 3 repetitions. The results are shown in **Table 3**. Averaged over the right and left hand, the athletes were able to pull 51.9 ± 11.9 kg, which corresponds to 76.1% ± 14.2% of their body weight.

Thereafter, the intermittent endurance test was performed, which should provide the basis to determine the relationship between finger flexor muscle endurance and climbing performance. For this purpose, the participants had to pull on the 23 mm deep rung in a rhythm of 7 s load and 2 s rest with 60% of the previously determined maximum force. The rung size of 23 mm had been chosen because it targets both finger flexor muscles optimally and is therefore used in many studies about finger strength and endurance testing (Baláš et al., 2021; Rokowski et al., 2021; Stien et al., 2021). The load and rest rhythm durations have been chosen because they map the load structure of lead climbing competitions (Winkler et al., 2022). Participants were randomly chosen to begin with the dominant or non-dominant hand. After a 5-min rest, they performed the test with the other hand. The participants were instructed to pull the determined force throughout the 7 s. In the 2-s rest, the athletes could put down and shake the arm and, very quickly, chalk their fingers. A tablet mounted approximately at head height displayed a line for the force value to be targeted (60% MVC) and the force-time curve in real time via the Entralpi© app, allowing participants to monitor whether they still generated the required force (**Figure 1**). Participants could stop the test at any time if they felt uncomfortable or if they could not manage another repetition. However, this occurred in only about 5% of cases. Normally, the test was terminated by the experimenter as soon as the force exerted by the athlete dropped 10% below the the required force for an extended period longer than 2 s in two consecutive trials.

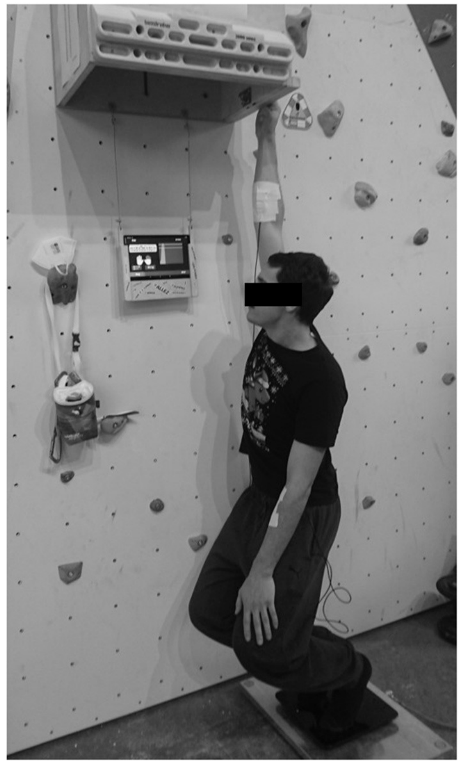

FIGURE 1 | Test setup. Participant standing on Entralpi© force plate, tablet for visual control at head height, one-hand pull on 23-mm rung.

Statistical Analysis

ter the test had been performed, the recorded data were evaluated retrospectively. To analyze which criterion one should apply in order to obtain the greatest correlation of the test with climbing performance, we calculated bilateral correlations between the lead climbing ability and the number of repetitions for different criteria for a valid repetition. For this purpose, all possible constellations of negative deviation from the required 60% MVC in one-percent increments up to a maximum of 10% undercutting and a deviation from the required pull duration of 7 s in 1-s decrements were considered. When considering the pulling time, only the time within the respective force target zone was taken into account. Also, the time at the beginning of the pulling was not taken into account until the target zone was reached. Lead climbing ability was assessed using the self-reported value on the IRCRA-scale as shown above.

To determine both the proportion of endurance and of maximum strength in lead climbing performance, regression analyses were performed. After adjusting for outliers, the data met the assumptions for regression analysis. All variables had equal variance and were found to be homoscedastic and normally distributed. The inclusion method was used with the best value from the above endurance test analysis for women and men, respectively, and the value of the relative maximum strength. The beta coefficient was consulted as an indicator of the level of influence on climbing performance. Analyses were performed using SPSS software (IBM SPSS, Version 26.0). The level of significance was set at $\alpha < 0.05$ for each procedure.

RESULTS

Number of Repetitions for Different Criteria

Tables 4, **5** show the number of repetitions on the fingerboard for women and men, respectively, for different criteria for a repetition to be counted as a valid repetition. Logically, the number of repetitions is lower when the criteria are stricter. Thus, on the one hand, the number of repetitions is reduced when the period of time over which the force must be applied during the pull is set longer. On the other hand, the number of repetitions is lower if a smaller decrease of force is tolerated. For women, there was little variation in the number of repetitions for the different tolerated decreasaes in pulling time. Considering that the force is mostly built up within the first second at the beginning of the repetition this means that the requirement to pull for 7 s was basically followed quite well by the women. With regard to the tolerated force deviation, it can be seen that the women hardly succeeded in meeting the specified force exactly. If no deviation was tolerated, they achieved just under 5 repetitions; if 10% deviation was tolerated, they achieved almost 10 repetitions.

In men, the repetition numbers increased even further when more than 3 s of time deviation was tolerated. This means that in some attempts they have just met half of the specified time period of 7 s. As in the women, almost twice as many repetitions were valid in the men when tolerating 10% force deviation than without any tolerance. However, the men already achieved

TABLE 4 | Number of repetitions for different criteria of a "valid" repetition in women.

Tolerated decrease in force			Tolerated decrease in pulling time	
			0–1 s	1–7 s
0%	REP	M	4.7	4.7
		SD	3.2	3.2
1%	REP	M	5.5	5.6
		SD	3.5	3.5
2%	REP	M	5.9	6.1
		SD	3.4	3.6
3%	REP	M	6.7	6.9
		SD	3.4	3.6
4%	REP	M	7.4	7.5
		SD	3.7	3.9
5%	REP	M	7.8	7.9
		SD	3.6	3.9
6%	REP	M	8.3	8.5
		SD	3.6	4.0
7%	REP	M	8.6	8.8
		SD	3.6	4.0
8%	REP	M	8.9	9.1
		SD	3.7	4.1
9%	REP	M	9.2	9.4
		SD	3.8	4.2
10%	REP	M	9.5	9.7
		SD	3.9	4.4

REP, number of repetitions.

almost the same value at 5% tolerated deviation as at 10% tolerated deviation.

Correlation Between Lead Climbing Ability and Number of Repetitions

In **Table 6** the results of the correlations between the lead climbing ability and the number of repetitions are shown for women and for men. Since the number of repetitions hardly differed between the tolerated time deviation of 3 and more seconds, the results for all force conditions and for time deviations up to 3 s are presented.

Obviously, irrespective of the tolerated deviation for the pulling time, the correlation became higher the more force deviation was tolerated. However, a ceiling effect was found at about 8% force deviation for women and about 5% force deviation for men, respectively. Further, for the men no matter which criterion one used, the correlation with lead climbing performance was always above 0.50. For the women, it was always below 0.50.

For the women, test performance did not correlate significantly with climbing performance unless at least a 7% force deviation was tolerated. The highest correlation, $R = 0.429$, was found for the condition of a tolerance of the pulling time of up to 1 s with a tolerated force deviation of 9%. According to Cohen (1988), a small correlation is found in the women from a force deviation of 3%, and a medium correlation from 6%. For the men, the choice of force deviation tolerance was not quite so decisive. Except for the 0% condition all correlations were higher than 0.6 and thus represented a large correlation. As with the women, the strictest criterion for the pulling time improved their respective correlation. The highest correlation, $R = 0.691$, was found for the condition of a tolerated decrease in pulling time of 1 swith a decrease of force of 6%.

Predictability of Lead Climbing Performance by Maximum Finger Strength and Endurance

As shown, in men, the correlation between the number of repetitions in the endurance test and lead climbing performance is much higher than in women. This means that endurance is clearly more relevant for men than for women concerning lead climbing performance. In men, lead climbing performance is predicted by almost 70%, whereas in women it is predicted by no more than 50%. The regression analyses revealed that lead performance is additionally strongly influenced by relative maximum strength in women, but not in men. For women, the R^2 for the overall model was 0.315 (*adjusted* $R^2 = 0.255$). The beta coefficient of endurance at 9% tolerated force deviation and 1 s deviation in pulling time was 0.388 ($P = 0.035$), while the beta coefficient of maximum strength was 0.414 ($P = 0.025$). The explained lead climbing performance for men was higher than for women, $R^2 = 0.463$ (*adjusted* $R^2 = 0.407$). However, the beta coefficient of endurance at 6% tolerated force deviation and 1 s deviation in pulling time was 0.682 ($P < 0.001$), whereas the beta coefficient of maximum strength was −0.003 ($P = 0.988$).

DISCUSSION

Based on the retrospective analysis, the intermittent finger flexor muscle endurance test could be optimized with regard to its validity for the correlation between finger endurance and lead climbing performance. While there has been great evidence to date that continuous test results correlate strongly with climbing performance, as far to our knowledge, no other study than ours has found significant correlations between the number of repetitions from intermittent tests and climbing performance. This might be due to unoptimized previous intermittent test protocols or participants of higher ability level in some previous studies. In the study with male elite and higher elite climbers by Rokowski et al. (2021), much lower, non-significant correlations were found between the time within the force target zone or the force-time integral and onsight and redpoint climbing performance in an intermittent test. In the study by Baláš et al. (2021) that also used an intermittent test and presented the relationship with lead climbing ability, a very similar correlation value as ours (R = 0.656) was obtained for a similar climbing level of the male participants, but only for the force-time integral. They did not consider the number of repetitions. There, the test was performed with a contraction relief ratio of 8:2 s at 60% MVC. The criterion for the termination of the test was,

TABLE 5 | Number of repetitions for different criteria of a "valid" repetition in men.

Tolerated decrease in force			Tolerated decrease in pulling time				
			0–1 s	**1–2 s**	**2–3 s**	**3–4 s**	**4–7 s**
0%	REP	M	5.4	5.4	5.7	5.7	5.7
		SD	4.8	4.8	5.4	5.4	5.4
1%	REP	M	6.2	6.3	6.5	6.5	6.5
		SD	4.8	4.8	5.3	5.3	5.4
2%	REP	M	6.8	6.9	7.1	7.1	7.1
		SD	4.8	4.8	5.3	5.3	5.4
3%	REP	M	7.7	7.7	8.0	8.0	8.0
		SD	4.4	4.4	4.9	4.9	5.0
4%	REP	M	8.3	8.3	8.5	8.5	8.6
		SD	4.2	4.2	4.7	4.7	4.8
5%	REP	M	9.2	9.3	9.5	9.5	9.5
		SD	4.1	4.0	4.6	4.6	4.6
6%	REP	M	9.8	9.9	10.1	10.1	10.2
		SD	3.9	3.9	4.4	4.4	4.4
7%	REP	M	10.1	10.2	10.5	10.5	10.6
		SD	3.9	3.9	4.4	4.3	4.3
8%	REP	M	10.5	10.6	10.9	10.9	11.0
		SD	3.8	3.9	4.4	4.3	4.3
9%	REP	M	10.6	10.8	11.1	11.1	11.2
		SD	3.9	3.9	4.5	4.3	4.3
10%	REP	M	10.7	10.9	11.2	11.3	11.4
		SD	3.9	3.9	4.5	4.4	4.3

? number of repetitions.

when the force dropped by more than 10% below the target force for more than 1 s, which is pretty much in line with the recommendations we derive from our results. Comparative results for female participants are not yet available.

In the studies on sustained contractions listed above, correlations are sometimes higher (Baláš et al., 2012; López-Rivera and González-Badillo, 2012), sometimes similar (Bergua et al., 2018; Michailov et al., 2018; Baláš et al., 2021) and sometimes lower (Ozimek et al., 2016, 2017). A meaningful comparison appears difficult, as the climbing levels of the test participants vary greatly. However, one can be quite content if a single test already explains 50–70% of the variance in climbing ability.

As in other studies, we considered maximum finger strength as a factor in lead climbing ability in addition to endurance. The regression analyses showed quite different results for men and women. Maximum strength was evidently more decisive ($\beta = 0.357$) for women than for men, for whom it is not a determining factor for lead performance at this climbing level ($\beta = -0.001$). This seems to contrast with some other studies that attribute a significant portion of climbing performance to maximum finger strength (e.g., Ozimek et al., 2017; Saul et al., 2019). However, the fact that maximum strength is more important for women than for men is also supported by Baláš et al. (2012), in which, for women, relative grip strength explained more than 50% of lead climbing performance but <30% for men.

Based on our results, we can make the following recommendations for intermittent finger flexor muscle endurance testing when using 60% MVC and 7:2 s contraction-rest ratio: For women, we propose to tolerate at least 7% up to 10% force deviation in relation to the predetermined force (significant moderate correlations). Since women pull fewer kilograms in absolute terms, the 5% tolerance is quickly undercut. Otherwise, the test measures not so much endurance as the ability to target the prescribed load very precisely. For men, on the other hand, a smaller percentage force deviation, e.g., of 5%, could also be chosen for test termination. The highest correlation value was reached for 6%, but all considered deviations showed strong correlations. Therefore, the threshold could be set to 10% for both genders for user friendliness.

In any case, it is necessary to be able to provide direct visual feedback on the force-time progression. Already 15 years ago, MacLeod et al. (2007) used "traffic lights" for feedback to maintain the correct force, showing green for correct force, blue for excessive force, and red for too little force. Nowadays, this is realized by means of a display that shows the force-time curve and the threshold line and can be monitored by the athlete, as is the case with our measuring system as well as with others (e.g., Michailov et al., 2018). For the practical test procedure, it is disadvantageous to have the participants perform many more repetitions than finally counted as valid after the retrospective analysis. Optimally, therefore, for example an acoustic or optic

TABLE 6 | Results of the correlations of the intermittent finger flexor muscle endurance test with lead climbing performance for different tolerated deviations of time and force.

Condition		Women		Men	
Time Deviation	**Force deviation**	**R**	**P**	**R**	**P**
0–1 s		0.418*	0.030	0.681*	<0.001
1–2 s	10%	0.369	0.058	0.678*	<0.001
2–3 s		0.371	0.056	0.661*	<0.001
0–1 s		**0.429***	0.026	0.684*	<0.001
1–2 s	9%	0.378	0.052	0.671*	<0.001
2–3 s		0.380	0.051	0.647*	<0.001
0–1 s		0.425*	0.027	0.677*	<0.001
1–2 s	8%	0.381	0.050	0.667*	<0.001
2–3 s		0.383	0.049	0.640*	0.001
0–1 s		0.389*	0.045	0.679*	<0.001
1–2 s	7%	0.354	0.070	0.668*	<0.001
2–3 s		0.354	0.070	0.627*	0.001
0–1 s		0.341	0.081	**0.691***	<0.001
1–2 s	6%	0.307	0.119	0.682*	<0.001
2–3 s		0.307	0.119	0.640*	0.001
0–1 s		0.289	0.144	0.669*	<0.001
1–2 s	5%	0.260	0.190	0.661*	<0.001
2–3 s		0.260	0.190	0.620*	0.001
0–1 s		0.261	0.189	0.626*	0.001
1–2 s	4%	0.235	0.239	0.619*	0.001
2–3 s		0.235	0.239	0.584*	0.002
0–1 s		0.157	0.435	0.638*	0.001
[illegible] s	3%	0.134	0.505	0.631*	0.001
2–3 s		0.134	0.505	0.595*	0.002
0–1 s		0.045	0.823	0.632*	0.001
1–2 s	2%	0.030	0.881	0.626*	0.001
2–3 s		0.030	0.881	0.593*	0.002
0–1 s		0.066	0.745	0.634*	0.001
1–2 s	1%	0.063	0.753	0.631*	0.001
2–3 s		0.063	0.753	0.600*	0.002
0–1 s		0.033	0.871	0.549*	0.005
1–2 s	0%	0.030	0.880	0.549*	0.005
2–3 s		0.030	0.880	0.523*	0.009

**Significant, bold = highest correlation for women and men, respectively.*

signal should be given, when the criteria for a valid repetition are no longer met as in Michailov et al. (2018).

With regard to the temporal extent of the force application, it should be noted that the specified pulling time was hardly ever completely maintained, because at the start of the test the force must be built up. At the end of the test, when experiencing fatigue, differences between men and women occurred. While the women performed almost no repetitions with more than 1 s time deviation, men performed more improper repetitions. Since a realized pulling time that was up to 1 s less than the specified time yielded the highest correlations with lead climbing performance, the consequence from our results is that the test should be terminated rather quickly after the applied force falls below the threshold. A tolerance of 1 s dropping below the threshold as in MacLeod et al. (2007) or Baláš et al. (2021) seems adequate. A two-second wait, as realized in some studies (e.g., Philippe et al., 2012), leads to a reduced correlation with lead climbing performance, especially in men, according to our results.

Unlike continuous tests, which assess local muscle anaerobic capacity, intermittent tests, like the one we used, can be considered a functional measure of climbers' local muscle aerobic capacity. One study suggests that local aerobic capacity is less important than local anerobic capacity in elite climbers. However, in accordance with Fryer et al. (2015c) and Fryer et al. (2016) our study suggests that local aerobic capacity is important for climbers at lower ability level.

Summing up, we think that the application of our recommendations can increase the intermittent tests' validity with respect to climbing performance and climbing specific endurance.

Limitations of the Study

A limitation of the study is that in the intermittent test, participants could choose whether or not to shake their arms during the 2-s rest after each load phase, as this compromises the standard conditions. However, there were hardly any cases in which the participants did not put their arms down and shake them briefly, so we assume that the influence on the results is not too great.

We did not tell the participants in our study that we were applying different criteria retrospectively as to when a repetition was valid. They assumed that they had to pull the given force over the 7 s. Of course, we could do it the other way around and give participants different target zones to stay within. However, we think that in practice it is quite difficult to target an exact force value and therefore it makes sense to prescribe an exact value but to tolerate a certain deviation. However, further studies could investigate the effects of prescribing different target zones.

Further research could also be conducted to further increase the intermittent test's validity. For example, we did not analyze different combinations of contraction and relaxation phases (e.g., 8:2, 7:3, 7:2 s, etc.). Also, we focused only on the final phase for test termination. One could also consider the initial phase of the test as a criterion for test termination.

The only dependent variable we considered in our study was the number of repetitions, rather than time till task failure and force-time integral, as in many studies cited above. This is because our approach of calculating a valid repetition retrospectively makes these values constants rather than variables. Once the termination criteria are fixed, these two parameters should also be used as performance criteria.

A relatively large number of participants took part in the study. Fortunately, many female participants, who are underrepresented in many studies, could also be recruited. However, the external validity of the findings can only refer to athletes of the climbing levels included in the study, in our case mainly advanced and intermediate athletes. Certainly, especially at the elite level, findings on the validity of performance tests would also be highly desirable.

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 University Augsburg, Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CA, MW, and SK: conception and preparation of the manuscript. MW and CA: performance of work, interpretation, and analysis of data. CA: supervision. All authors contributed to the article and approved the submitted version.

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Cortical Bone Thickness, Base Osteophyte Occurrence and Radiological Signs of Osteoarthritis in the Fingers of Male Elite Sport Climbers: A Cross-Sectional 10-Year Follow-Up Study

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Background: Sport climbing places high mechanical loads on fingers. In 2012, our research group demonstrated adaptations of climbers' cortical bones with the presence of osteophytes compared to non-climbing controls.

Objectives: 1) To investigate 10-year changes in cortical bone thickness, base osteophyte occurrence and radiological signs of osteoarthritis in the fingers of elite male sport climbers with more than 25 years of climbing history and 2) to compare cortical bone thickness, base osteophyte occurrence and radiological signs of osteoarthritis between male sport climbers and age-matched controls at the 10-year follow-up.

Methods: All 31 elite sport climbers who participated in both the baseline and 10-year follow-up assessments (follow-up rate 100%) were examined by means of X-rays. Cortical bone thickness, presence of osteophytes and signs of osteoarthritis according to Kellgren-Lawrence were obtained and compared to the baseline values 10 years earlier and to age-matched controls at the follow-up (n = 15).

Results: Significantly increased cortical bone thickness over the past 10 years was observed in climbers (mean absolute difference with 95% CI:0.98 mm (0.77 mm, 1.19 mm); p <0.001). Moreover, compared to age-matched controls, climbers had significantly thicker cortical bone at the 10-year follow-up (mean absolute difference with 95% CI:0.86 mm (0.61 mm, 1.12 mm); p <0.001). In climbers, osteophytes and clear signs of osteoarthritis were mainly seen in DIP joints. Signs of osteoarthritis according to Kellgren-Lawrence were more prevalent than 10 years before in most joints. In lateral radiographs, base osteophytes were not significantly more prevalent than 10 years before in most of the joints. The percentage of climbers who had osteophytes in any DIP (PIP) joint increased from 93.5% (67.7%) at baseline

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to 100% (74.2%) at the 10-year follow-up. The percentage of climbers who had clear signs of osteoarthritis according to Kellgren-Lawrence in any DIP (PIP) joint increased from 12.9% (9.7%) at baseline to 74.2% (64.5%) at 10-year follow-up. Only a few such degenerative changes were found in age-matched controls.

Conclusion: An accumulation of repetitive climbing-related stress to the fingers of elite sport climbers over the career may induce lifelong mechano-adaptation of the cortical bone thickness of all phalanges. At the 10-year follow-up, a further significant increase in radiographic signs of osteoarthritic changes was observed.

Keywords: climbing, degeneration, overuse, finger degeneration, osteophyte, load adaption

INTRODUCTION

With inclusion in the Olympic program for the 2020 Tokyo Summer Games, sport climbing continues to become a popular and fast-growing sport (Lutter et al., 2017). However, research in this area is still about to develop, and the long-term impact of intensive sport climbing to the human body is relatively unknown, as previous research mainly focused on acute climbing-related injuries and performance. Climbing requires holding the entire body weight with sometimes only one finger, resulting in extreme forces on the bones and connective tissue (Moor et al., 2009). Cortical adaptations in long-term climbers and a correlation with their years of climbing have already been demonstrated (Bollen and Wright, 1994; Rohrbough et al., 1998; Morrison and Schoffl, 2007; hoffl et al., 2007; Allenspach et al., 2011; Hahn et al., 2012; Schoffl al., 2015; Schoffl et al., 2018).

Ten years ago, our research group investigated the influence of high mechanical stress from climbing on the fingers of 31 elite level sport climbers and demonstrated a remarkably high occurrence of osteophytes and thicker cartilage in PIP and DIP joints compared to age-matched controls (Allenspach et al., 2011; Pastor et al., 2020). Other authors have also reported osteoarthritis-like changes in the fingers of long-time climbers; although slightly different populations were investigated and other assessment criteria were applied, likely leading to different occurrence frequencies (Bollen and Wright, 1994; Schoffl et al., 2018). However, whether these findings are early signs of osteoarthritis or just mechano-adaptation could not be conclusively clarified at that time. Furthermore, it is unclear how these adaptations evolve over a long observation period in elite sport climbers compared to non-climbing controls.

Therefore, the aims of this study were to investigate the 10-year changes in cortical bone thickness, base osteophyte occurrence and radiological signs of osteoarthritis in the fingers of male sport climbers with more than 15 years of climbing history at baseline and 25 years at follow-up and to compare these parameters between the climbers at the 10-year follow-up and age-matched controls.

METHODS

Study Design and Participants

Ten years after baseline assessments (Allenspach et al., 2011; Hahn et al., 2012), all 31 elite rock climbers were reinvestigated as part of follow-up assessments. At the reinvestigation, climbers were aged 48.3 ± 5.0 years on average (**Table 1** *for detailed characteristics*). Inclusion criteria in addition to participation in the two baseline studies were rock climbing on the elite level (minimum 7b + on the French scale) and a minimum of 25 years of climbing (range of climbing experience: 25–42 years; mean: 32 years). At the time of the baseline examination, climbers were at a level of 7b + to 9a + (average 8b +), and at the time of the follow-up, climbers were at a level of 6b to 9a (average 7c +). Exclusion criteria were major operations or injuries to the hands, quitting climbing activities or rejected informed consent; however, none of the climbers had to be excluded. All participants were contacted over a time period from April to August 2019 by telephone and could be examined 10 years after both baseline studies (follow-up rate of 100%).

In contrast to the climbers, the age-matched controls investigated 10 years earlier were unfortunately not available for re-examination in the current study due to the fact that we either had no current contact data, they had moved, or they were unwilling to participate after being re-contacted by phone and/or email. Therefore, 15 new non-climbing participants (mean age 48.1 ± 6.1 years) from different occupational fields at Balgrist University Hospital were recruited through personal inquiry and served as sex- and age-matched controls. In addition to not participating in any climbing activities or regularly performing physically demanding tasks, the eligibility criteria were the same as those for the climbers. This study was approved by the local ethics committee (Cantonal Ethics Commission Zurich, Switzerland, BASEC-Nr. 2019–00677), and all participants signed a written informed consent form.

TABLE 1 | Characteristics of the climbers at the 10-year follow-up.

Variable	Mean ± SD	95%CI
Age (y)	48.3 ± 5.0	(46.5, 50.0)
Body Weight (kg)	72.8 ± 7.2	(70.3, 75.3)
Body Height (m)	1.78 ± 0.04	(1.76, 1.79)
Body Mass Index (kg/m^2)	23.0 ± 2.3	(22.2, 23.8)
Years of Climbing (y)	31.6 ± 4.4	(30.1, 33.2)
Average Weekly Climbing Hours (h)	13.9 ± 7.3	(11.4,16.4)

SD, standard deviation; CI, confidence interval.

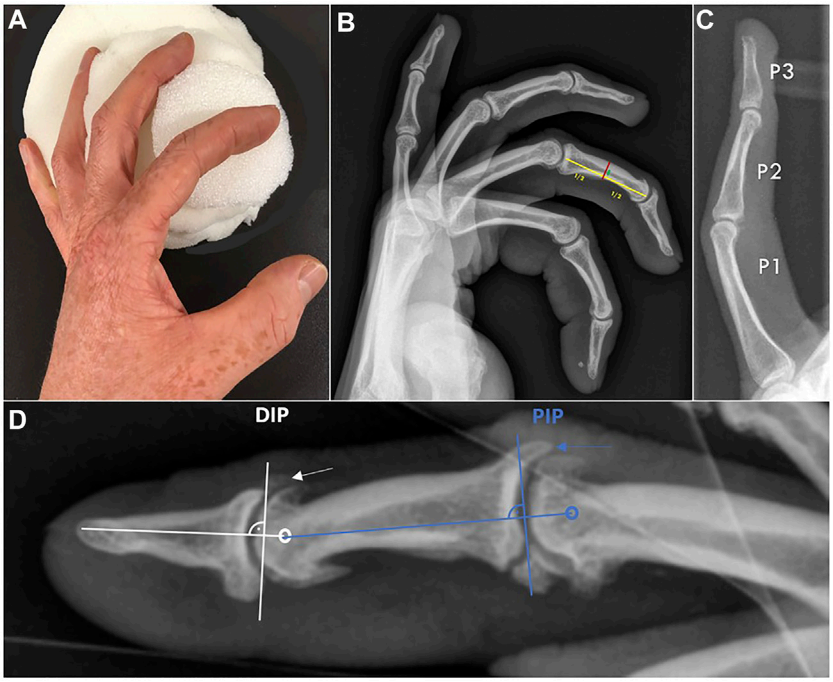

FIGURE 1 | (A) To obtain standardized lateral radiographs of all fingers, a custom-made device was used. **(B)** Climbers: lateral radiograph of a left hand using this device. Note how all fingers are projected strictly laterally and every single cortex is visible. Measurement of the intermediate phalanx of digit III is demonstrated as an example. Red line: outer cortical width. Green line: inner cortical width. Yellow line: length of the phalanx. **(C)** Controls: exemplary depicted lateral radiograph of a left middle finger. Note the clear differences in cortical thickness and medullary canal width in contrast to the climber. P1: proximal phalanx, P2: intermediate phalanx, P3: distal phalanx. **(D)** Lateral standardized radiograph of a left digit II in a climber. Modified measurement principles according to Allenspach et al. are demonstrated. Dorsal base osteophytes were rated as present or absent at the DIP and PIP joints, respectively. The arrows mark the presence of osteophytes at the DIP and PIP joints.

Data Collection and Evaluation

All participants received standardized anterior-posterior and lateral X-ray views (Ysio wi-D system, Siemens, Erlangen, Germany) of all fingers except the thumb of both hands using a custom-made positioning devise to ensure standardized lateral X-ray images (**Figure 1A**). The same device was used in both previously conducted baseline studies (Allenspach et al., 2011; Hahn et al., 2012). No blinding of the investigators was applied. For each phalanx of all fingers except the thumb, two measurements were obtained digitally in the lateral view (**Figure 1B**) according to Bollen and Wright (Bollen and Wright, 1994). After the length of the phalanx was determined, the inner cortical width and the outer cortical width were measured exactly in the middle of the phalanx as previously done in the baseline investigation (Hahn et al., 2012). With these two parameters, cortical bone thickness was determined as the difference between outer cortical width and medullary width. Cortical bone thickness was only evaluated in the lateral view due to the more pronounced differences compared to non-climbers in the baseline investigation (Hahn et al., 2012).

Base osteophyte occurrence was evaluated in lateral radiographs according to Allenspach et al. (Allenspach et al., 2011). Due to the most pronounced osteophyte occurrence on the dorsal base of the phalanx of PIP and DIP joints in the baseline investigation, only these osteophytes were rated as present or absent in the current study as follows (**Figure 1D**): a line was laid through the centre of rotation of the joint and along the axis of the related finger bone in the distal direction. Afterwards, a line was drawn perpendicular to this line adjacent to the socket. Osteophytes in DIP and PIP joints were rated as present if they reached the vertical line or if they were already broken.

Radiological signs of osteoarthritis (OA) were rated on antero-posterior radiographs according to the Kellgren-Lawrence (K-L) classification (Kellgren and Lawrence, 1957). Kellgren and Lawrence developed the score in 1957, which is used to classify the severity of osteoarthritis based on conventional radiographs and was later accepted by the World Health Organization (WHO) as the radiological definition of OA for the purpose of epidemiological studies (Sangha, 2000; Schiphof et al., 2008). The following signs of osteoarthritis are considered: evidence of osteophytes, decrease in joint space width (cartilage thickness), increased subchondral sclerosis and deformity of the joint-forming bone parts (osteophytes). PIP and DIP joints were rated to one of the following grades:

grade 0 (none): definite absence of X-ray changes of osteoarthritis;

grade 1 (minimal): doubtful joint space narrowing and possible osteophytic lipping;

grade 2 (moderate): definite osteophytes and possible joint space narrowing;

TABLE 2 | Descriptive and inferential statistics for the bone thickness at phalanx 1–3 of both hands and digits II-V for climbers at baseline and at 10 years follow-up, as well as their age-matched controls.

Structure	Climbers at baseline (A)[a]		Climbers at 10-years follow-up (B)		Age-matched Controls (C)		Pairwise comparisons (t-tests[b])			
	n	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD	B-A (95%CI)	*p* value	C-B (95%CI)	*p* value
Right hand	—	—	—	—	—	—	—	—	—	—
P1 D2 (mm)	31	4.3 ± 0.6	31	5.6 ± 0.5	15	5.0 ± 0.6	1.3 (1.0, 1.5)	0.001***	0.6 (0.3, 1.0)	0.002**
P2 D2 (mm)	31	3.2 ± 0.5	31	4.7 ± 0.5	15	3.8 ± 0.5	1.5 (1.2, 1.7)	0.001***	0.9 (0.6, 1.2)	0.001***
P3 D2 (mm)	31	3.0 ± 0.5	31	3.0 ± 0.4	15	2.4 ± 0.4	0.1 (-0.1, 0.3)	0.499[ns]	0.7 (0.4, 0.9)	0.001***
P1 D3 (mm)	31	4.5 ± 0.5	31	6.2 ± 0.8	15	5.2 ± 0.6	1.7 (1.3, 2.0)	0.001***	1.0 (0.6, 1.5)	0.001***
P2 D3 (mm)	31	3.3 ± 0.5	31	4.9 ± 0.7	15	3.9 ± 0.6	1.6 (1.3, 1.9)	0.001***	0.9 (0.5, 1.3)	0.001***
P3 D3 (mm)	31	3.1 ± 0.5	31	3.2 ± 0.5	15	2.5 ± 0.4	0.1 (-0.2, 0.4)	0.308[ns]	0.7 (0.4, 1.0)	0.001***
P1 D4 (mm)	31	3.9 ± 0.5	31	5.1 ± 0.6	15	4.5 ± 0.5	1.3 (1.0, 1.5)	0.001***	0.6 (0.3, 0.9)	0.002**
P2 D4 (mm)	31	2.8 ± 0.4	31	4.5 ± 0.6	15	3.5 ± 0.5	1.7 (1.4, 1.9)	0.001***	1.0 (0.7, 1.3)	0.001***
P3 D4 (mm)	31	2.8 ± 0.4	31	3.1 ± 0.7	15	2.2 ± 0.4	0.3 (-0.1, 0.6)	0.135[ns]	0.9 (0.6, 1.2)	0.001***
P1 D5 (mm)	31	3.2 ± 0.4	31	4.0 ± 0.5	15	3.5 ± 0.7	0.8 (0.6, 1.1)	0.001***	0.5 (0.1, 0.9)	0.009**
P2 D5 (mm)	1	2.8 ± 0.4	31	3.3 ± 0.5	15	2.7 ± 0.5	0.5 (0.3, 0.8)	0.001***	0.7 (0.4, 0.9)	0.001***
P3 D5 (mm)	31	2.3 ± 0.3	31	2.5 ± 0.4	15	1.8 ± 0.3	0.2 (0.0, 0.4)	0.022*	0.7 (0.5, 0.9)	0.001***
Left hand	—	—	—	—	—	—	—	—	—	—
P1 D2 (mm)	31	4.4 ± 0.5	31	5.8 ± 0.8	15	4.9 ± 0.7	1.4 (1.1, 1.7)	0.001***	1.0 (0.6, 1.4)	0.001***
P2 D2 (mm)	31	3.2 ± 0.5	31	4.5 ± 0.6	15	3.7 ± 0.4	1.4 (1.1, 1.7)	0.001***	0.9 (0.6, 1.1)	0.001***
P3 D2 (mm)	31	2.9 ± 0.5	31	3.0 ± 0.5	15	2.1 ± 0.3	0.1 (-0.2, 0.3)	0.426[ns]	1.0 (0.7, 1.2)	0.001***
P1 D3 (mm)	31	4.5 ± 0.5	31	6.4 ± 0.7	15	5.2 ± 0.6	1.9 (1.6, 2.2)	0.001***	1.2 (0.8, 1.6)	0.001***
P2 D3 (mm)	31	3.2 ± 0.5	31	5.1 ± 0.7	15	3.8 ± 0.6	1.9 (1.6, 2.2)	0.001***	1.3 (0.9, 1.6)	0.001***
P3 D3 (mm)	31	3.1 ± 0.6	31	3.2 ± 0.6	15	2.3 ± 0.4	0.1 (-0.1, 0.4)	0.371[ns]	0.9 (0.6, 1.2)	0.001***
P1 D4 (mm)	31	3.8 ± 0.5	31	5.4 ± 0.7	15	4.2 ± 0.5	1.6 (1.2, 1.9)	0.001***	1.1 (0.8, 1.5)	0.001***
P2 D4 (mm)	31	2.8 ± 0.5	31	4.5 ± 0.7	15	3.5 ± 0.5	1.7 (1.4, 2.0)	0.001***	1.1 (0.7, 1.4)	0.001***
P3 D4 (mm)	31	2.7 ± 0.4	31	3.4 ± 1.2	15	2.0 ± 0.4	0.7 (0.3, 1.2)	0.037*	1.4 (1.0, 1.9)	0.006**
P1 D5 (mm)	31	3.2 ± 0.4	31	3.9 ± 0.6	15	3.6 ± 0.8	0.8 (0.5, 1.0)	0.001***	0.4 (-0.1, 0.8)	0.113[ns]
P2 D5 (mm)	31	2.7 ± 0.4	31	3.2 ± 0.5	15	2.7 ± 0.4	0.5 (0.3, 0.7)	0.001***	0.5 (0.2, 0.7)	0.001***
P3 D5 (mm)	31	2.2 ± 0.3	31	2.6 ± 0.4	15	1.9 ± 0.4	0.4 (0.2, 0.6)	0.001***	0.8 (0.6, 1.0)	0.001***

[a]Data already partially presented in Hahn et al. (2012). The climbers at the 10-year follow-up (B) were the same subjects as the climbers at baseline (A).
*[b]Level of significance-based t-tests and backed up by bias-corrected accelerated bootstrapping with 10,000 samples: [ns], not significant, *p <0.05, **p <0.01, ***p <0.001.*
P1, proximal phalanx; P2, intermediate phalanx; P3, distal phalanx; D2, Dig II; D3, Dig III; D4, Dig IV; D5, Dig V; n, number of observations.

grade 3 (severe): moderate multiple osteophytes, definite narrowing of joint space, sclerosis and deformity of bone ends.

According to Kellgren and Lawrence, osteoarthritis is deemed present at grade 2 (Kellgren and Lawrence, 1957; Rohrbough et al., 1998; Schoffl et al., 2018).

Statistical Analysis

Statistical analysis included the following steps: 1) Cortical bone thickness from the lateral view at phalanx 1–3 [proximal (P1), intermediate (P2), distal (P3)] of both hands and digits II-V was reported as the mean ± SD; 2) corresponding cortical bone thickness differences and interaction effects were tested by the use of a repeated-measures multivariate ANOVA ($p < 0.05$). Within-subject factors were phalanx [proximal (P1), intermediate (P2), distal (P3)], side (right and left) and digit (Dig II-V), and between-subject factor was the group (climbers at baseline, climbers at 10 years follow-up, and age-matched controls). Effect sizes were reported as partial eta^2, and following Cohen (Cohen, 1988), effect size thresholds were taken as 0.01 (small effect), 0.06 (medium effect), and 0.14 (large effect); 3) detailed group differences for each joint/side/digit were tested using unpaired sample t-tests backed up by bias-corrected accelerated bootstrapping with 1,000 samples ($p < 0.05$); and 4) for all groups, the relative frequency of base osteophyte occurrence, as well as of subjects with K-L scores of 2 or higher (='clear' signs of OA), was plotted as the percentage proportion (number affected subjects/number of subjects per group × 100) with corresponding 95% CI. Non-overlapping 95% CIs between the groups were interpreted as significant differences at $p < 0.05$.

RESULTS

Differences in Bone Thickness

The descriptive statistics of cortical bone thickness from the lateral view for the 3 groups (climbers at baseline, climbers at 10-year follow-up and age-matched non-climbing controls), phalanx (proximal (P1), intermediate (P2) and distal (P3), sides (right and left), and digits (Dig II-V) are presented in **Table 2**. Climbers demonstrated thicker cortical bones than age-matched controls as well as 10 years earlier. The exact statistical results of the repeated-measures multivariate ANOVA were as follows: There were significant differences and large effects in cortical bone thickness between the groups ($p < 0.001$; partial eta^2 = 0.667), phalanx ($p < 0.001$; partial eta^2 = 0.945), and digits ($p < 0.001$; partial eta^2 = 0.862) on the multivariate level. Interaction effects revealed for phalanx*group ($p < 0.001$, partial eta^2 = 0.661), side*group

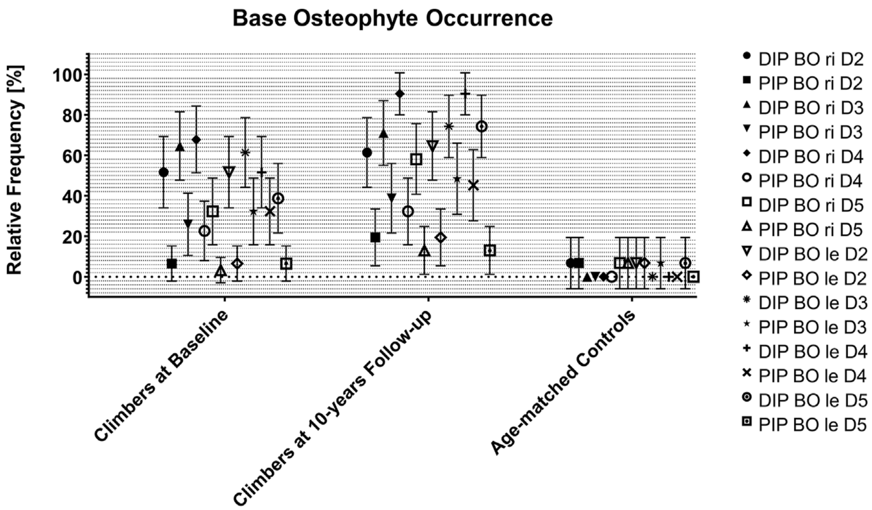

FIGURE 2 | Base osteophyte occurrence in climbers at baseline and at 10 years follow-up, as well as in their age-matched controls. Data are expressed as joint, side and digit-specific relative proportion group means with 95% CI. BO: base osteophyte; DIP: distal interphalangeal joint; PIP: proximal interphalangeal joint; ri: right; le: left; D: digit.

($p = 0.001$, partial eta^2 = 0.185), digit*group ($p < 0.001$, partial eta^2 = 0.348), phalanx*digit ($p < 0.001$, partial eta^2 = 0.406) and phalanx*digit*group ($p < 0.001$, partial eta^2 = 0.224). Significantly increased cortical bone thickness over the past 10 years was observed in the climbers (mean absolute difference with 95% CI: 0.98 mm (0.77 mm, 1.19 mm); $p < 0.001$). Moreover, compared to age-matched controls, climbers had significantly thicker cortical bone at the 10-year follow-up (mean absolute difference with 95% CI: 0.86 mm (0.61 mm, 1.12 mm); $p < 0.001$). In part, non-significant differences in cortical bone thickness existed between climbers at baseline and at the 10-year follow-up at the distal phalanx (P3).

Differences in Base Osteophyte Occurrence

Figure 2 and **Supplementary Figures S1A–D** show the relative proportions of osteophyte occurrence at the base in climbers at baseline and after 10 years and in age-matched controls.

The age matched controls at the 10-year follow-up showed relative frequencies of base osteophytes between 0 and 10% in all joints of all fingers. The climbers at the 10-year follow-up showed relative frequencies higher than 60% in all DIP joints and between 10 and 50% in all PIP joints. Thus, mainly the DIP joints were affected by base osteophytes, most severely on Dig IV, followed by Dig III and Dig V.

In all DIP joints of all fingers, the relative occurrence of base osteophytes showed a significant difference between the climbers at the 10-year follow-up and the non-climbing controls. In PIP joints, this difference was only seen in Dig III (both sides), Dig IV (both sides), and Dig V (left side only).

The comparison between climbers at baseline and climbers at the 10-year follow-up revealed significant differences only for the DIP joints of the left Dig IV and V, while all other joints showed no significant differences. However, the relative frequency of base osteophytes slightly increased in all other joints over the 10-year follow-up period without reaching statistical significance (**Supplementary Figures S1A–D**). The percentage of climbers who had osteophytes in any DIP joint increased from 93.5% at baseline to 100% at the 10-year follow-up (non-climbing controls: 13.3%). For any PIP joint, this percentage increased from 67.7 to 74.2% (non-climbing controls: 13.3%).

Differences in ‘Clear’ Signs of OA

Figure 3, **Figure 4** and **Supplementary Figures S2A–D** show the relative proportions of subjects with K-L scores of 2 or higher (‘clear signs of OA) in climbers at baseline and after 10 years and in age-matched controls.

Climbers at baseline and non-climbing controls both showed relative frequencies of clear signs of osteoarthritis in all joints of all fingers between 0 and 20%. Climbers at the 10-year follow-up showed relative frequencies between 5 and 60%, depending on the joint and finger. Clear signs of osteoarthritis in terms of a Kellgren-Lawrence score of 2 or higher were most frequently seen in the DIP joints of several fingers. The DIP joints of Dig III were affected most frequently, and the PIP joints of Dig V were affected least frequently.

Compared to the climbers at baseline 10 years before, the relative frequency of clear signs of osteoarthritis was significantly increased in the right DIP joint of Dig II, in both PIP joints of Dig II, in both DIP joints and both PIP joints of Dig III, in both DIP joints and the right PIP joint of Dig IV, and in the left DIP joint of Dig V. Climbers at the 10-year follow-up presented significantly more frequently with clear signs of osteoarthritis in the left PIP joint of Dig II, in both DIP joints and both PIP joints of Dig III, and in the left DIP joint and both PIP joints of Dig IV than non-climbing controls (**Supplementary Figures S2A–D**). The percentage of climbers who had clear signs of osteoarthritis in any DIP joint increased from 12.9% at baseline to 74.2% at the 10-year follow-up (non-climbing controls: 26.7%). For any PIP joint, this percentage increased from 9.7 to 64.5% (non-climbing controls: 6.7%).

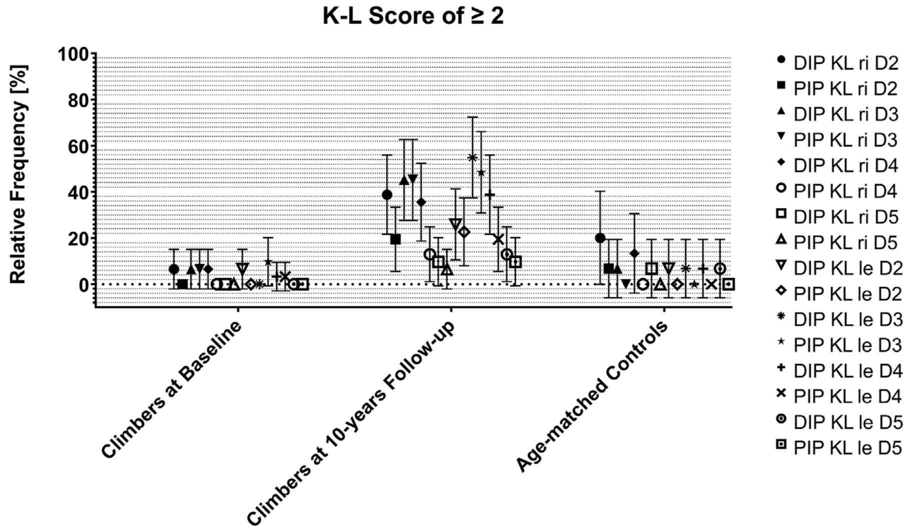

FIGURE 3 | Occurrence of 'clear' signs of OA (= K-L scores of 2 or higher) in climbers at baseline and at the 10-year follow-up, as well as in their age-matched controls. Data are expressed as joint, side and digit-specific relative proportion group means with 95% CI. KL: Kellgren-Lawrence Score; DIP: distal interphalangeal joint; PIP: proximal interphalangeal joint; ri: right; le: left; D: digit.

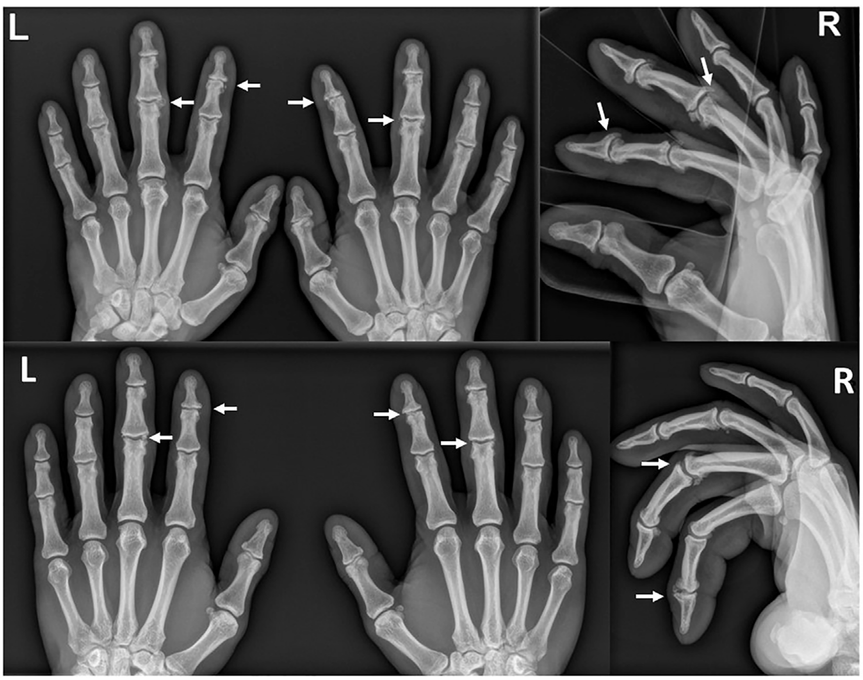

FIGURE 4 | Anteroposterior (left) and lateral (right) radiographs of the same climber: top, current images; bottom, images at baseline 10 years earlier. Note the increased signs of osteoarthritis with larger osteophytes and decreased joint spaces in the current images in contrast to the baseline examination. Particularly impressive findings are marked with arrows as an example.

DISCUSSION

The main findings of the current study, which is the study with the longest climbing history (25–41 years) of its participants, were as follows: 1) in climbers, a significant increase in cortical bone thickness over the last 10 years was observed; 2) at the 10-year follow-up, cortical bone thickness was still significantly larger in climbers than in age-matched, non-climbing controls; 3) in climbers, the frequency of the occurrence of base osteophytes (in lateral radiographs) has not significantly increased during the

10-year observation period in most joints; 4) in contrast to the base osteophytes, the frequency of clear signs of osteoarthritis in ap-radiographs has significantly increased over the 10 years in most joints; 5) in climbers, DIP joints are more frequently affected by both base osteophytes and osteoarthritis than PIP joints; 6) base osteophytes and osteoarthritis are significantly more frequent in climbers than in age-matched controls in many, but not all finger joints; 7) while base osteophytes in the lateral view in climbers are most pronounced in Dig IV, clear signs of osteoarthritis in the ap-view are most pronounced in Dig III.

Mechano-Adaptation of Cortical Bone Thickness

In the baseline investigation 10 years earlier, thicker cortical bones in all phalanges of elite sport climbers compared to age-matched non-climbing controls have been reported (Hahn et al., 2012). The current study revealed a further increase in cortical thickness in all phalanges of the same elite sport climbers. This is in line with previously published reports regarding mechano-adaptation of fingers in sport climbers. Bollen et al. and Schöffl et al. reported cortical reactions to stress in the fingers of elite sport climbers (Bollen and Wright, 1994; Schoffl et al., 2004; Schoffl et al., 2007; Schoffl et al., 2018). However, only the study by Schöffl et al. was a longitudinal study, with a similar follow-up time of 11 years, but with significantly younger participants (Schoffl et al., 2018). In addition to mechano-adaptation of bones, several studies have demonstrated adaptations in other structures of the fingers of elite sports climbers. Schreiber et al. reported adaptations with thicker palmar plates, pulleys and flexor tendons compared to a non-climbing control group (Schreiber et al., 2015). In a 10-year follow-up study of the same climbers, all investigated soft tissue parameters were thicker compared to the baseline investigation, which suggests a theory of a life-long build-up of these soft tissue structures (Fröhlich et al., 2021). Similar findings were also reported by Rohrbough et al. (Rohrbough et al., 1998), Garcia et al. (Garcia et al., 2018) and Klauser et al. (Klauser et al., 2000). Furthermore, thicker capsules and collateral ligaments were reported in 20 sport climbers compared to an age-matched control group (Heuck et al., 1992). Thus, the findings of the current study suggest a career-long build-up of cortical bone thickness in the fingers of elite sport climbers.

Development of Osteophytes and Osteoarthritis in the Fingers of Elite Sport Climbers

In contrast to cortical bone thickness, the occurrence of base osteophytes did not significantly increase in most joints of the climbers over the 10-year observation period. A possible explanation is the fact that all climbers already had at least 15 years of intensive climbing experience at baseline (Allenspach et al., 2011). Therefore, the authors suggest that the formation of base osteophytes in high-level climbers occurs primarily during the first 15 years of the climbing career and progresses less than other structural adaptations thereafter (i.e., the upcoming 10 years). This seems to be true at least for the question of whether an osteophyte is present or not, regardless of its extent.

With regard to clear signs of osteoarthritis in the ap-view, these are significantly more frequent in most joints of the climbers than 10 years earlier. The baseline study of climbers with more than 15 years of climbing experience has already shown that osteophytes can be seen early in lateral radiographs, while ap radiographs can still look relatively normal (Allenspach et al., 2011). The new findings (now 10 years later in climbers with more than 25 years of climbing experience) indicate that previously already present osteophytes have increased to such an extent that they may be considered as visible signs of osteoarthritis in the ap-view.

The finding that DIP joints are more affected by degenerative changes than PIP joints is novel, as previous studies have reported a similar occurrence of osteophytes in both proximal and distal interphalangeal joints (Allenspach et al., 2011; Pastor et al., 2020). This finding suggests that at later stages of the career, the DIP joints seem to be more prone to degeneration than the PIP joints. This might be explained by the long-term effect of the particularly high loads on the DIP joints, for example, when applying the "crimp position", which also served as an explanation for the particularly pronounced thickening of the palmar plates in the DIP joints of climbers (Schreiber et al., 2015). A consequence could be the recommendation that the crimp position should no longer be trained in excess at an older age. However, the current study is not fully able to justify this recommendation and more research is needed.

While osteophytes and signs of osteoarthritis are significantly more frequent in climbers than in age-matched controls in most finger joints, this is still not the case for all joints. This may allow two conclusions to be drawn: on the one hand, it can be assumed that even after many years of intensive climbing, certain finger joints are still subjected to significantly less stress than others: the joints least prone to osteophyte formation and other signs of osteoarthritis are PIP at Dig V and PIP at Dig II. On the other hand, the age-matched control subjects of the current study are now also 10 years older than those of the baseline studies, and with correspondingly increasing age, it can be assumed that generally more joints show certain degenerations, which may lead to a convergence between climbers and non-climbers.

The finding that osteophytes in the lateral view are most common in the DIP joints of Dig IV is in line with the theory that this finger must withstand the greatest mechanical forces, which has been stated in previous studies (Roloff et al., 2006; Schoffl and Schoffl, 2007; Vigouroux et al., 2008; Schoffl et al., 2018). However, we found most of the clear signs of osteoarthritis in the ap-view in the DIP joints of Dig III. Other studies have also found both fingers, Dig III and IV, to be frequently subject to degeneration (Allenspach et al., 2011; Pastor et al., 2020). Therefore, we recommend considering both fingers as particularly affected by degenerative changes in climbers.

Methodological Considerations

Although a follow-up rate of 100% over 10 years was achieved and it is worth mentioning that the climbers assessed in the current study represent the study sample with the longest climbing history (25–41 years) at the elite level reported in the literature to date, some possible limitations should be considered when interpreting the study results.

First, the sample size was identical to the population selected 10 years ago, which is why only a limited number of 31 elite male climbers were examined. As a direct consequence, the generalizability of the current findings for other cohorts may be limited and with regard to conclusions for clinical practice, some caution is advised. With respect to the reported significant results, potential type I errors of statistical testing (the risk of rejecting the null hypothesis when it's actually true, i.e., concluding that there is a difference between groups when in fact such difference does not exist) may have occurred. In addition, with regard to the reported nonsignificant results, there could be potential type II errors of statistical testing (i.e., the risk of accepting the null hypothesis when it's actually false, i.e., concluding that there is no difference between groups when in fact such a difference exists).

Second, radiographic measurements were performed by two different examiners 10 years ago and now. Although all examinations were highly standardized and easy to perform, interobserver bias still may have been possible. Furthermore, all examinations were performed using the same technical devices and protocols to minimize discrepancies, and the senior author was involved in both studies.

Third, the non-climbing controls of 15 men examined in the baseline investigation could not be recruited again for the current study; therefore, a new age-matched control group was recruited. In addition, the recruitment of the control group by personally enquiring employees at our hospitals may have led to some selection bias. However, this potential bias was counteracted by selecting subjects from different health care professions, but who mainly worked in an office setting (i.e., did not perform physically demanding tasks). Finally, examiners have not been blinded to the climbing status, as the hand radiographs of elite climbers are usually immediately recognizable.

CONCLUSION

Climbing at the elite level likely induces mechano-adaptation of cortical bones in the fingers, and build-up takes place over the career. Climbers show higher frequencies of base osteophytes in PIP and DIP joints of most fingers compared to controls; however, it does not significantly increase over the later 10 years of the career in most fingers. In contrast, clear radiographic signs of osteoarthritis also increase at later stages of the climbing career (i.e., more than 15 years of climbing), especially in DIP joints and Dig III and IV. These results were obtained from a population of climbers with the longest climbing experience compared to the literature (mean 32 years).

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Cantonal Ethics Commission Zurich, Switzerland, BASEC-Nr. 2019–00677. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

TP, SF, JS, and AS conceptualized and designed the study. TP recruited the participants, collected the data and performed all measurements. JS and SF processed the data and JS performed the statistical analysis. All authors substantially contributed to the interpretation of the data. SF, TP, JS, and TP drafted the current manuscript; all authors revised it critically, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work. AS is primarily responsible for the work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2022.893369/full#supplementary-material

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Effects of Forearm Compression Sleeves on Muscle Hemodynamics and Muscular Strength and Endurance Parameters in Sports Climbing: A Randomized, Controlled Crossover Trial

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Purpose: Wearing compression garments is a commonly used intervention in sports to improve performance and facilitate recovery. Some evidence supports the use of forearm compression to improve muscle tissue oxygenation and enhance sports climbing performance. However, evidence is lacking for an effect of compression garments on hand grip strength and specific sports climbing performance. The purpose of this study was to evaluate the immediate effects of forearm compression sleeves on muscular strength and endurance of finger flexor muscles in sports climbers.

Materials and Methods: This randomized crossover study included 24 sports climbers who performed one familiarization trial and three subsequent test trials while wearing compression forearm sleeves (COMP), non-compressive placebo forearm sleeves (PLAC), or no forearm sleeves (CON). Test trials consisted of three performance measurements (intermittent hand grip strength and endurance measurements, finger hang, and lap climbing) at intervals of at least 48 h in a randomized order. Muscle oxygenation during hand grip and finger hang measurements was assessed by near-infrared spectroscopy. The maximum blood lactate level, rate of perceived exertion, and forearm muscle pain were also determined directly after the lap climbing trials.

Results: COMP resulted in higher changes in oxy[heme] and tissue oxygen saturation (StO_2) during the deoxygenation (oxy[heme]: COMP –10.7 ± 5.4, PLAC –6.7 ± 4.3, CON –6.9 ± 5.0 [μmol]; $p = 0.014$, $\eta_p^2 = 0.263$; StO_2: COMP –4.0 ± 2.2, PLAC –3.0 ± 1.4, CON –2.8 ± 1.8 [%]; $p = 0.049$, $\eta_p^2 = 0.194$) and reoxygenation (oxy [heme]: COMP 10.2 ± 5.3, PLAC 6.0 ± 4.1, CON 6.3 ± 4.9 [μmol]; $p = 0.011$, $\eta_p^2 = 0.274$; StO_2: COMP 3.5 ± 1.9, PLAC 2.4 ± 1.2, CON 2.3 ± 1.9 [%]; $p = 0.028$, $\eta_p^2 = 0.225$) phases of hand grip measurements, whereas total [heme] concentrations were not affected. No differences were detected between the conditions for the parameters of peak force and fatigue index in the hand grip, time to failure and hemodynamics in the finger hang, or performance-related parameters in the lap climbing measurements ($p \leq 0.05$).

Conclusions: Forearm compression sleeves did not enhance hand grip strength and endurance, sports climbing performance parameters, physiological responses, or perceptual measures. However, they did result in slightly more pronounced changes of oxy [heme] and StO_2 in the deoxygenation and reoxygenation phases during the hand grip strength and endurance measurements.

Keywords: sport climbing, muscle oxygenation, near infrared spectroscopy, compression garments, hand grip strength, finger flexor muscles

INTRODUCTION

Wearing compression garments is a popular intervention used by recreational and elite athletes to improve current or subsequent exercise performance, reduce the risk of injury, and mitigate exercise-induced discomfort (MacRae et al., 2011; Beliard et al., 2015). Compression garments are elastic clothing items that apply mechanical pressure at the surface of needed body zones, thereby improving venous return and stabilizing, compressing, and supporting the underlying tissues (Bochmann et al., 2005; MacRae et al., 2011; Xiong and Tao, 2018). The use of lower body and lower limb compression garments as a recovery tool has gained popularity both during and after exercise, and the beneficial effects of compression garments on recovery mechanisms are well investigated (MacRae et al., 2011; Hill et al., 2014; Marqués-Jiménez et al., 2016; Brown et al., 2017).

However, evidence remains controversial regarding the neficial effects on muscle strength and muscle endurance ien compression garments are applied during exercise (Born et al., 2013; Beliard et al., 2015; Engel and Sperlich, 2016; Ballmann et al., 2019). The advantages of wearing compression garments during exercise for an enhancement of exercise performance have largely been studied in endurance-based aerobic activities, and the available studies have produced mixed results (Dascombe et al., 2011; Born et al., 2013; Driller and Halson, 2013; Engel et al., 2016). Consequently, evidence for an improvement in exercise performance by wearing compression garments in high-intensity exercise is still insufficient (Ballmann et al., 2019). A few studies have proposed the effectiveness of compression garment application in improving muscle blood flow and repeated sprint cycling performance (Broatch et al., 2018), high-intensity intermittent exercise performance (Sear et al., 2010), or high-intensity exercise performance in basketball players (Ballmann et al., 2019). Wearing compression garments also reduced fatigue-induced strength loss after 100 maximal isokinetic eccentric contractions (Négyesi et al., 2021) and reduced the maximal voluntary contraction force decrements observed immediately after handball-specific exercise circuits that included intermittent sprints, jumps, and agility drills (Ravier et al., 2018). Another investigation reported that wearing compression socks during high-intensity running had a positive impact on subsequent running performance (Brophy-Williams et al., 2019). Conversely, although compression garments lead to a lower effort perception and a reduced self-reported muscle soreness, they are not found to result in performance changes in team-sport activities (Duffield et al., 2008), the 400 m sprint (Faulkner et al., 2013), or during high intensity exercise (Da Silva et al., 2018). Given these contradictory results, further studies are needed to investigate the effects of compression garments on high-intensity exercise performance with relation to specific sports disciplines.

Climbing performance is highly dependent on the high-intensity exercise performance of the finger flexor muscles (Watts et al., 1993; España-Romero et al., 2009; Vigouroux et al., 2015). In general, climbing consists of an acyclic movement pattern that requires repeated isometric contractions of the forearms, combined with dynamic whole-body movements (Baláš et al., 2016). Thus, intermittent finger flexor muscle strength and muscle endurance are key elements of sport-climbing performance (Michailov, 2014; Fryer et al., 2015), and climbing performance and failure in competitive climbing tasks are often related to muscle fatigue of the finger flexor muscles (Watts et al., 1993; Philippe et al., 2012).

During climbing, handgrip strength and endurance decrease significantly because of muscle contraction-induced ischemia in the finger flexor muscles. This ischemia is associated with a decline in muscle oxygenation and results in muscle fatigue and performance decrements (Watts, 2004; Fryer et al., 2016; Engel et al., 2018). The forearm flexor oxidative capacity index is another important determinant of rock climbing performance (Fryer et al., 2016). External forearm compression, induced by wearing forearm compression sleeves, has been shown to increase forearm arterial blood flow (Bochmann et al., 2005); therefore, this enhanced blood flow could be beneficial for sports climbing performance. The enhanced flow is associated with an increased ability of all tissues (including working muscles) to utilize lactate, the metabolic response to an increased glycolytic flux elicited by an increasing work rate (Giles et al., 2006; Poole et al., 2021).

Although the beneficial effects of compression garments remain uncertain for high-intensity performance and the improvement of muscular strength and endurance, a broad interest exists, from a practical point of view, in the potential benefits of wearing compression garments in complex sport tasks, such as sports climbing. At present, only one study has investigated the effects of wearing forearm compression sleeves on climbing performance (Engel et al., 2018). This recent study suggested the occurrence of a compression-induced improvement in oxygenation and reduction in ischemia, but no changes were evident in blood lactate concentrations, heart rates, rates of perceived exertion, or local muscle pain in the forearms when elite bouldering athletes wore forearm compression sleeves during and after a set of severe climbing (Engel et al., 2018). Therefore, further studies are needed to

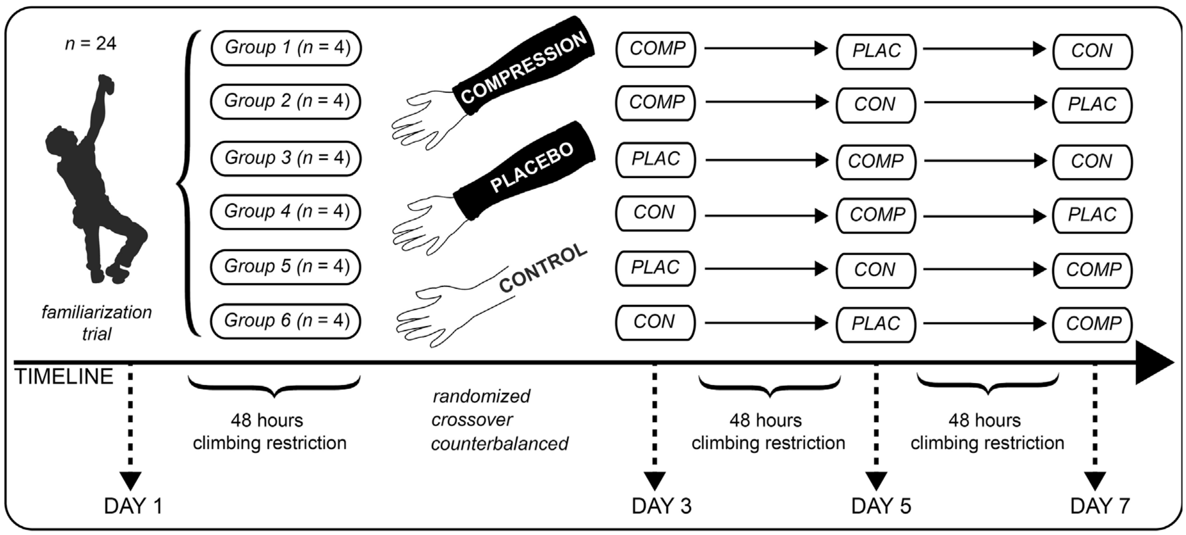

FIGURE 1 | Experimental design.

confirm the potential effects of compression garments on sports climbing performance. The aim of our study was to examine the immediate effects of the use of forearm compression sleeves on sports climbing performance in recreationally trained sports climbers. We hypothesized that wearing forearm compression sleeves over the finger flexor muscles would affect muscle strength d endurance and would be reflected in altered sports climbing r -rformance-related parameters.

MATERIALS AND METHODS

Experimental Design

The present study was conducted as a double-blind, counterbalanced, placebo-controlled crossover study. The experimental protocol was completed in 4 visits, separated by at least 48 h and not more than 72 h (**Figure 1**). All test trials were conducted on an indoor climbing wall and the evaluation of each participant took place at approximately the same time of day to minimize the effects of diurnal variations on the measured variables. The interference of uncontrolled variables was reduced by instructing all participants not to exercise within 48 h before the test trials and to avoid alcohol and caffeine ingestion during the experimental period. Participants were asked to maintain their normal dietary habits and habitual lifestyle before and during the experimental period.

Before beginning each assessment, each participant completed a standardized 10 min warm-up that included a general activation of the cardiovascular system, coordination, and light dynamic stretching. The first visit served as a familiarization trial for the test procedures and for determination of the onsight climbing ability, and each participant was advised of the purpose, benefits, and risks associated with the investigation. During the familiarization trial, the body weight and body fat percentage were determined with a digital scale (Tanita BC 601; Tanita Europe, Amsterdam, Netherlands) and height was measured (to the nearest 0.1 cm) using a stadiometer. The onsight climbing ability was determined by first asking the subjects about their most difficult ascent by top rope or red point style, whichever was higher, rated on the UIAA (Union Internationale des Associations d'Alpinisme) scale. The participants then had to climb a predefined route at the self-reported level of difficulty in top rope style. If this route was accomplished without falling, the route difficulty was increased for the next route until no better attempt was possible. If the predefined route was not accomplished, the degree was decreased accordingly for the next attempt. A break of 20 min was given between the attempts. The best attempt was rated as the participant's onsight climbing performance within this study. The UIAA scale for free climbing difficulty currently extends from I to XII (Draper et al., 2016). For statistical analyses and a better international comparability, the UIAA climbing scale was converted to the metric IRCRA (International Rock Climbing Research Association) scale, according to recommendations for the statistical analysis of sports-climbing grades (Watts et al., 1993; Draper et al., 2016). On the following three visits, the participants completed the test trials in a crossover design, either with compression forearm sleeves (COMP), with non-compressive placebo forearm sleeves (PLAC), or without forearm sleeves (CON). The three test trials (COMP, PLAC, and CON) included three different measurements (hand grip endurance, finger hang, and lap climbing) after completion of the standardized 10 min warm-up. Between the measurements, each subject was required to take a 10 min rest break.

Participants

An *a priori* power calculation indicated that 21 participants were needed to detect significant differences between the conditions COMP, PLAC, and CON, based on an estimated α level of 0.05 and a power of 90% (based on blood lactate concentration results

TABLE 1 | Anthropometric data and climbing ability of male (n = 12) and female (n = 12) participants.

	Male (n = 12)	Female (n = 12)
Age (years)	30.0 ± 7.2	28.2 ± 6.2
Body mass (kg)	74.8 ± 10.2	59.4 ± 5.6
Height (cm)	180.8 ± 6.1	166.6 ± 5.8
BMI (kg/m2)	22.8 ± 2.3	21.4 ± 1.0
Body fat (%)	9.7 ± 3.7	16.5 ± 4.2
CA (IRCRA)	15.3 ± 1.6	14.3 ± 1.0
Forearm circumference (cm)	28.8 ± 1.9	24.6 ± 1.0

Note: Data is presented as mean ± standard deviation of the mean.
BMI, body mass index. Climbing ability (CA) is indicated according to the IRCRA (International Rock Climbing Research Association) scale. For further details see ***Section 2***.

after maximum-intensity climbing bouts (forearm compression sleeves vs placebo sleeves) from an earlier study with an effect size of η_p^2 = 0.10 (Engel et al., 2018)). A total of 26 (13 male, 13 female) recreationally and moderately trained climbers volunteered to participate in this study. Of those, two dropped out during the study due to busy schedules. The results presented were obtained from the remaining 24 participants (12 male, 12 female). The participants had a mean (±SD) age of 29.1 ± 6.6 years and showed climbing abilities ranging from IRCRA 13 to 18 (14.8 ± 1.4). Characteristics of male and female participants are shown in **Table 1**.

All participants underwent a medical screening before entering the study. Participants had to be in good health, with no pre-existing cardiac or pulmonary conditions. Exclusion criteria included acute infections, alcohol consumption at any time during the test period, and chronic medication intake, as well as acute muscular injuries or restrictions. Inclusion criteria were a top rope onsight climbing ability (CA) of at least UIAA grade VII- (IRCRA 13), at least 3 years of climbing experience, an average training load of at least 2 days per week with 3 h per session within the last 3 months, and a self-report of sports climbing as a predominant discipline. All participants gave their written informed consent prior to participation, and all procedures were approved by the ethical committee of the German Sports University Cologne in accordance with the Declaration of Helsinki.

Compression Sleeves

During warm-up and the test trials, the participants wore either compression forearm sleeves (VERTICS.Sleeves, Vertics, Wiesbaden, Germany), non-compressive placebo forearm sleeves (Kiprun Forearm Sleeves, Kalenji/Decathlon S.A., Villeneuve d'Ascq, France), or no forearm sleeves (as control condition). The compression forearm sleeves were made from a 75% polyamide and 25% spandex fabric and exerted a graduated compression from distal (22.4 mmHg) to proximal (12.4 mmHg) (Engel et al., 2018). The placebo forearm sleeves consisted of 83% polyester, 13% polyamide, and 4% spandex and were non-compressive.

The placebo and graduated compression sleeves were visually similar, and the participants were informed that the effectiveness of the two types of forearm sleeves was being tested; they remained unaware of differences in capacity for compression. The investigators were informed about the capacity of compression of both forearm sleeves. The forearm circumference was used to select the size of the forearm sleeves in accordance with the manufacturer's instructions.

Hand Grip Strength and Endurance

An adjustable Jamar® Plus+ (Patterson Medical/Sammons Preston, Illinois, United States) digital hand dynamometer was used for handgrip measurements. The participants were seated, without leaning, with an elbow flexion at 90°, a slight shoulder abduction of about 15°, and with their forearms in a neutral supination/pronation position (Trampisch et al., 2012). For the hand grip endurance measurement, an audible signal was given every 3 s to indicate the change between maximal effort and relaxation. Each participant was required to complete 10 trials of maximum voluntary contraction (MVC) (Ozimek et al., 2016). MVC had to be built up from zero to maximum effort within 3 s and was followed by a 3 s rest for each trial. The participants were asked to grip the handle of the dynamometer with maximum effort and were verbally encouraged throughout the test. We determined the following variables over the 10 MVC trials: peak force (F_{max}), lowest force (F_{min}), and fatigue index (FI). The F_{max} and F_{min} were defined as the highest and lowest forces, respectively, achieved within the 10 MVC trials, whereas FI was calculated as FI (%) = $[(F_{max}–F_{min})/F_{max}] \times 100$. The variables F_{max} and FI were used for further statistical analyses. We eliminated a potential hand dominance by averaging the right and left hand values for F_{max} and FI, and both variables were defined as non-specific muscle endurance parameter dominance (Watts, 2003; Baláš et al., 2012; Kim and Kim, 2016).

Finger Hang

The participants' muscle endurance (resistance to fatigue) of the finger flexors was assessed by having the climbers hold onto a 4 cm ledge with their arms straight (Ozimek et al., 2016). The hold on the ledge was carried out with four fingers in an open grip; the thumb was not included in the grip and was positioned at the bottom of the ledge (Baláš et al., 2012). The elbow, shoulder, and hip joints had to remain fully extended while the participant was hanging on the ledge. The time to failure was determined as the point when the climber could no longer maintain this position on the ledge and was defined as a specific muscle endurance parameter (hang time in seconds).

Lap Climbing

The third measurement was lap climbing (LC) to assess each participant's sports climbing endurance performance. In the LC test, the participants were required to climb a predefined route as many times as possible on top rope belay, with no rest between the ascents. The route was set at one UIAA grade below the assessed maximum onsight climbing level (climbing ability VIII > LC route VII). The climbing routes were chosen on a 15 m high vertical to slightly overhanging wall. Only homogeneous, mainly regular, and topographically similar routes were included to induce high levels of perceived exertion and muscle fatigue (Button et al., 2018). The climbing routes consisted of climbing hand holds, with only a few differences in the types of hand holds. The route difficulty was established mainly with buckets, ledges, and crimps. Only routes without pronounced "cruxes" (demanding regions of the route where more advanced climbing actions could be required for further progress) were included in the LC test (Button et al., 2018). The potential influence of recovery strategies on climbing performance was standardized by forbidding the participants from chalking or shaking their hands during climbing or lowering (Baláš et al., 2016). The LC was to be accomplished until a fall occurred due to fatigue. The total covered climbing distance (LCD) in m and the climbing time (LCT) in min were assessed by video analysis. Once the subject had to cease due to fatigue, capillary blood samples (20 μL) were collected from the earlobe directly and after 2, 4, 6, and 8 min after the LC trials to assess blood lactate values. Capillary blood samples were taken while the participants were sitting, without any further physical activity, next to the climbing wall. Blood lactate measurements were conducted directly after the LC trials (Biosen S-Line, EKF-diagnostic GmbH, Magdeburg, Germany). The maximum post-exercise lactate concentration (La_{max}) was used for statistical analyses. The rate of perceived exertion (RPE) and forearm muscle pain were also assessed using Borgs' RPE scale (Borg, 1982) and the visual analog (VAS) graphic rating scale (Lee et al., 1991), respectively.

Near-Infrared Spectroscopy

Near-infrared spectroscopy was assessed during the hand grip strength and endurance measurements, as well as during the finger hang. The oxygenation and blood volume changes were assessed using a continuous-wave near-infrared (NIR) spectrophotometer (NIRS; OxyMon MKIII, Artinis Medical System, BV, Elst, Netherlands) and Oxysoft software (Artinis Medical System, BV). The OxyMon MK III instrument generates NIR light with wavelengths at 765 and 855 nm; a sampling rate of 10 Hz and a fixed differential path-length factor of 4.0 were used, as suggested by van Beekvelt et al. (2002). The Lambert-Beer law, in which a path-length factor is incorporated to correct for scattering of light in the tissue, was used to convert the changes in absorption at the discrete wavelengths into concentration changes in oxygenated and deoxygenated hemoglobin/myoglobin/cytochrome oxidase (Barstow, 2019). The spectrum of these hemes compounds overlaps, so differentiation between changes was not possible using NIRS measurements. However, since exercise performance studies are mainly interested in the total amount of O_2 consumed during exercise, the results are not affected by this aspect (van Beekvelt et al., 2002). We therefore reported the sum of the main absorbing chromophores in skeletal muscle as [heme] in the present study, following the suggestion of Barstow (2019).

The flexor digitorum profundus (FDP) muscle was chosen for NIRS measurements because it has been proposed as the most important forearm muscle for sports climbing performance (Michailov, 2014; Fryer et al., 2015) and has been used in previous research on hemodynamics in sports climbers (Philippe et al., 2012; Fryer et al., 2015; Baláš et al., 2018; Feldmann et al., 2020). NIRS optodes were placed between the medial epicondyle of the humerus and the styloid process of the ulna at 1/3 of the proximal distance (Schweizer and Hudek, 2011; Baláš et al., 2018). Following recent recommendations for the location of the FDP (Fryer et al., 2016), the participants were asked to squeeze their thumbs and the first fingers together, and the investigator then palpated the FDP muscle to locate the middle of the muscle belly. The specific point was marked with a skin-friendly permanent pen to avoid variations in the placement of the optodes over all test trials.

The optodes were placed in a template holder on the skin with an interoptode distance of 40 mm, and the template holder was fixed to the skin using dark opaque tape to prevent possible ambient light interference. The effectiveness of the optodes is affected by the presence of excessive adipose tissue in the body (van Beekvelt et al., 2001). However, all participants had a generally low percentage body fat (**Table 1**), and the forearms are not a major site of subcutaneous body fat. Therefore, we assumed that subcutaneous adipose tissue thickness did not interfere with data collection (Fryer et al., 2015).

The NIRS outcome measures were oxygenated [heme] (oxy[heme]) and deoxygenated [heme] (deoxy[heme]) concentrations. The sum of the oxy[heme] and deoxy[heme] values were the total [heme] concentrations (total[heme]), and the tissue oxygen saturation (StO_2) was calculated as oxy[heme]/(deoxy[heme] + oxy[heme]). In accordance with the approach reported in earlier studies (MacLeod et al., 2007; Philippe et al., 2012; Fryer et al., 2015; Baláš et al., 2018), during the hand grip strength and endurance measurements, the changes in the tissue oxygenation and blood volume (ΔStO_2, Δoxy [heme], Δtotal[heme]) were calculated from the maximum concentrations of StO_2, oxy[heme], and total[heme], while the minimum concentrations were used to represent the mean deoxygenation in the 3 s contraction periods and the mean reoxygenation in the 3 s relief periods (**Figure 2A**). The mean deoxygenation (ΔStO_{2Deoxy}, $\Delta oxy[heme]_{Deoxy}$, $\Delta total[heme]_{Deoxy}$) and reoxygenation ($\Delta StO_{2Reoxy}$, $\Delta oxy\ [heme]_{Reoxy}$, $\Delta total[heme]_{Reoxy}$) concentration changes were calculated over all 10 MVC trials. Because of missing NIRS data, the results of the variables ΔStO_{2Deoxy}, $\Delta oxy\ [heme]_{Deoxy}$, $\Delta total[heme]_{Deoxy}$, ΔStO_{2Reoxy}, $\Delta oxy[heme]_{Reoxy}$, and $\Delta total[heme]_{Reoxy}$ in hand grip strength and endurance measurements are presented for the remaining 16 full data sets only.

The statistical analyses of the continuous finger hang incorporated the changes in tissue oxygenation and blood volume during the continuous finger hang exercise (ΔStO_2, Δoxy[heme], Δtotal[heme]) for all 24 full data sets. The changes were calculated as the decrease from the maximum concentrations of StO_2, oxy[heme], and total[heme] at the beginning of the finger hang to the minimum concentration (MacLeod et al., 2007) (**Figure 2B**).

Statistical Analyses

Data are presented as means ± standard deviations. The Shapiro-Wilk test was used to identify all departures from normal distribution. The effects of treatments (COMP, PLAC, and CON) on the parameters F_{max}, FI, hang time, LCD, LCT, La_{max}, and all NIRS output parameters were tested by one-way repeated measures ANOVA, with sex (male or female) as a between subject factor. Violations of the assumption of sphericity were corrected using Greenhouse–Geisser adjustments. Two-tailed paired *t*-tests were utilized as *post hoc* tests to indicate significant differences. A Bonferroni procedure was used (p^*) to retain an $\alpha = 0.05$, and

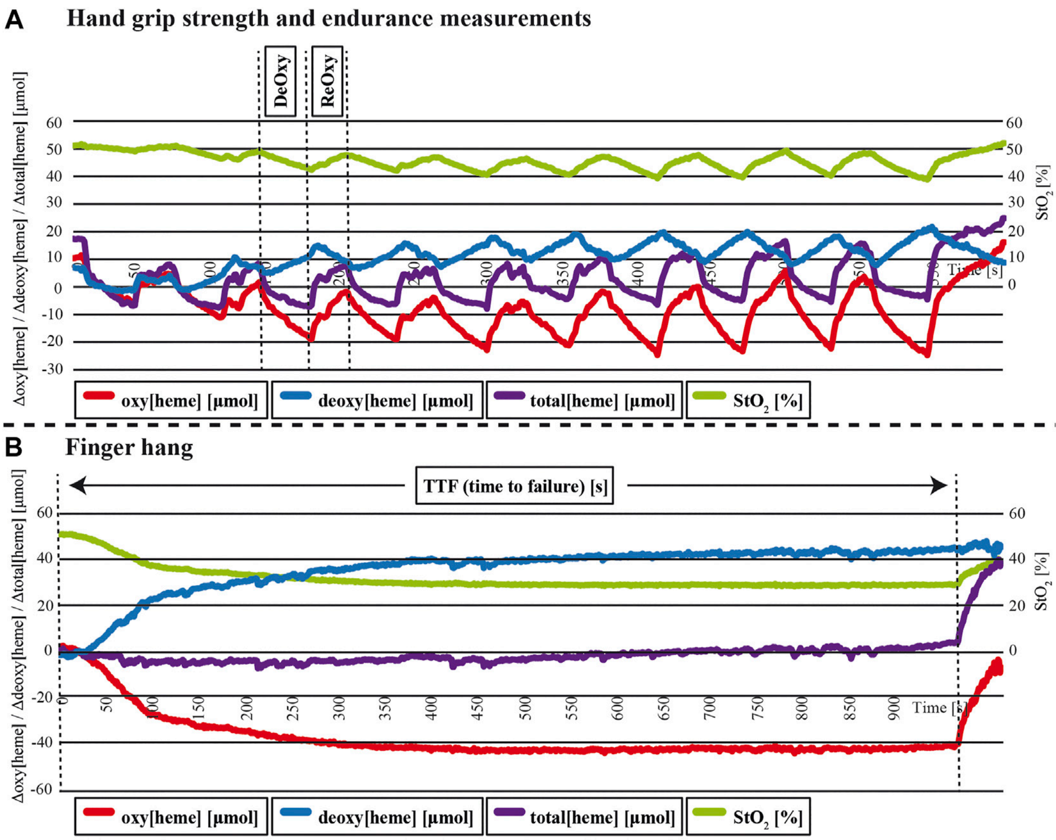

FIGURE 2 | Representative changes in tissue oxygen saturation (StO_2), oxygenated (oxy[heme]), deoxygenated (deoxy[heme]), and total (total[heme]) [heme] during hand grip strength and endurance **(A)** and finger hang **(B)** measurements.

TABLE 2 | Performance outputs for intermittent hand grip strength and endurance measurements of female (n = 12), male (n = 12), and all (n = 24) participants.

		COMP	CON	PLAC	*p*	η_p^2
F_{max} (N)	female	332.7 ± 51.5*	344.2 ± 56.8*	334.5 ± 48.1*	*<0.001*	0.542
	male	485.8 ± 95.0	488.9 ± 97.0	496.0 ± 87.0		
	all	409.3 ± 108.2	416.5 ± 107.2	415.3 ± 107.4	0.442	0.036
FI (%)	female	32.1 ± 7.0	30.1 ± 9.2	29.0 ± 9.6	0.764	0.004
	male	29.3 ± 5.1	29.3 ± 4.7	30.3 ± 6.5		
	all	30.7 ± 6.2	29.7 ± 7.1	29.6 ± 8.1	0.695	0.016

Note: Data are presented as mean ± standard deviation of the mean.
COMP, compression trial; CON, control trial; PLAC, placebo trial; F_{max}, peak force; FI, fatigue index; asterisks (*) indicate significant differences compared to male participants.
p *and η_p^2 indicate pairwise comparisons between female and male participants (*"male", "female"*), and main treatment effects for the conditions COMP, CON, and PLAC (*"all"*). For further details see the **Section 2**.*

the significance level was set at $p \leq 0.05$ for all comparisons. Effect sizes were calculated using partial η squared (η_p^2), and were interpreted as small (0.01), medium (0.06), and large (0.14). For the ordinal parameters RPE and VAS, the Friedman test was used to identify differences between treatments (COMP, PLAC, CON). Dunn-Bonferroni tests were used for post-hoc comparisons of the means with corrections for multiple tests to retain an alpha level of 0.05. Kendall's *W* (coefficient of concordance) was used to interpret the effect sizes. Student's *t*-test was calculated for differences in IRCRA climbing ability between female and male participants and Cohen's d (*d*) was used to calculate effect size. The alpha level was set at $p \leq 0.05$, and all analyses were conducted using SPSS 28 (IBM Corp., Armonk, NY, United States).

RESULTS

Hand Grip Strength and Endurance

We found no significant main treatment effects for F_{max} (p = 0.442, η_p^2 = 0.036) and FI (p = 0.695, η_p^2 = 0.016) (**Table 2**). The

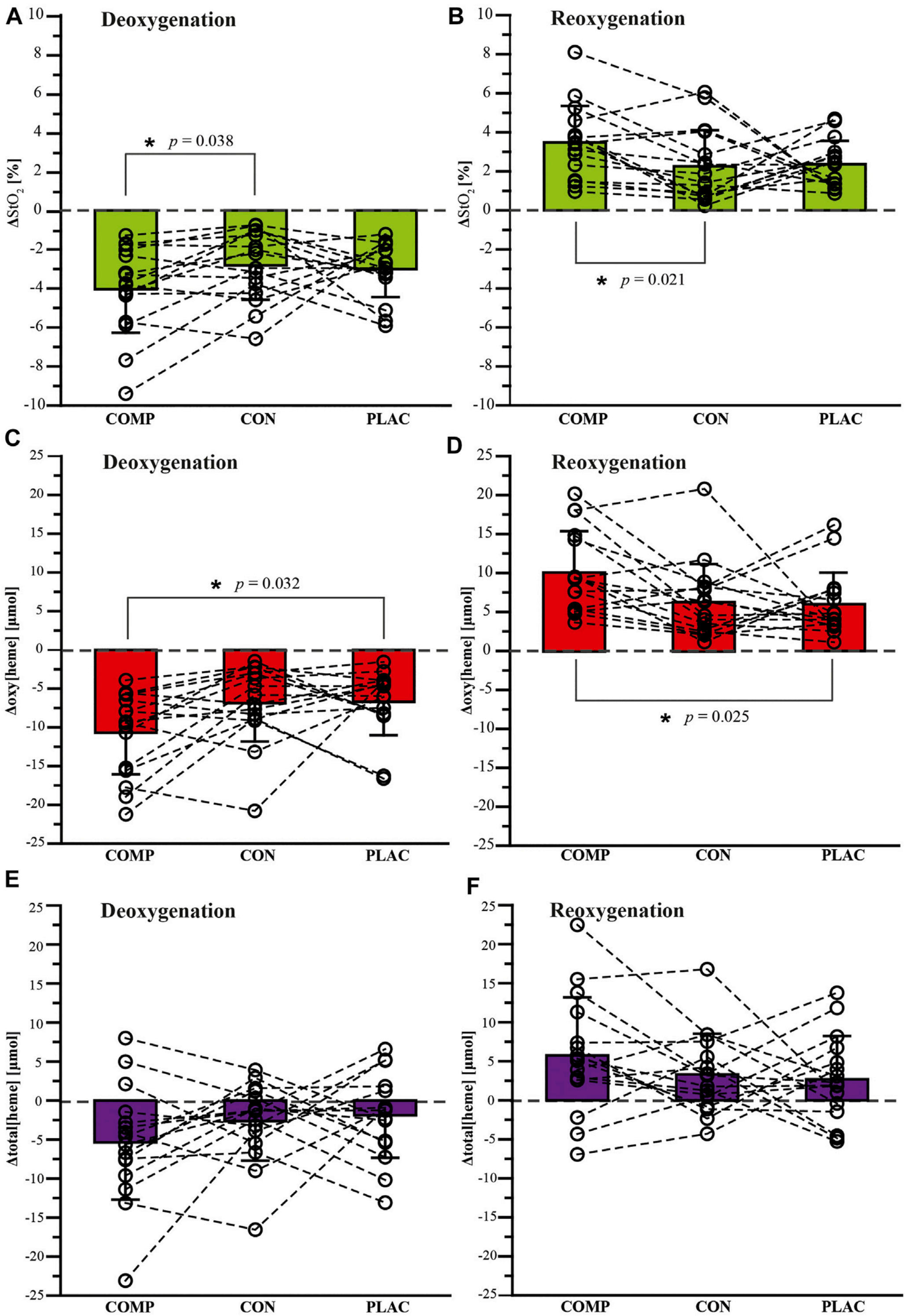

FIGURE 3 | Near-infrared spectroscopy (NIRS) changes during hand grip strength and endurance measurements (n = 16) under compression (COMP), control (CON), and placebo (PLAC) conditions for: **(A,B)** tissue oxygen saturation (ΔStO_2), **(C,D)** oxygenated (Δoxy[heme]), and **(E,F)** total (total [heme]) [heme]. Data points represent individual values (○). Bar charts are means ± SD. See the **Section 2** for further details, $^*p < 0.05$.

TABLE 3 | Near-infrared spectroscopy changes and pairwise comparisons during intermittent hand grip strength and endurance measurements of female (n = 10) and male (n = 6) participants.

			COMP	CON	PLAC	p	η_p^2
ΔStO_2 (%)	DeOxy	female	–3.4 ± 2.1	–2.4 ± 1.9	–3.2 ± 1.7	0.243	0.096
		male	–5.1 ± 2.3	–3.6 ± 1.4	–2.6 ± 0.7		
	ReOxy	female	2.8 ± 1.6	1.8 ± 1.7	2.6 ± 1.4	0.200	0.114
		male	4.5 ± 1.9	3.0 ± 2.0	1.9 ± 0.7		
Δoxy[heme] (µmol)	DeOxy	female	–10.0 ± 5.5	–6.2 ± 5.9	–7.5 ± 5.3	0.777	0.006
		male	–11.9 ± 5.5	–8.0 ± 3.0	–5.4 ± 1.3		
	ReOxy	female	9.5 ± 5.5	5.8 ± 5.9	6.8 ± 5.1	0.863	0.002
		male	11.2 ± 5.4	7.3 ± 2.9	4.6 ± 1.1		
Δtotal[heme] (µmol)	DeOxy	female	–6.6 ± 3.8	–3.1 ± 5.3	–2.1 ± 6.2	0.432	0.045
		male	–3.3 ± 11.3	–1.9 ± 5.1	–1.6 ± 4.5		
	ReOxy	female	7.2 ± 4.7	3.7 ± 5.3	2.6 ± 6.3	0.493	0.034
		male	3.3 ± 10.7	2.7 ± 5.5	2.8 ± 4.7		

Note: Data are presented as mean ± standard deviation of the mean.
COMP, compression trial; CON, control trial; PLAC, placebo trial; StO_2, tissue oxygen saturation; oxy[heme], oxygenated [heme]; Δ, mean decrease (DeOxy = deoxygenation) and increase (ReOxy = reoxygenation) from the contraction and release phases of hand grip measurement; p *and η_p^2 indicate pairwise comparisons between female and male participants; For further details see the **Section 2**.*

TABLE 4 | Time to failure and near-infrared spectroscopy changes during continuous finger hang tests of female (n = 12), male (n = 12), and all (n = 24) participants.

		COMP	CON	PLAC	p	η_p^2
TTF (s)	female	74.8 ± 23.8	73.6 ± 23.5	77.8 ± 19.7	0.882	0.001
	male	75.3 ± 19.6	75.7 ± 16.6	79.0 ± 28.7		
	all	75.0 ± 21.4	74.7 ± 19.9	78.4 ± 24.1	0.327	0.049
ΔStO_2 (%)	female	–19.9 ± 11.0	–16.6 ± 7.9	–18.4 ± 11.7	0.242	0.062
	male	–24.2 ± 10.7	–22.2 ± 11.7	–20.6 ± 11.2		
	all	–22.0 ± 10.8	–19.4 ± 10.2	–19.5 ± 11.3	0.488	0.032
xy[heme] (µmol)	female	–20.2 ± 12.0	–19.4 ± 11.1	–17.6 ± 11.5	0.313	0.046
	male	–25.2 ± 10.8	–22.4 ± 13.6	–21.7 ± 13.0		
	all	–22.7 ± 11.5	–20.9 ± 12.2	–19.7 ± 12.2	0.512	0.030
Δtotal[heme] (µmol)	female	–1.9 ± 7.1	–1.7 ± 6.2	2.0 ± 4.8	0.592	0.013
	male	–1.6 ± 8.0	–1.7 ± 12.1	–2.0 ± 11.3		
	all	–1.7 ± 7.4	–1.7 ± 9.4	–0.0 ± 8.7	0.709	0.016

Note: Data are presented as mean ± standard deviation of the mean.
COMP, compression trial; CON, control trial; PLAC, placebo trial; TTF, time to failure, StO_2, tissue oxygen saturation; oxy[heme], oxygenated [heme]; Δ, decrease from the maximum concentrations at the beginning of the finger hang to the concentration at the time point of task failure; p *and η_p^2 indicate pairwise comparisons between female and male participants ("male", "female"), and main treatment effects for the conditions COMP, CON, and PLAC ("all"). For further details see the **Section 2**.*

condition sex also had no influence on the intervention-induced changes in F_{max} (p = 0.384, η_p^2 = 0.043) and FI (p = 0.349, η_p^2 = 0.047), but the F_{max} values were significantly lower for female than for male participants (p < 0.001, η_p^2 = 0.542) (**Table 2**). Conversely, the IRCRA climbing abilities did not differ between female and male participants (female 14.3 ± 1.0, male 15.3 ± 1.6; p = 0.070, d = –0.776). We also found a significant main treatment effect for the NIRS-related parameters ΔStO_{2Deoxy} (COMP –4.0 ± 2.2, PLAC –3.0 ± 1.4, CON –2.8 ± 1.8 [%]; p = 0.049, η_p^2 = 0.194), $\Delta oxy[heme]_{Deoxy}$ (COMP –10.7 ± 5.4, PLAC –6.7 ± 4.3, CON –6.9 ± 5.0 [µmol]; p = 0.014, η_p^2 = 0.263), ΔStO_{2Reoxy} (COMP 3.5 ± 1.9, PLAC 2.4 ± 1.2, CON 2.3 ± 1.9 [%]; p = 0.028, η_p^2 = 0.225), and $\Delta oxy[heme]_{Reoxy}$ (COMP 10.2 ± 5.3, PLAC 6.0 ± 4.1, CON 6.3 ± 4.9 [µmol]; p = 0.011, η_p^2 = 0.274) (**Figures 3A–D**). The parameters $\Delta total[heme]_{Deoxy}$ (COMP –5.4 ± 7.4, PLAC –1.9 ± 5.4, CON –2.6 ± 5.1 [µmol]; p = 0.302, η_p^2 = 0.082) and $\Delta total[heme]_{Reoxy}$ (COMP 5.8 ± 7.4, PLAC 2.7 ± 5.6, CON 3.3 ± 5.2 [µmol]; p = 0.424, η_p^2 = 0.059) had no significant differences (**Figures 3E,F**). The condition sex showed no influence on NIRS-related parameters in hand grip strength and endurance measurements (ΔStO_{2Deoxy}: p = 0.123, η_p^2 = 0.139; $\Delta oxy[heme]_{Deoxy}$: p = 0.352, η_p^2 = 0.072; $\Delta total[heme]_{Deoxy}$: p = 0.774, η_p^2 = 0.018; ΔStO_{2Reoxy}: p = 0.090, η_p^2 = 0.158; $\Delta oxy[heme]_{Reoxy}$: p = 0.364, η_p^2 = 0.070; $\Delta total[heme]_{Reoxy}$: p = 0.573, η_p^2 = 0.039) (for data and pairwise comparisons see **Table 3**).

Finger Hang

No significant main treatment effect was detected for the time to failure in the finger hang (p = 0.327, η_p^2 = 0.049) and the condition sex had no influence on the changes in hang time (p = 0.955, η_p^2 = 0.002) (**Table 4**). We also found no significant main treatment effect for the NIRS-related parameters ΔStO_2, Δoxy[heme], and Δtotal[heme] (**Table 4**). The condition sex

TABLE 5 | Lap climbing performance measurements of female (n = 12), male (n = 12), and all (n = 24) participants.

		COMP	CON	PLAC	p	η_p^2/W
LCT (s)	female	484 ± 197	495 ± 218	575 ± 414	0.847	0.002
	male	421 ± 133	584 ± 321	496 ± 203		
	all	452 ± 167	540 ± 272	535 ± 321	0.169	0.078
LCD (m)	female	74.9 ± 42.7	72.7 ± 47.8	88.2 ± 82.2	0.502	0.021
	male	74.6 ± 25.5	106.8 ± 55.5	91.9 ± 41.5		
	all	74.7 ± 34.4	89.7 ± 53.5	90.0 ± 63.7	0.188	0.073
La_{max} (mmol/l)	female	7.05 ± 2.29	7.77 ± 2.68	7.01 ± 2.15	0.391	0.034
	male	7.71 ± 2.68	8.34 ± 2.55	8.01 ± 2.81		
	all	7.38 ± 2.02	8.05 ± 2.57	7.51 ± 2.50	0.245	0.062
RPE	female	15.9 ± 2.3	16.2 ± 2.1	16.3 ± 2.0	0.395	0.033
	male	16.8 ± 2.0	16.8 ± 1.4	16.6 ± 1.5		
	all	16.4 ± 2.1	16.5 ± 1.8	16.5 ± 1.7	0.950	0.002
VAS	female	6.1 ± 1.7	6.3 ± 1.9	5.8 ± 1.9	0.964	0.000
	male	6.3 ± 1.7	6.0 ± 1.6	5.8 ± 1.6		
	all	6.2 ± 1.7	6.2 ± 1.7	5.8 ± 1.7	0.431	0.035

Note: Data is presented as mean ± standard deviation of the mean.

COMP, compression trial; CON, control trial; PLAC, placebo trial; LCT, lap climbing time; LCD, lap climbing distance; La_{max}, maximum blood lactate concentration; RPE, Borgs' rate of perceived exertion; VAS, visual analog scale; p *and η_p^2 indicate pairwise comparisons between female and male participants ("male", "female"), and main treatment effects for the conditions COMP, CON, and PLAC ("all"). For further details see the* ***Section 2***.

showed no influence on NIRS-related parameters in the finger hang for ΔStO_2 (p = 0.790, η_p^2 = 0.011), Δoxy[heme] (p = 0.887, η_p^2 = 0.005), and Δtotal[heme] (p = 0.589, η_p^2 = 0.024) (**Table 4**).

Lap Climbing

We found no significant main treatment effects for LCT (p = 0.169, η_p^2 = 0.078), LCD (p = 0.188, η_p^2 = 0.073), and La_{max} (p = 0.245, η_p^2 = 0.062) (**Table 5**). The condition sex had no influence on changes in LCT (p = 0.210, η_p^2 = 0.068), or LCD (p = 0.147, η_p^2 = 0.084), or La_{max} (p = 0.858, η_p^2 = 0.007). A further comparison of treatments revealed no influence of the wearing of compression forearm sleeves on RPE (p = 0.950, W = 0.002) or VAS (p = 0.431, W = 0.035) (**Table 5**).

DISCUSSION

The aim of this investigation was to determine whether wearing forearm compression sleeves during exercise has immediate effects on sports climbing performance and diminishes the effects of muscle fatigue. We found no effect of using forearm compression sleeves over the finger flexor muscles on sports climbing-related muscle strength, muscle endurance parameters, maximum blood lactate, or parameters of perceived exertion and muscle pain, but we did note effects on hemodynamic responses. The wearing of forearm compression sleeves resulted in greater changes in oxy[heme] and StO_2 during the deoxygenation and reoxygenation phases of hand grip strength and endurance measurements, whereas the total [heme] concentrations and hemodynamic changes in finger hang measurements were unaffected. The findings therefore did not clearly support the positive effects on muscle strength and endurance claimed by the manufacturers of forearm compression sleeves and believed in by elite and recreational athletes. The results do, however, suggest that forearm compression sleeves can improve muscle blood flow and tissue saturation.

Our results reflect recent findings of inconsistent beneficial effects when wearing compression sleeves during exercise. Several studies have reported positive effects of sports compression garments on hemodynamics in participants in passive resting positions (Bringard et al., 2006; Lee et al., 2017; O'Riordan et al., 2021) or during exercise (Ménétrier et al., 2011; Broatch et al., 2018). However, compression sleeves often give rise to only a slight increase in tissue oxygen saturation at rest and during recovery from aerobic running exercise, with no influence on time to exhaustion (Ménétrier et al., 2011).

Coza et al. (2012) found changes in tissue blood flow and perfusion in participants wearing calf compression sleeves during short-term dynamic exercise and concluded that these compression-induced changes were a result of improved oxygenation during short-term exercise. They further assumed that the increased muscle oxygen availability positively influenced performance and concluded that compression of muscles may enhance performance, especially in sports that require repeated short bouts of exercise (Coza et al., 2012). Indeed, recent studies suggest positive effects of compression garments on repeated-sprint exercise (Broatch et al., 2018), prolonged high-intensity intermittent exercise (Sear et al., 2010), repeated maximal isokinetic eccentric contractions (Négyesi et al., 2021), and continuous high-intensity performance assessed using the Wingate Anaerobic Test (Ballmann et al., 2019). Conversely, compression garments were found to increase femoral artery diameter, arterial blood flow, and markers of blood oxygen extraction in muscle during repeated-sprint exercise, but they showed no effect on blood lactate or glucose levels on exercise performance (Broatch et al., 2021).

Climbing performance is highly dependent on high-intensity exercise performance and intermittent finger flexor muscle strength and endurance (Michailov, 2014; Fryer et al., 2015; Vigouroux et al., 2015), but neither the study by Engel et al. (2018) nor our present study found beneficial effects of forearm compression sleeves on climbing performance. Even a recent meta-analyses has concluded that wearing lower limb compression garments has only negligible or no effects on performance and physiological responses following high-intensity exercise (Da Silva et al., 2018). However, the results in the present study for hemodynamic changes during repeated hand grip strength measurements support the finding of hemodynamic changes caused by compression garments during high-intensity exercise suggested by Coza et al. (2012).

The lack of evidence for performance-enhancing effects of forearm compression sleeves in sports climbing could arise for several reasons. One is that hemodynamic changes during contraction and relief periods in climbing-specific intermittent tasks are recommended to exceed ~4.5% for StO_2 and ~18.5 mmol for total[heme] to be considered a meaningful change (Baláš et al., 2018). In the present study, we found only small mean changes of ~3% and ~4 mmol for StO_2 and total[heme], respectively, during the intermittent hand grip strength and endurance measurements. The hemodynamic changes may therefore have been insufficient to influence sports climbing-related performance parameters. Although, as presented in **Figure 3**, large interindividual differences were evident in the hemodynamic responses to wearing forearm compression sleeves, a subgroup might exist that would benefit from the potential effects of compression sleeves. However, our data do not allow us to draw any conclusion regarding the parameters that indicate a higher physiological response. Further research is needed to prove this assumption.

The possibility that wearing forearm compression sleeves may not result in ergogenic effects has also been suggested, as the sleeves cover only a small area and therefore a small percentage of the body surface (Engel et al., 2018). Nevertheless, circulatory and neuromuscular demands in sports climbing rely highly on finger flexor muscles; consequently, ischemia-induced muscle fatigue in the forearm muscles leads to performance decrements in climbing (Schweizer, 2012; Engel et al., 2018). We therefore assume that forearm compression sleeves should be one of the most effective compression garments in sports climbing. However, investigating the effects of full upper body compression garments on sports climbing performance might be interesting in this context, as these other garments cover a higher percentage of the body surface and still include the forearms.

Studies in the existing literature on participants' sports climbing performance have rarely described the effect of arm compression sleeves on muscle hemodynamics and exercise performance has indeed rarely been described in literature so far. Bochmann et al. (2005) described an increase in forearm arterial blood flow compression induced by wearing forearm compression sleeves at rest and during a simultaneous low-intensity hand grip, but they did not assess actual exercise performance changes. In addition, Pereira et al. (2014) concluded that the use of a graduated arm compression sleeve does not enhance isokinetic elbow flexion muscle performance, but they did not measure oxygenation or blood volume changes. By contrast, wearing a long-sleeved full upper body compression garment resulted in a more maintained external shoulder rotation at 40–50% of maximum voluntary isometric contraction (Tsuruike and Ellenbecker, 2013) and in an enhanced perceptual recovery from manual-labor exercise (Chan et al., 2016). In summary, the research on the wearing of upper limb compression garments and its effects on muscle hemodynamics and exercise performance is still insufficient, especially compared to similar research on lower limb compression aids. Therefore, this might be an interesting area for future investigations.

A second consideration is that the applied graduated compression from distal (22.4 mmHg) to proximal (12.4 mmHg) within our present study might also explain the lack of evidence for performance-enhancing effects of forearm compression sleeves in sports climbing. Differences in pressure levels applied via compression garments are supposed to influence their effectiveness for exercise performance output and to result in different physiological responses (Mizuno et al., 2017; Williams et al., 2020), but this assumption is still questioned (Beliard et al., 2015). The new types of restrictive compression garments have also been viewed as more effective than the more popular graduated compression garments, as they integrate novel resistance technology into compression garments that are now designed to provide variable resistance to movement (Baum et al., 2020).

A further concern is that sports climbing is a highly complex sports task. Successful sports climbing performance depends on maintenance of forearm muscle strength and endurance (España-Romero et al., 2009; Vigouroux et al., 2015; Rokowski et al., 2021), as well as on the physiological components of shoulder and upper body strength and power, core-body and aerobic endurance, flexibility, and balance (MacKenzie et al., 2020; Draper et al., 2021). Psychological and skill-related components, such as route preview, a good climbing movement repertoire, climbing technique, risk management, route management, and mental balance are also required for successful sport-climbing performance (Sanchez et al., 2019; Draper et al., 2021). These additional factors might explain the lack of effects in the present study when recreational climber participants wore forearm compression sleeves while performing sport-climbing activities, so they should be considered in future studies.

A final potential reason for the lack of significant results, and therefore a limitation of the present study, could be that sports compression garments are supposedly more effective during periods of recovery than during actual exercise (Hill et al., 2014; Brown et al., 2017; Cullen et al., 2021). Sports climbing has been an Olympic discipline since 2020; therefore, the enhancement of athletic performance and recovery in climbing has become increasingly important (Engel et al., 2018). The new Olympic combined competition formats, in particular, require high demands from elite athletes. In the Tokyo Olympics in 2021, the single disciplines of lead climbing, bouldering, and speed climbing were combined, and the Paris Olympics in 2024 will include a combined competition of bouldering and lead events, but the speed discipline will be separated. Both combined formats are characterized by long durations, high competition loads, and short recovery periods. Recovery strategies in sports climbing have therefore become increasingly important, and future investigations may focus on compression garments as a recovery aid in sports climbing.

A further limitation of the present study is the choice of test procedures. We decided to combine the less-specific hand grip strength and endurance measurements with the more climbing-specific finger hang and lap climbing measurements. Maciejczyk et al. (2021) proposed that maximal grip force and all-out isometric contractions are equally decisive physical performance indices of climbing performance. However, the continuous finger hang applied in the present study, in particular, does not adequately reflect the requirements of repeated isometric contractions of the forearms in sports climbing (Baláš et al., 2016). Intermittent finger hang tests with alternating contraction and relaxation intervals of 8–10 and 2–3 s are viewed as more climbing-specific and should be implemented in future studies that investigate potential ergogenic compression garment effects in sports climbing (Philippe et al., 2012; Giles et al., 2019; Baláš et al., 2021; Maciejczyk et al., 2021).

We also found significant differences in NIRS outputs between the treatment conditions, but only for the non-specific hand grip strength and endurance measurements, and not for the more climbing-specific finger hang test. We chose the FDP muscle for NIRS measurements because of its importance in climbing-specific performance (Fryer et al., 2016). However, in contrast to climbing performance, hand grip strength and endurance are not mainly dependent on the FDP muscle, but also involve the flexor pollicis longus muscle (Ambike et al., 2014). The lack of effects on NIRS measurements during the finger hang test is therefore unexpected and may be explained by highly different interindividual responses in oxygenation changes that are probably associated with the relatively low climbing level of our participants. Participants with a higher climbing level might show lower interindividual differences due to better habituation to climbing-specific tests.

In summary, our results suggest that wearing forearm compression sleeves over the finger flexor muscles did not enhance hand grip strength and endurance or the sports climbing performance parameters of finger hang, lap climbing distance and time, nor did it affect maximal blood lactate values or the parameters of perceived exertion and muscle pain after lap climbing. However, wearing forearm compression sleeves resulted in slightly higher changes in oxy[heme] and StO_2 during the deoxygenation and reoxygenation phases of hand grip strength and endurance measurements, but did not alter the total[heme] concentration changes or hemodynamic changes in finger hang measurements. Therefore, we could not confirm any benefit of the use of forearm compression sleeves during climbing exercise for a performance enhancement in sports climbing and bouldering this study, and claims of benefits should be considered with caution.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by ethical committee of the German Sports University Cologne. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

ML, MM, and RR conceived of and designed the research; ML performed experiments; ML analyzed data; ML interpreted results of the experiments; ML prepared figures; ML drafted the manuscript; ML, MM, and RR edited and revised the manuscript; and ML, MM, and RR approved the final version of manuscript.

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Differences in Upper-Body Peak Force and Rate of Force Development in Male Intermediate, Advanced, and Elite Sport Climbers

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The aim of this study was to investigate the difference in climbing-specific strength and rate of force development (RFD) between intermediate, advanced, and elite male sport climbers. Seventy-eight male climbers were recruited and divided into groups based on the International Rock Climbing Research Association (IRCRA) numerical (1–32) grading system (intermediate (10–17) group (IG; $n = 28$)), advanced (18–23) group (AG; $n = 30$) and elite (24–27) group (EG; $n = 20$). Peak force (F_{peak}) and average force (F_{avg}) were measured while performing an isometric pull-up on a 23 mm thick campus rung. RFD was calculated from the onset of force to maximal peak force. The elite group performed better in all test parameters than the advanced (F_{peak}: 39.7%, ES = 1.40, $p < 0.001$; F_{avg}: 45.6%, ES = 4.60, $p < 0.001$; RFD: 74.9%, ES = 1.42, $p = 0.001$) and intermediate group (F_{peak}: 95.7%, ES = 2.54, $p < 0.001$, F_{avg}: 131.1%, ES = 5.84, $p < 0.001$, RFD: 154.4%, ES = 2.21, $p = 0.001$). Moreover, the advanced group demonstrated greater F_{peak} (40.1%, ES = 1.24, $p < 0.001$), F_{avg} (59.1%, ES = 1.57, $p < 0.001$) and RFD (45.5%, ES = 1.42, $p = 0.046$), than the intermediate group. Finally, climbing performance displayed strong correlations with F_{peak} ($r = 0.73$, $p < 0.001$) and F_{avg} ($r = 0.77$, $p < 0.001$), and a moderate correlation with RFD ($r = 0.64$, $p < 0.001$). In conclusion, maximal force and RFD in a climbing specific test are greater among climbers on higher performance levels. Independent of climbing level there is a moderate-to-strong association between maximal and rapid force production and climbing performance.

Keywords: climbing, finger strength, performance, testing, rate of force development (RFD)

INTRODUCTION

Competitive climbing is divided into the three disciplines lead climbing (sport climbing), bouldering, and speed climbing, with sport climbing being the most practiced discipline (Saul et al., 2019). Generally, both in the climbing community and in research, the self-reported grade performed on a sport climbing route or boulder problem indicates climbing ability (Draper et al., 2011). A variety of climbing ability groups have been examined in climbing research on (Baláš et al., 2014; Hermans et al., 2017; Levernier and Laffaye, 2019, 2021). The International Rock-Climbing Research Association (IRCRA) recommend for research to use standardized climbing ability levels with the following classifications: lower grade, intermediate, advanced, elite, and higher elite (Draper et al., 2015). The performance ability levels are valuable to climbing research by allowing for standardization of the classification of climbers within a study, and to compare data between studies.

Several recent studies support finger strength and rate of force development (RFD) being significantly different between IRCRA ability groups and important predictors of climbing performance (Giles et al., 2020; Levernier and Laffaye, 2021; Rokowski et al., 2021; Stien et al., 2021b). For example, Giles et al. (2020) and Rokowski et al. (2021) showed that higher-elite and elite climbers had higher finger strength compared to elite and advanced climbers, respectively. Moreover, Torr et al. (2020) and Baláš et al. (2014) found significant correlations ($r = 0.42–0.79$) between relative finger strength and climbing performance. Finally, Stien et al. (2021b) reported that male elite climbers had significantly higher peak finger strength and RFD than advanced and intermediate climbers. Of note, the study is limited by a skewed distribution of climbers within performance levels. There is, to the authors' knowledge, no study that has used the average grade of the IRCRA ability groups when comparing finger strength and RFD between groups.

With the recent inclusion of climbing in the Olympic program, the demand for sound methods for testing athletes is increasing. The 2021 IRCRA study (Draper et al., 2021) included a suggestion of tests examining climbing performance. However, these tests do not necessarily represent valid measurements or reliable outcomes across climbing skill levels. Therefore, more knowledge about objective measurements that predict and differentiate between climbing performance levels is warranted. Although finger strength and RFD are considered important predictors of sport climbing performance (Laffaye et al., 2016; Michailov et al., 2018; Giles et al., 2020; Stien et al., 2021b), very few studies have compared these metrics across several levels of climbers. Therefore, the main aim of this study was to examine maximal isometric force (F_{peak}), average force for 2 s (F_{avg}), and RFD in male intermediate, advanced, and elite level sport climbers. It was hypothesized that F_{peak}, F_{avg} and RFD would increase with increasing sub-class levels and that there would be a significant relationship between F_{peak}, F_{avg} and RFD and climbing performance.

METHODS

Experimental Approach to the Problem

A cross-sectional design was used to examine maximal isometric strength and RFD, and their association to climbing performance in climbers at three different performance levels. The testing included one visit to the laboratory for all participants.

Subjects

Seventy-eight male sport climbers at different performance levels volunteered for this study. A criterion for the study was that the average performance level for the three groups should match the average IRCRA grade for intermediate (13.5), advanced (20.5) and elite (25.5) ability level. The participants had to be strong enough to perform a pull-up on the 23-millimeter (mm) thick rung, free of injuries, and have a minimum self-reported climbing ability of IRCRA grade 10 [French grade (f)5+] in the last 6 months. Based on the recommendations by Draper et al. (2015), the intermediate group (IG; =28) was defined as IRCRA 10–17 (f5+-f7a), the advanced group (AG; $n = 30$) as IRCRA 18–23 (f7a–f8a), and the elite group (EG; $n = 20$) as IRCRA 24–27 (f8a+-f8c). All participants were informed orally and in writing about the procedures and the potential risks and benefits of participating in the testing. A written consent had to be signed before data collection began. The study conformed to the latest revision of the Declaration of Helsinki and was conducted in accordance with the ethical guidelines of the Western Norway University of Applied Sciences. The preservation of the participants' safety and privacy was reviewed by the Norwegian Centre for Research Data.

Testing Procedures

The participants had to refrain from high intensity climbing related or upper body training in the 48 h prior to testing. The testing started with a short questionnaire about age, climbing experience, prioritized discipline, maximal self-reported redpoint grade last 6 months, and if they had injuries that could affect performance in the testing. Anthropometrics were gathered using a Tanita bioelectric impedance scale (MC 780MA S, Tokyo, Japan) and a wall-mounted measuring tape.

To prepare for physical testing, a 15-min light-to-moderate warm-up was performed on a bouldering wall. The participants were instructed to start with easy bouldering (two-to-three number grades below their limit) and to progressively increase the intensity but to avoid fatigue. After 5 min of rest the participants were familiarized with the isometric test set-up and informed about how the procedures were performed. Participants were given three practice attempts with a sub-maximal effort before the experimental testing began.

The maximal voluntary isometric contraction (MVIC) in the pull-up exercise was conducted on a 23 mm thick wooden rung with a fixed 90° elbow joint angle (measured with a goniometer) and a half-crimp grip with a passive thumb while anchored to a force cell at the floor with a static cord (**Figure 1**). The participants were allowed to use chalk on their fingers and hands during the testing. The rung was brushed between trails to avoid reduced friction due to excessive chalk left from previous tests. The cord had to be completely taut before the test began and no kipping with the legs or creating a countermovement were allowed. The force-time curves criteria have been described previously (Stien et al., 2021a). The participants had to hang still on the rung (no more than ±5 N fluctuation in force for 1,000 ms) before exerting maximal force (Stien et al., 2021b). The MVIC and RFD were measured using a force sensor sampling at 200 Hz (Ergotest Innovation A/S, Porsgrunn, Norway) and analyzed using commercial software (MuscleLab v.10.4, Ergotest Innovation A/S, Porsgrunn, Norway). The MVIC tests included three different parameters: (1) peak isometric force (F_{peak}), (2) average isometric force across 2 s (F_{avg}), and (3) RFD. The RFD was calculated from onset to peak force (Stien et al., 2021b). Three attempts separated by 3 min of rest were given and the attempt with the highest values was used in the analyses. Absolute values

FIGURE 1 | Image showing a participant performing the isometric pull-up test.

TABLE 1 | Anthropometric data, climbing experience, weekly climbing sessions and self-reported climbing ability (IRCRA scale).

	Intermediate ($n = 28$)	Advanced ($n = 30$)	Elite ($n = 20$)
Age (year)	26.7 ± 6.2	29.0 ± 6.9	28.2 ± 7.2
Height (cm)	178.8 ± 7.3	180.1 ± 6.9	180.3 ± 6.3
Body mass (kg)	74.6 ± 9.3	72.5 ± 7.5	70.9 ± 6.2
Fat mass (%)	14.3 ± 3.5*	11.4 ± 4.0	12.0 ± 2.6
Year of climbing experience	5.0 ± 4.8	8.0 ± 5.8	13.7 ± 6.4*†
Weekly climbing sessions	2.4 ± 1.2	3.2 ± 1.0	4.4 ± 1.0*†
Red-point (IRCRA grade)	14.0 ± 1.7	20.5 ± 1.3†	25.4 ± 1.1*†

*Greater than advanced ($p < 0.01$).
†Greater than intermediate ($p < 0.01$).

were used since (1) the body mass appears to be accounted for when the test is performed hanging, and (2) near identical results were found using absolute and relative values.

Statistical Analyses

All statistical analyses were performed in SPSS (IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp) and statistical significance was accepted at $p < 0.05$. A Shapiro-Wilk test revealed that IRCRA level ($p = 0.031$), years of experience ($p < 0.001$), and RFD ($p = 0.002$) were not normally distributed, whereas the remaining variables were ($p = 0.059$–0.739). To compare the F_{avg} and F_{peak} between groups, a one-way ANOVA with Bonferroni *post-hoc* correction was used. The RFD was analyzed using a Kruskall-Wallis test with Bonferroni *post-hoc* tests. The Cohen's *d* effect size (ES) for the differences between the climbing levels was calculated as the means divided by the pooled standard deviation. An ES < 0.2 was considered trivial, between 0.2 and 0.5 as small, between 0.5 and 0.8 as moderate and above 0.8 as large (Cohen, 1998). The correlation between climbing performance and the three performance variables F_{avg}, F_{peak}, and RFD was assessed using Spearman's rho. Correlation values <0.3, between 0.3 and 0.5, between 0.5 and 0.7, and >0.7 were considered very weak, weak, moderate, and strong, respectively (Cohen, 1998).

RESULTS

Anthropometrics

Age, height, and body mass were not different between the groups ($F = 0.344$–1.321, $p = 0.273$–0.710). Relative fat mas (% of body mass) was significantly different between groups ($F = 5.349$, $p = 0.007$) and *post-hoc* tests showed that the intermediate group had a greater fat mass than the advanced group (ES = 0.77, $p = 0.007$). No differences in fat percentage between the intermediate and elite groups (ES = 0.75, $p = 0.097$) or between the elite and advanced groups were observed (ES = 0.18, $p = 1.000$; see **Table 1**).

Climbing Experience, -Volume, and -Performance

Climbing experience (years) was different between groups ($F = 14.147$, $p < 0.001$). *Post hoc* tests revealed no difference between the intermediate and advanced groups (ES = 0.57, $p = 0.140$). The elite group had significantly longer experience than the intermediate (ES = 1.55, $p < 0.001$) and advanced groups (ES = 0.94, $p = 0.002$). The number of weekly climbing sessions was significantly different between groups ($F = 14.036$, $p < 0.001$). No difference was found between the intermediate and advanced groups (ES = 0.73, $p = 0.140$). The elite group had a significantly higher number of weekly sessions than intermediate (ES = 1.82, $p < 0.001$) and advanced groups (ES = 1.20, $p = 0.002$). Self-reported climbing ability (IRCRA) was significantly different between all groups ($F = 14.147$, $p < 0.001$; see **Table 1**).

TABLE 2 | Absolute values from isometric pull-ups, percent difference between groups.

	Intermediate ($n = 28$)	Advanced ($n = 30$)	Elite ($n = 20$)
F_{peak} (N)	353 ± 105	494 ± 122*	690 ± 155†
F_{avg} (N)	227 ± 88	361 ± 82*	524 ± 126†
RFD (N·s^{-1})	948 ± 357	1379 ± 721	2412 ± 865†

*Higher than the intermediate group ($p < 0.01$).
†Higher than the intermediate and advanced groups ($p < 0.01$).

Force and RFD

For the elite group, all three variables were significantly greater than the advanced and intermediate groups ($p < 0.001$ for both). The elite group demonstrated greater F_{peak} (39.7%, ES = 1.40, $p < 0.001$), F_{avg} (45.6%, ES = 4.60, $p < 0.001$), and RFD (74.9%, ES = 1.30, $p < 0.001$) than the advanced group and the intermediate group (F_{peak}: 95.7%, ES = 2.54, $p < 0.001$; F_{avg}: 131.1%, ES = 5.84, $p < 0.001$; RFD: 154.4%, ES = 2.21, $p < 0.001$). The advanced group demonstrated greater F_{peak} (40.1%, ES = 1.24, $p < 0.001$) and F_{avg} (59.1%, ES = 1.57, $p < 0.001$) than the intermediate group, whereas RFD was not significantly different between the two groups (45.5%, ES = 1.42, $p = 0.057$; **Table 2**).

Correlations

A strong correlation with climbing performance was found for F_{peak} ($r = 0.73$, $p < 0.001$) and F_{avg} ($r = 0.79$, $p < 0.001$), while a moderate correlation was found between RFD and climbing performance ($r = 0.65$, $p < 0.001$; **Figures 2A–C**).

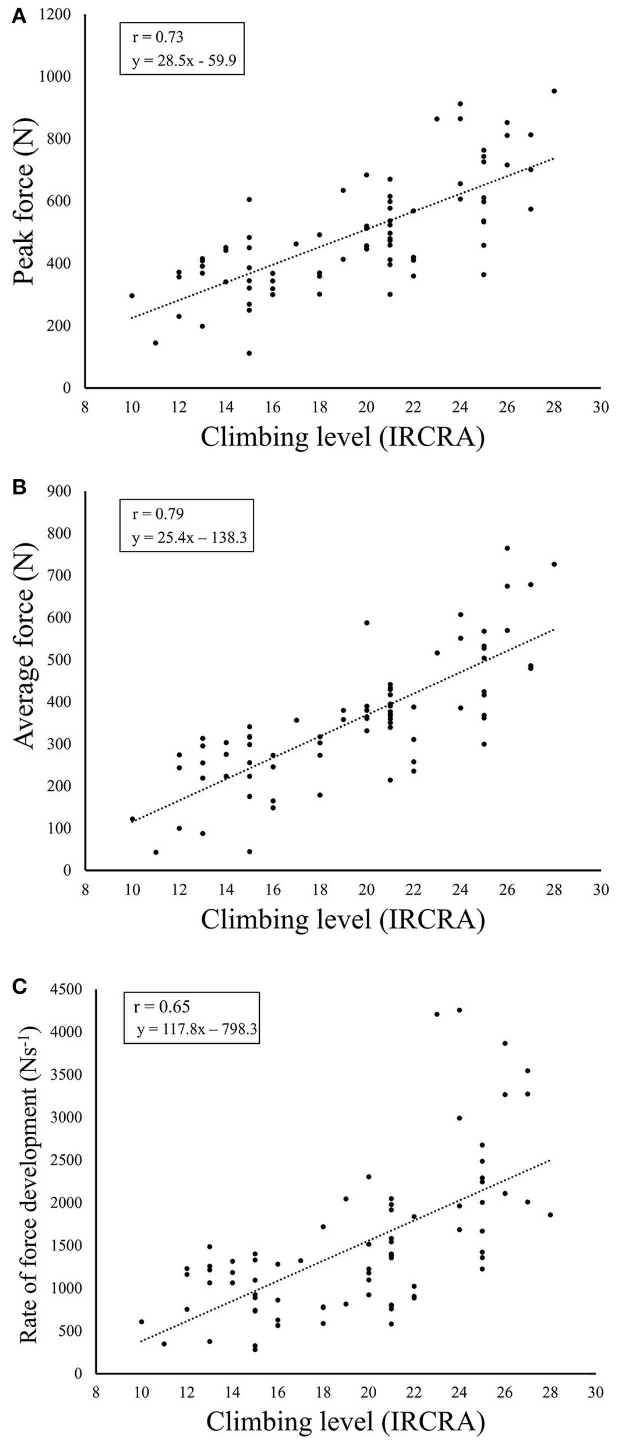

FIGURE 2 | Scatter plots with imbedded Spearman's rho (r) values for the correlation between the International rock climbing research association (IRCRA) climbing performance level and **(A)** peak- and, **(B)** average force output in Newtons (N), and **(C)** rate of force development.

DISCUSSION

This study compared the peak and average force outputs, as well as the RFD during an isometric pull-up performed on a 23 mm thick rung in intermediate, advanced, and elite sport rock climbers. In accordance with the hypothesis, F_{avg}, F_{peak} and RFD were different between the three groups with the higher performance levels displaying greater maximal and rapid force production.

The F_{peak} increased similarly between the three groups, with 40.1% (ES = 1.24) from intermediate to advanced and 39.7% (ES = 1.40) from advanced to elite. These results contrast with the findings by Stien et al. (2021b) who found no difference in F_{peak} between the intermediate and advanced groups and speculated that maximal strength was less important than other factors (e.g., climbing technique) when transitioning between the two levels. However, the findings by Stien et al. (2021b) are challenged by the fact that the intermediate group had an average red-point grade of IRCRA 15.8 which is close to the advanced classification of ≥18. The current study might provide a clearer picture of the differences between the groups as the average red-point grades within the groups was close to the averages of each performance level according to the IRCRA classifications (Draper et al., 2015).

In contrast with the F_{peak}, the percentage difference in F_{avg} between the advanced and elite groups (45.6%) was smaller than the difference between the advanced and intermediate climbers (59.1%). This could be explained by the difference in hold types (smaller sizes and less positive shapes) that often characterize routes graded IRCRA ≥18 (advanced) compared to the intermediate grades. Importantly, the observed effect sizes suggest that the difference between advanced and elite climbers (ES = 4.60) was more meaningful than that between intermediate and advanced (ES = 1.57). This trend is supported by the findings for RFD which displayed a 75% difference (ES = 1.30, $p < 0.001$) between advanced and elite groups, as well as a non-significant (p = 0.057) tendency for a 45% difference (ES = 1.42) between the intermediate and advanced groups. This could indicate that RFD becomes an increasingly important limiting factor for climbing performance when the elite grades are reached (IRCRA ≥24 for men). One potential explanation for this could be that the demands of the elite grades (e.g., steep routes and long distances between holds) challenge the RFD more directly than the F_{avg} through high-intensity movements similar to those observed in bouldering (White and Olsen, 2010). Previous findings highlighting the importance of RFD for climbing- (Levernier and Laffaye, 2021; Stien et al., 2021b) and bouldering-performance (Fanchini et al., 2013; Stien et al., 2019) support this speculation.

The validity of the relationship between F_{peak}, F_{avg} and climbing performance is further supported by the strong correlation revealed for these parameters in this and previous studies (Baláš et al., 2014; Torr et al., 2020). Interestingly, the correlation between absolute strength and climbing performance in this study (r = 0.73–0.79) was similar to that observed using relative strength (r = 0.79) by Baláš et al. (2014). The current test set-up likely accounts for body mass to a greater degree since the test is performed hanging rather than standing. The association between climbing performance and RFD was lower (r = 0.64), which could imply that maximal strength is more important than RFD strength for climbing performance when analyzed irrespective of climbing performance level. This novel finding should be considered when examining climbers as the relatively wide ranges within groups (e.g., IRCRA 18–23 for the advanced classification) could hide potential differences between levels when the exact IRCRA grade is neglected.

For anthropometric variables, the only between-groups difference was found for relative fat mass between the intermediate and advanced groups, with the intermediate climbers having higher fat mass than the advanced climbers. Since no further differences were observed, it cannot be concluded that this metric has a meaningful impact on performance among climbers. This speculation is supported by previous research concluding that fat mass has a low predictive power for climbing performance (Laffaye et al., 2016). More interestingly, years of experience and number of weekly sessions were notably greater among the elite climbers than the other two groups, whereas no differences were found between the intermediate and advanced groups. Combined, these findings suggest that the magnitudes of training and climbing experience may be crucial factors for improving climbing performance. This speculation is supported by Mermier et al. (2000) who concluded that trainable factors were predictive of climbing performance, whereas specific anthropometric characteristics are less important to excel in climbing performance.

The reader should consider some potential limitations of this study when interpreting the findings. First, only male climbers were included, and the results may not be generalizable to females. Likewise, it is not certain that the findings would be similar if other grip positions or hold types were tested. No separate familiarization session was performed. Instead, several practice attempts were given, as well as three attempts in the experimental test to ensure that the optimal performance was measured. Still, we cannot exclude the possibility that a familiarization session could have improved the test performance. Moreover, since maximal and rapid force production were measured in the same attempts, it is possible that neither was optimized. Indeed, current recommendations (Maffiuletti et al., 2016) suggest performing separate attempts focusing on either reaching peak force as fast as possible (i.e., RFD focus) or reaching the highest possible force (i.e., maximal strength focus). We chose to focus on both parameters in all attempts to avoid fatigue by reducing the number of attempts that had to be conducted. Finally, it should be noted that climbing performance was not assessed directly. Importantly, self-reported climbing grades have previously been demonstrated as reliable and useable in scientific research (Draper et al., 2011).

In conclusion, maximal strength and RFD measured in an isometric pull-up on a 23 mm thick rung was able to differentiate between climbers performing on an intermediate-to-elite level and there were moderate to strong correlations between maximal strength and RFD and climbing performance. The results suggest that increases in maximal strength and RFD of the fingers are required to advance in performance, both within and between different climbing levels. To the authors' best knowledge, this is the first study to compare the strength across the three groups with averages adjusted to correspond to the IRCRA level average.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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

VV and NS wrote the original draft. All authors contributed to the conceptualization, data collection, and critical revision of the first draft. All authors contributed to the article and approved the submitted version.

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Visual Perception in Expert Athletes: The Case of Rock Climbers

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The purpose of the present study was to examine the visual perception system in expert climbers through a psychophysical optical test in a cross-sectional study. Twenty-seven male participants with an International Rock Climbing Research Association (IRCRA) best on-sight lead skill level ranging between 18 and 27 and a best red-point level ranging between 18 and 29 completed a series of psychophysical optic tests assessing their visual field, visual acuity, and contrast sensitivity. Climbers were divided by their best red-pointed lead level, and, following IRCRA recommendations, two groups were created: an advanced group (IRCRA redpoint level between 18 and 23), and an elite-high elite group (IRCRA redpoint level between 24 and 29). The elite group presented more training days per week (5.25 ± 1.28), best on-sighted lead level (24.63 ± 1.92 IRCRA), and best red-pointed lead level (26.63 ± 2.56 IRCRA) than the advanced group (3.67 ± 0.91 training days per week, 19.50 ± 1.04 IRCRA on-sighted level and 20.67 ± 1.57 IRCRA red-pointed level). Better visual perception outputs were produced by the group of elite climbers in visual field tests; no differences were observed between the two groups for visual acuity and contrast sensitivity tests. Overall, findings indicate that best climbers performed better at the visual perception tasks that tested their visual field. Such better perception from best climbers is discussed given (1) the greater time they spend coercing the visual system during practicing climbing and (2) the specific complexity of the stimuli as they are confronted to harder routes where holds are less perceptible and the time to find best hold sequences is constrained.

Keywords: contrast sensitivity, expertise, visual acuity, visual field, visuo-motor development

INTRODUCTION

The sport of climbing, included in Tokyo 2021 Olympic Games and in the Olympic program for the forthcoming Games, has been examined from physiological (España-Romero et al., 2012), anthropometric (Laffaye et al., 2015), biomechanical (Guo et al., 2019), psychological (Jones and Sanchez, 2017) and nutritional perspectives (Potter et al., 2019). A critical aspect outlined by most when it comes to optimizing climbing performance is that of route previewing (Pezzulo et al., 2010; Sanchez et al., 2019). Such a pre-ascent climbing route visual inspection is defined as the ability to visualize and remember climbing hold configurations and to interpret the movement sequences

(Sanchez et al., 2012). To better understand such a key process, the present study assessed visual perception parameters in expert climbers.

When it comes to the perceptual constraints, two different climbing styles can be distinguished given previous knowledge of the route; on-sight and red-point climbing (Draper et al., 2011). An on-sight ascent is performed when a route is completed on the first attempt without any prior knowledge of its features. The hardest routes are typically climbed in red-point style, in which the climber successfully completes the route after two or more attempts, so the climber already knows the best hold scheme. The lack of knowledge of hold features and sequence has been identified as a key impediment to optimal performance when attempting an on-sight ascent (Ferrand et al., 2006; Sanchez et al., 2012).

Recent studies have associated route information gathering—hold features and movement combinations—with exploratory actions. Indeed, the ability to find best options relative to constraints and capabilities influences climbers ascent performances (Sanchez et al., 2012; Orth et al., 2017b). Research has also examined climbers' exploratory actions (Button et al., 2018), with findings linking route exploration to climbing performance improvements (Seifert et al., 2015). Previewing both the physical characteristics of the route as well as the way holds are best to-be-grasped and used has been shown to be a factor for success; it allows climbers to determine the time needed to hold a difficult position, climb upwards by enchaining different holds, and ultimately affects the speed of the climb overall (Sanchez et al., 2012; Seifert et al., 2015). In that line, climbers have expressed that failing to identify the correct strategy and hold order may result in a fall during the ascent (Boschker et al., 2002). The viability to grasp a hold may differ depending on its rugosity, adherence and depth (Amca et al., 2012). Knowledge generated from climbing experience may help to complete this information needed. Thus, an experienced climber may visually perceive the hold's rugosity and texture before reaching it. Whitaker et al. (2020) have recently suggested that skilled climbers may have a better tuned perceptual system. The visual system would indeed be the first to intervene in such an information gathering process.

Vision is the capacity to both recognize and interpret the environment, which involves several physical and biochemical processes. The study of vision includes visual system (hardware) and visual strategy (software). Hardware is related to the optometric features of the visual system whereas software is related to the analysis and coding of the visual data (Williams et al., 1999). Whilst the latter has been examined within the sport of climbing (Nieuwenhuys et al., 2008; Sanchez et al., 2012), the study of the former is scarce. Previous research, in general, suggests examining contrast sensitivity in combination with visual acuity and visual fields to gather a comprehensive picture on how well one's visual system functions (Elliot and Flanagan, 2007; Hadlow et al., 2018). Such testing provides useful information about real-world vision and control of body balance. Visual field refers to the total area in which it is possible to detect and react to stimuli in the peripheral vision as the eyes focus on a central point. The photoreceptors are distributed over the retina, and the purpose of visual field assessment is to rate the thresholds of light sensitivity of these receptors, measured in decibels (dB). The threshold indicated the minimum light intensity that the receptors were able to capture. In the study, the visual fields were divided into 54 points that were grouped into two major areas: The upper visual field, and the lower visual field. Visual acuity represents a complex function that can be defined as the combination of three capacities: (1) The smallest spatial unit that the visual system is able to discern, (2) the minimum distance between two objects that can be distinguished as separate, and (3) the ability to recognize the details of an object (Bailey and Lovie-Kitchin, 2013). Visual acuity provides information about the limits of an individual's vision, but it does not provide information about what happens within these limits. Contrast sensitivity represents the capacity of the visual system to filter and process figures and background information under varying conditions (Elliot and Flanagan, 2007).

Climber's movements are thought to be highly dynamic (Wright et al., 2018). As climbers ascend, their perspective changes, as does their perception of the holds they use to climb up the route; that is, the visual system is persistently perceiving and processing information (Boschker et al., 2002; Sanchez et al., 2012; Seifert et al., 2015). Vision provides predictive information for prospective control of movement pattern (Patla, 1991). As previous findings suggest, the vision allows to scan the environment and ascertain the relevant information (Williams et al., 2004; Broadbent et al., 2015).

Given the functionality of the visual perception system in sport climbing, the present study aimed at gaining knowledge and understanding in this area by assessing, through a series of psychophysical optic tests, expert climbers' visual perception hardware system. Given the lack of research in this area, we adopted an exploratory, cross-sectional design whereby it was suggested that elite climbers would perform better at the psychophysical optic tests than advanced climbers. That is, the visual hardware system would be further developed in elite climbers.

MATERIALS AND METHODS

The protocol of the present study was approved by the Ethics Research Committee of the first author's regional government (C.I. PI3/0100). Every procedure was conducted in accordance with the principles of the Declaration of Helsinki. Each participant was informed of the nature of the study, the voluntariness of the participation and of any potential adverse effects and signed an informed consent form.

Participants

Twenty-seven climbers with a self-reported outdoor sport climbing redpoint lead level (Draper et al., 2011) ranging between 7a + and 9a on the French Rating Scale of Difficulty (F-RSD) participated. We used F-RSD as it is the scale our participants were used to report climbing ability levels. However, to statistically process the data and following recommendations from the climbing research community, the F-RSD grades were transformed into climbing levels of the International Rock Climbing Research Association (IRCRA; Draper et al., 2016). Thus, our study sample's redpoint IRCRA levels ranged between 18 and 29.

In this cross-sectional study, visual parameters were examined and participants were grouped as a function of their best redpoint ascent. The inclusion criteria were: (a) To be over 18 years old with an outdoor climbing best redpoint lead within the month prior to testing of at least 18 IRCRA; and (b) to possess a healthy, free of anomalies anatomo-structural integrity of the retina (retinal nerve fiber layer was evaluated by Optical Coherence Tomography; Spectralis®, Heidelberg Engineering Inc. Carlsbad, CA, United States). See sample demographic characteristics and climbers' years of experience as well as IRCRA levels in **Table 1**.

Measurements and Procedures

Participants completed a series of psychophysical optics tests at the Visual Function Unit of a university hospital. The exploratory protocol was carried out by an academic expert in optic and ophthalmologic research.

Visual Field

Two visual field (VF) tests were carried out with our sample of climbers: that is, the contrast sensitivity to coarse vertical grating targets and the white-on-white 30–2 automated perimetry. The contrast sensitivity to coarse vertical grating targets was performed using the frequency-doubling technology perimeter (FDT; Matrix Frequency-Doubling Perimeter, Carl Zeiss Meditec, Dublin, CA, United States). The FDT perimeter displays sine waves that vary stimuli in temporal frequencies at 25 Hz and spatial frequencies at 0.25 cycles/deg. The first stimulus is characterized by a low temporal frequency that increases progressively until it becomes not visible; that is, it reaches the temporal threshold for a given spatial frequency and contrast. Then, the spatial frequency is increased until another threshold is reached. The process continues until a threshold for the combinations of spatial and temporal frequencies for each specific photoreceptor group visual system is established (Anderson and Johnson, 2003). The white-on-white 30–2 automated perimetry (SITA-Standard strategy) was performed using the Heidelberg Edge Perimeter (HEP; Heidelberg Engineering, Germany). HEP assesses the threshold of light sensitivity of a white point on a white background for all photoreceptor groups (Kaczorowski et al., 2015).

Visual Acuity

Three outcome measures were gathered utilizing the Bailey-Lovie charts, and scored in logMAR units (logarithm of the Minimum Angle of Resolution): high contrast 100% (VA100), low contrast 2.5% (VA2.5), and low contrast 1.25% (VA1.25). These charts have standardized spacing arrangements between optotypes (letters)—charts have the same number of optotypes in each row, a constant ratio of size progression, and the spacing between optotypes within rows and between rows is proportional to the given optotype size (see full details in Bailey and Lovie-Kitchin, 2013).

Contrast Sensitivity

Contrast sensitivity was evaluated with the CSV 1000E test (Vector Vision, Dayton, OH, United States), which assesses the whole contrast sensitivity function from the lowest to the highest spatial frequencies. The instrument presented a series of photocells that automatically monitored and calibrated the instrument light level. The test was composed of eight contrast levels. Across the first four levels, the contrast decreased by steps of 0.17 logarithm units, while it decreased by steps of 0.15 logarithm units across the last four levels. The test was performed at 2 m distance.

Four outcome measures were gathered in relation to four spatial frequencies in the translucent chart: 3 (CS3), 6 (CS6), 12 (CS12), and 18 (CS18) cycles/degree. Each spatial frequency was presented on a separate row of the test. Each row contained 17 circular patches that were 3.8 cm in diameter. The first patch in the row presented a very high contrast grating. The remaining 16 patches appeared in eight columns. In each column, one patch presented a grating, and the other patch was blank. The patches that presented gratings decreased in contrast from left to right across the row. Participants were asked to observe the first patch and then told to look for the grating pattern in each column. While reading across the row, they had to indicate whether the grating appeared at either the top patch or the bottom patch of each column. The contrast threshold was taken as the last correct answer. This test determined the contrast function curve and the behavior of the visual system. Contrast sensitivity provides information about real-world vision, including balance control or probability of falling.

Statistical Analysis

Following recommendations from the field that advise to use climbers' skill level as an indicator of expertise instead of years of experience (see Whitaker et al., 2020), participants in the present study were grouped based on their redpoint climbing skill level. The grouping was based on the IRCRA ability grouping. Following IRCRA recommendations, climbers were grouped in either as advanced (IRCRA 18–23) or elite—high elite (24–29) climbers.

Descriptive statistics [mean ± standard deviation (SD)] were calculated. Normal distribution of continuous variables was tested using the Shapiro-Wilk test, Kolmogorov-Smirnov test. All statistical procedures were completed on IBM^{TM} SPSS^{TM} Statistics (version 21, IBM Corporation, Somers, NY). A first-level analysis that compared visual acuity, contrast sensitivity, and visual fields between groups was carried out using independent *t*-test when data was normally distributed and U Mann-Whitney when data was not normally distributed. The magnitude of each change was assessed using Cohen *d* effect size (Cohen, 1988) (ES; $d \leq 0.2$, small; 0.5–0.79, moderate; ≥ 0.8, strong). Significance level was set at $p \leq 0.05$.

RESULTS

Differences between groups were observed for both climbing days per week, best on-sighted lead level and best red-pointed lead level. No differences were found for chronological age, age participants began to practice and years of training (see **Table 1**).

With regards to the visual perception parameters assessed, differences were found between groups in the upper visual field and the lower visual field for the test FDT (see **Figure 1**), and for the test HEP (see **Figure 2**). Both figures provide an overview of the complete 54 visual field points, which are divided into two upper areas comprising 27 points and two lower areas comprising 27 points. 14 FDT points presented significant differences, ranging between ES = 0.27 and ES = 0.36 and 15 HEP points presented significant differences, ranging between ES = 0.27 and ES = 0.46. In all cases, but one FDT point, better visual perception scores were observed for the elite—high elite group. With regards to the remaining visual perception parameters, no differences between groups were found for visual acuity or contrast sensitivity (see **Table 1**).

DISCUSSION

The present study examined visual perception parameters in expert climbers. Findings showed that better climbers—the elite group—performed better at the tasks testing their visual field. These results may suggest that best climbers possess better perception of visual field. The group of elite climbers comprised those with more training days per week, and who had climbed the hardest routes. Thereby, we can assert that these climbers have been exposed, in general, to a higher number and variety of climbing stimuli than the advanced group.

The visual information about the extra-personal space has been related to route finding and hold identification. It has been observed that climbing style affects the number and duration of sight fixations in the upper visual field. For example, climbers look more frequently and for longer times overhead, searching for the next hold to reach (Sanchez and Dauby, 2009; Seifert et al., 2015). In the present study, climbers who have been exposed to a higher number and variety of climbing stimuli, and who have climbed harder routes showed some better perception in the visual field. This better perception could be mediated by the neural process underlying the ventral pathway. As climbers face more climbing stimuli (i.e., more and harder routes) it may facilitate the neural process in this neural stream (Sheth and Young, 2016). Nevertheless, due to the cross-sectional nature of the study, one cannot establish whether such better perception system (visual hardware) is due to such environmental demands and challenges, even though past research associated the development of the visual hardware with the environment in which one develops and interacts (Schoups et al., 2001).

With regards to visual acuity, no differences between the two groups were found; however, climbers in our study showed a similar trend to that shown by other athletes (Zimmerman et al., 2011). Indeed, Zimmerman et al. (2011) found that similar age expert baseball players showed –0.16 logMAR

ADVANCED dB mean(SD) ELITE dB mean(SD) *p*-value / ES	Nasal Superior area		25,76 (3,98) 27,19 (4,55) 0,24/0,16	27,16 (4,89) 28 (3,63) 0,72/0,05	27,08 (4,5) 27,81 (4,56) 0,67/0,06	26,87 (4,71) 28,44 (3,85) 0,18/0,18		Temporal Superior area
		26,29 (3,89) 28,5 (3,37) 0,07/0,25	27,29 (3,87) 28,25 (5,26) 0,44/0,11	27,95 (4,61) 30,88 (3,38) 0,06/0,26	27,21 (5,63) 29,69 (4,03) 0,15/0,2	26,79 (4,29) 29,13 (3,77) 0,06/0,26	28,55 (4,58) 29,94 (3,42) 0,31/0,14	
	27,71 (3,46) 28,31 (2,75) 0,59/0,07	28,79 (3,75) 29,81 (2,56) 0,46/0,1	29,66 (3,74) 31,25 (2,67) 0,08/0,24	30,03 (3,91) 32,13 (2,22) 0,03/0,29	29,26 (4,68) 31,06 (3,21) 0,29/0,14	28,82 (3,97) 29,5 (3,31) 0,53/0,09	27,79 (4,36) 31,06 (3,21) 0,01/0,33	28,71 (4,37) 29,63 (2,75) 0,53/0,09
28,13 (3,02) 27,44 (3,67) 0,53/0,08	29,18 (3,34) 31,63 (3,16) 0,02/0,31	31 (3,59) 32,31 (3,03) 0,09/0,23	36,58 (31,85) 33,06 (2,24) 0,05/0,27	31,08 (4,15) 31,88 (3,83) 0,25/0,16	29,68 (5,74) 30,94 (4,48) 0,33/0,13	29 (3,25) 31,13 (2,58) 0,03/0,29	26,74 (4,54) 29,56 (3,01) 0,02/0,33	27,47 (3,67) 29,5 (4,37) 0,09/0,23
28,53 (3,9) 28,31 (4,21) 0,61/0,07	29,32 (3,81) 29,63 (4,22) 0,63/0,06	31,39 (3,28) 31,81 (2,56) 0,44/0,1	31,39 (3,62) 31,94 (1,48) 0,71/0,05	31,16 (3,44) 31,19 (3,29) 0,85/0,03	29,34 (6,73) 33,06 (2,24) 0,01/0,36	28,42 (6,35) 32 (2,16) 0,05/0,27	25,39 (4,86) 28,38 (2,5) 0,03/0,29	26,34 (3,79) 27,88 (3,1) 0,23/0,16
	28,03 (3,17) 28,94 (3,84) 0,22/0,17	28,66 (2,8) 29,63 (2,75) 0,17/0,19	29,45 (3,45) 30,94 (3,13) 0,22/0,17	29,26 (3,75) 30,63 (3,26) 0,27/0,15	29,16 (4,86) 32,19 (3,25) 0,02/0,31	29,21 (3,21) 30,69 (2,65) 0,05/0,27	27,97 (2,94) 29,56 (4,62) 0,09/0,23	28,39 (3,13) 29,13 (4,27) 0,29/0,14
		28,18 (3,51) 30,25 (2,65) 0,05/0,27	27,82 (4,04) 30,25 (2,65) 0,05/0,27	28,26 (3,89) 29,19 (2,56) 0,26/0,15	29,34 (2,67) 30,56 (2,53) 0,13/0,2	29,08 (3,09) 30,38 (2,78) 0,12/0,21	29,26 (2,85) 31,38 (3,03) 0,01/0,34	
	Nasal Inferior area		27,74 (4,03) 29,19 (3,29) 0,23/0,16	27,21 (3,6) 28,56 (3,72) 0,25/0,16	29,24 (2,87) 29,31 (2,75) 0,95/0,01	29,21 (3,11) 30,69 (2,65) 0,07/0,24		Temporal Inferior area

FIGURE 1 | Frequency-doubling technology perimeter (FDT) visual field results between advanced and elite groups. The complete sector shaded cells represent significant differences ($p < 0.05$). *P*-values of 0.00 represents *P*-values < 0.005.

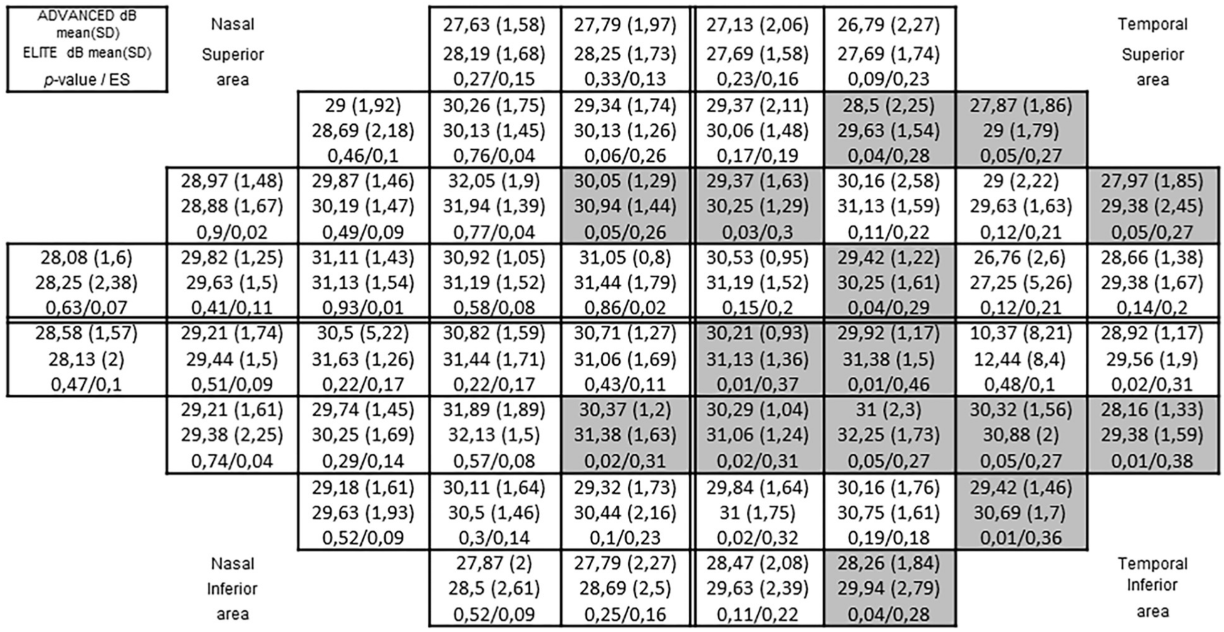

FIGURE 2 | Heidelberg edge perimeter (HEP) Visual field results between advanced and elite groups. The complete sector shaded cells represent significant differences ($p < 0.05$).

(advanced climbers scored −0.15 logMAR; elite climbers scored –20 logMAR). They also suggested that these baseball players' visual acuity may be superior to those in the general population. As far as the authors know, there is no established normative data for visual field tests in healthy and young population. Ve Ramesh et al. (2007) have described normative data comparing patients with a control group of healthy subjects. The control group in their study showed a mean threshold sensitivity in the frequency-doubling technology perimeter test that ranged between 26 dB in peripheral visual field, and 29 dB in central visual field. Climbers' thresholds, especially in the elite group seem higher, ranging between 28 and 33 dB. Ve Ramesh et al. (2007) applied a variant of the frequency-doubling technology perimeter test, and their control group was around 20 years older than the climbers of our study. Though, it is worth mentioning that a decrease between 0.6 and 0.9 dB per decade of age is suggested (Adams et al., 1999).

Previous studies have shown that expert climbers have better visual strategies than lower-level climbers (Boschker et al., 2002; Sanchez et al., 2012; Seifert et al., 2014a). Whitaker et al. (2020) suggested that skilled climbers are "more sensitive to the properties of their environment that specify affordances" (Whitaker et al., 2020, p. 507). Affordances have been defined as opportunities for action that a subject is able to perceive (Gibson, 1979). As mentioned earlier, it has been suggested that expert climbers better perceive the wall functionality, compared to novices (Boschker et al., 2002). Whitaker et al. (2020) discussed the advantage in perception found in expert climbers in terms of a more tuned perceptual system (Whitaker et al., 2020). When climbing, better perception of the shape, depth, contrast and other route details are considered as assets that may help climbers to perform a difficult movement, a *crux*, and climb more dynamically, with fewer and shorter stops for exploratory movements (Sanchez et al., 2012). Such stops may lead to an increase in the overall isometric work and thereby increase energy expenditure, and ultimately deteriorate climbing performance (España-Romero et al., 2012) and climbing fluency (Nieuwenhuys et al., 2008; Sanchez et al., 2012; Seifert et al., 2015; Orth et al., 2017b). Isometric work can also alter the forearm blood flow, another aspect that could decrease climbing performance (Fryer et al., 2016).

Perceptual and cognitive processing has been barely studied (e.g., Seifert et al., 2014b; Whitaker et al., 2020). Seifert et al. (2014b) suggested that perceiving the features of holds could improve perceiving affordances. According to Orth et al. (2017b), more successful climbers are most effective in how they explore new routes. Seifert et al. (2017) proposed expert climbers display better perceptual "attunement" that enables them to better perceive the environmental information needed to use the climbing holds with accuracy. Before applying any strength to the hold, an expert climber may adjust according to how the hold is perceived. Such behavior may enhance the way holds are grasped (Orth et al., 2017a; Fuss et al., 2020). This mechanism has been studied in ice climbing; expert ice climbers showed a better perceptual performance for acoustic, haptic and visual information when compared to non-experts (Seifert et al., 2014a). Interestingly, Orth et al. (2017a) suggested that an important difference between diverse skill level climbers was the perceptual information that they pay attention to; that is, the affordances available.

Visual strategies such as route finding have been studied and associated with sport climbing performance (Boschker et al., 2002; Sanchez et al., 2019). Given the findings of the present

TABLE 1 | Mean (SD), *p*-values and Effect Size (ES) for the demographic, anthropometric and ophthalmologic data.

	Advanced mean (*SD*)	Elite-high mean (SD)	*P*-value	ES
Age (years)	32.22 (6.93)	27.27 (5.95)	0.15	0.2
Age start climbing (years)	17.72 (4.76)	14.88 (6.03)	0.37	0.12
Years training (years)	7.78 (5.42)	10 (4.72)	0.14	0.2
Days/week climbing	3.67 (0.91)	5.25 (1.28)	0.01*	0.38
Best on-sight lead (IRCRA scale)	19.50 (1.04)	24.63 (1.92)	0.00*	0.55
Best red point lead (IRCRA scale)	20.67 (1.57)	26.63 (2.56)	0.00*	0.55
VA100	–0.15 (0.08)	–0.20 (0.05)	0.26	0.15
VA2.5	0.24 (0.11)	0.18 (0.1)	0.22	0.17
VA1.25	0.37 (0.09)	0.29 (0.13)	0.15	0.2
CS3	1.81 (0.13)	1.86 (0.14)	0.38	0.12
CS6	2.07 (0.15)	2.14 (0.08)	0.18	0.18
CS12	1.82 (0.12)	1.8 (0.07)	0.57	0.08
CS18	1.4 (0.15)	1.4 (0.16)	0.91	0.02

Advanced, IRCRA advanced ability group; Elite-High, IRCRA Elite and High Elite ability; VA100, Visual Acuity 100% contrast; VA2.5, Visual Acuity 2.5% contrast; VA1.25, Visual Acuity 1.25% contrast; CS3, Contrast sensitivity 3 cycles/degree; CS6, Contrast sensitivity 6 cycles/degree; CS12, Contrast sensitivity 12 cycles/degree; CS18, Contrast sensitivity 18 cycles/degree.

ıows significant differences between Advanced and Elite-High groups. P-values)0.00 represents P-values < 0.005.

study, we suggest that the visual system may, at least partially, influence somehow the visual strategies climbers will employ. It has been recently suggested that differences in visual search between experts and no-experts may be explained by experts' superior use of their peripheral vision (Mitchell et al., 2020). Climbers would benefit from a training program based on peripherical vision to be able to obtain more and/or better information. Probably, the best stimuli for this training routines would be focus on contrast to low sensitivity to be able to better appreciate the holds features.

STRENGTHS AND LIMITATIONS

To the best of the authors' knowledge, this study is the first of its kind to examine the visual hardware in climbing. The study of visual perception in new disciplines such as sport climbing is warranted given its specific in-nature type of activity. The sport of climbing requires route examination, which is critical for the discipline for both performance and safety issues.

Whilst the present study is a first step toward a better understanding of the perception system in climbing, some limitations shall be addressed. Firstly, the cross-sectional nature of the design entail a cautious interpretation of findings; experimental studies are warranted to test whether given visual training programs may ultimately influence climbing performance, as it has been shown for other sports (Seya and Mori, 2007). Secondly, optic tests conducted in the present study were not climbing-specific. It would be interesting to examine visual perception further using more climbing-specific stimuli, and including testing whilst actual performance takes place (e.g., on a climbing treadmill). Lastly, we must acknowledge the increase in familywise error rate across the statistical analysis, which was not controlled for.

Overall, we consider the present research relatively preliminary and encourage further replication. To better understand peripheral perception in climbers it is necessary to (a) perform similar analysis while measuring dynamic visual acuity, as it has been proven to obtain better results than static visual acuity (Souissi et al., 2021); and (b) evaluate the visual fields stimuli more similar to climbing holds, where the perception of depth and contrast of different hold-types could be analyzed (e.g., by using a climbing treadmill, or an eye-movement registration system (Button et al., 2018; Mitchell et al., 2020). The ability to navigate a climbing route is a high cognitive function and as such, is necessary to link the perception performance to motor action (Wolbers and Hegarty, 2010; Whitaker et al., 2020) and even in stress situations, specific of this sport (Broadbent et al., 2015).

CONCLUSION

The present study was the first to investigate visual perception amongst expert rock climbers through a series of psychophysical optic tests. Interestingly, climbers with more experience and higher on-sight and red-point best lead skill levels better perceived the stimuli in the visual field. Such better perception may be explained by (1) the greater time spent coercing the visual system during the process of climbing and (2) the complexity of the stimuli climbers encounter when climbing harder routes, in which holds are less perceptible and time to find the best hold sequence is constrained. Further studies on visual fields in climbing may contribute to a better understanding on how expert climbers perceive hold characteristics, thus influencing positively route previewing and, ultimately, actual climbing performance.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Research Committee of Aragón (CEICA) (C.I. PI3/0100). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

NM-C and SO contributed to the conception of the study and performed the experiment. NM-C, XS, AB-C, and CC-O performed data analysis and contributed to the production of a first draft of the manuscript. NM-C and XS wrote subsequent drafts and produced the final version of the manuscript. All authors of the present study contributed to the work submitted and approved the final version for publication.

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Prevalence of amenorrhea in elite female competitive climbers

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Elite competitive sport climbers exhibit a high strength-to-weight ratio and are reported in the literature to be lighter and leaner than their athletic counterparts. Current research regarding nutrition among climbers is sparse but suggests that they may be at high risk for low energy availability and Relative Energy Deficiency in Sport (RED-S). The prevalence of amenorrhea, one of the primary indicators of RED-S, is unknown in this athletic population. The purpose of this study was to determine the prevalence of current (previous 12 months) amenorrhea among elite level competitive sport climbers.

Methods: An anonymous online survey was distributed *via* email to 1,500 female climbers registered as competitors within the International Federation of Sport Climbing to assess the prevalence of amenorrhea over the past 12 months.

Results: A total of 114 female sport climbers answered all survey questions regarding menstrual function and 18 athletes (15.8%) presented with current amenorrhea. The majority of the athletes (72%; $n = 82$) were categorized with eumenorrhea. An additional 14 athletes (12.3%) provided information that indicated irregular cycles, but answers to all menstrual cycle questions were not congruent to elicit a classification of amenorrhea and these athletes were categorized with a menstrual status of unsure. The average BMI for climbers with eumenorrhea was 20.8 ± 1.8 kg/m^2 and 19.9 ± 2.4 kg/m^2 for those with amenorrhea. A higher percentage of climbers with amenorrhea revealed they currently struggle with an eating disorder compared to those without amenorrhea (13.5 vs. 22.2%, respectively).

Conclusion: This study indicates that some female climbers competing at the World Cup level do have menstrual disturbances with relatively normal BMIs and some currently struggle with one or more eating disorders. Even though World Cup competitions use BMI critical margins to screen competitors, this research highlights the need for more medical supervision of competitive elite female sport climbers in order to protect their overall health, including menstrual function. Further research is required to clarify how many climbers suffer from endocrine abnormalities related to RED-S. With more scientific evidence in this area practitioners will be better equipped to educate the athlete and coach with evidence-based nutrition recommendations.

KEYWORDS

competition, rock, climbing, diet, sports medicine, menstrual dysfunction, low energy availability risk

Introduction

Research has demonstrated that female athletes display a higher prevalence of menstrual disturbances than their non-athletic counterparts (De Souza and Williams, 2004; Beals and Hill, 2006; De Souza et al., 2010). Furthermore, athletes participating in lean-build sports where strength-to-weight ratio may be a performance attribute, such as in climbing, are at increased risk for menstrual disturbances due to a variety of reasons, one being low energy availability (LEA) with or without body weight changes. LEA is a condition in which energy intake is inadequate to cover all physiological functions after compensating for exercise energy expenditure (Mountjoy et al., 2018), which in athletes is most commonly referred to as Relative Energy Deficiency in Sport (RED-S). Climbers often strive to reach an optimal strength-to-weight ratio, which is a characteristic known to assist climber success (Saul et al., 2019). The pursuit to achieve this competitive attribute may place athletes at an increased risk for menstrual disturbances (Beals, 2002; Torstveit and Sundgot-Borgen, 2005; Nichols et al., 2007; Meng et al., 2020).

Adequate energy is required to maintain reproductive processes and data support that disruptions to the hypothalamic pituitary ovarian axis (HPO axis) leads to reproductive function suppression during conditions of chronic LEA (Estienne et al., 2021). The HPO axis helps to monitor and prioritize fuel for vital bodily processes such as heart and lung function and locomotion, and to conserve energy from current non-relevant functions such as gestation and lactation (De Souza and Williams, 2004; Mountjoy et al., 2018; Meng et al., 2020; Estienne et al., 2021). Therefore, it is likely that menstrual disturbances may occur in athletes training with RED-S.

Previous studies have examined the prevalence of menstrual disturbances in a variety of athletes as presented in Table 1. The criteria for defining amenorrhea and oligomenorrhea vary between studies, but 7 of the 9 studies define secondary amenorrhea by the same definition used in the current study: *absence of menstrual bleeding for at least three consecutive months or fewer than 4 cycles in the past year* (Wade et al., 1996; Goodman and Warren, 2005; Beals and Hill, 2006; Nattiv et al., 2007; Nichols et al., 2007; O'Donnell et al., 2009; Logue et al., 2018; Estienne et al., 2021). The studies which examined elite athletes found that menstrual disturbances were more prevalent among athletes compared to control populations (Wade et al., 1996; Torstveit and Sundgot-Borgen, 2005; Nattiv et al., 2007). The studies which compared athletes in lean-build sports to those in non-lean-build sports found that menstrual disturbances were more prevalent among athletes in lean-build sports than those in non-lean-build sports (Beals, 2002; Goodman and Warren, 2005; Nichols et al., 2007; Estienne et al., 2021). These studies concluded that athletes participating in sports that emphasize leanness report menstrual disturbances at a higher rate than athletes participating in less weight-sensitive sports. Additionally, one study reported that beginning high-intensity training at a young age is related to delayed onset of menarche (O'Donnell et al., 2009).

Menstrual dysfunction in athletes may increase susceptibility to injury, and/or lead to long-term health complications, such as endothelial dysfunction and low bone mineral density (De Souza and Williams, 2004; Beals and Hill, 2006; Warren and Chua, 2008; Pollock et al., 2010; Myrick et al., 2014; Armento et al., 2021). Research has indicated that the longer the duration of menstrual disturbance, the larger the bone mineral deficit at non-weight bearing sites (De Souza and Williams, 2004; Armento et al., 2021). Further, later in life when bone loss occurs more rapidly, women may already have significantly depleted bone mineral stores, placing them at higher risk for osteoporosis (Beals and Hill, 2006; Pollock et al., 2010; Myrick et al., 2014). To mitigate these health concerns, when athletes miss a period or recognize they are experiencing an irregular menstrual cycle patterning, it should serve as an obvious warning sign of potential RED-S, and athletes should seek immediate help from a health professional. Unfortunately, an absence of menstruation is often rejoiced and normalized within the sports environment (Goodman and Warren, 2005; Armento et al., 2021).

Sport climbing is highly competitive. Research indicates that elite climbers are generally shorter, leaner, and lighter than

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TABLE 1 Prior research examining menstrual dysfunction in athletes*.

Study	Sample	Criteria for amenorrhea classification	Results	Conclusion
Beals, 2002	23 elite volleyball players	Not stated	Amenorrhea: 17% Oligomenorrhea: 13% Irregular cycles: 48%	Elite adolescent volleyball players are at risk for MD (worse during competitive season) and have energy and nutrient intakes that placed them at risk for nutritional deficiencies and compromised performance.
Cobb et al., 2003	91 competitive female distance runners - Age: 18–26 years	Amenorrhea: fewer than 4 cycles in the past year Oligomenorrhea: 4–9 cycles in the past year	Amenorrhea: 10% Oligomenorrhea: 26%	In young competitive female distance runners disordered eating was strongly related to MI and MI was associated with BMD.
Torstveit and Sundgot-Borgen, 2005	669 Norwegian elite athletes and 607 controls - Total population of elite female athletes in Norway - Age: 13–39 years	Primary amenorrhea: absence of menarche by age 16 Secondary amenorrhea: absence of three or more consecutive menstrual cycles after menarche Oligomenorrhea: menstrual cycles of 35 days or more	Primary amenorrhea: - Athletes-7.3% - Controls-2.0% Secondary amenorrhea: - Athletes in leanness sports-24.8% - Non-leanness sports-13.1%	Age at menarche was later and prevalence of primary amenorrhea was higher in elite athletes than controls. A higher percentage of athletes competing in sports that emphasize thinness reported MD than athletes in less weight sensitive sports.
Castelo-Branco et al., 2006	38 adolescent dancers engaged in high intensity training and 77 controls - Age: 12–18 years	Primary amenorrhea: absence of menarche by age 16 Secondary amenorrhea: absence of three or more consecutive menstrual cycles after menarche	Amenorrhea: - Athletes: 8% Oligomenorrhea: - Dancers-34% - Controls-14%	Early, high-intensity training delayed onset of menarche.
Beals and Hill, 2006	112 US collegiate athletes - Lean-build: 65 - Non-lean-build: 47 - Age: avg 19.5 years	Delayed menarche: absence of menarche by age 16 Secondary amenorrhea: absence of three or more consecutive menstrual cycles after menarche Menstrual irregularity: fewer than 12 cycles in past 12 months, greater than 10-day variation in cycle	Menstrual dysfunction: 25% of athletes - Lean -build: 32% - Non-lean build: 17% Delayed menarche: 9% of athletes Secondary amenorrhea: 21%, greater prevalence among lean-build	Amenorrhea was more common among athletes in lean-build sports. MI increased for both lean-build and non-lean-build sport athletes during the competitive season.
Nichols et al., 2007	423 high school athletes - Lean-build: 146 - Non-lean-build: 277	Primary amenorrhea: absence of menarche by age 15 Secondary amenorrhea: absence of three or more consecutive menstrual cycles after menarche Oligomenorrhea: menstrual cycles of <21 or >35 days	Menstrual irregularity: 20.1% - Lean-build: 26.7% - Non-lean-build: 16.6% Primary amenorrhea: 0.5% Secondary amenorrhea: 1.7% Oligomenorrhea: 18%	Prevalence of MI was higher in lean-build athletes than non-lean-build athletes. Athletes with DE were over two times as likely to report MI than athletes without DE.

(Continued)

TABLE 1 Continued

Study	Sample	Criteria for amenorrhea classification	Results	Conclusion
Myrick et al., 2014	95 Division I collegiate athletes	Primary amenorrhea: absence of menarche by age 15 Secondary amenorrhea: absence of three or more consecutive menstrual cycles after menarche, no OC use Oligomenorrhea: <10 cycles in past 12 months, no OC use	Primary amenorrhea: 9.5% Secondary amenorrhea: 17.9% Oligomenorrhea: 35.8%	Athletes were at risk for MD. MD was perceived as common and normal in the female athlete. Prevalence of this perception was especially common in lean-build sports.
Rost et al., 2014	149 Swedish elite athletics (track and field) athletes	Not stated	Amenorrhea: 25%	Swedish female athletics athletes reported high prevalence of amenorrhea compared to normal population. More runners reported amenorrhea than athletes in throwing and jumping events.
Ravi et al., 2021	178 Finnish adolescent athletes and 105 non-athletes - Adolescence (14–16 years) - Young adult (18–20 years) 52 Finnish young adult athletes and 159 non-athletes	Primary amenorrhea: absence of menarche by age 15 Secondary amenorrhea: absence of three or more consecutive menstrual cycles after menarche Oligomenorrhea: menstrual cycles of 35 days or < 10 cycles per year	Current primary amenorrhea: - Adolescence: 4.7% - non-athletes: 0% Current MD - Young adult athletes: 38.7% - Non-athletes: 5.6%	Primary amenorrhea and MD were more common among athletes than non-athletes.

*MD, Menstrual dysfunction; MI, menstrual irregularity; DE, Disordered eating; OC, Oral contraceptive.

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non-climbing athletes and they exhibit anthropometric profiles similar to gymnasts, ballet dancers, and long-distance runners (Watts et al., 2003; Sheel, 2004; Giles et al., 2006). Athletes competing in these types of sports have displayed an increased prevalence of disordered eating and chronically low body weight (Sundgot-Borgen and Garthe, 2011). Studies assessing eating behavior or nutrient intake among climbers have found disordered eating (Joubert et al., 2020), energy restriction (Zapf et al., 2001; Michael et al., 2019; Sas-Nowosielski and Wycislik, 2019), and iron deficiencies (Gibson-Smith et al., 2020). Some research indicates no correlation of low BMI and high climbing performance (Grønhaug, 2019), yet anecdotal evidence points to a climbing culture that values thinness and often encourages athletes to minimize weight through restrictive eating habits (Leslie-Wujastyk, 2019; Lucas, 2021). This drive for a high strength-to-weight ratio may cause athletes to maintain a state of chronic LEA, which may subsequently lead to menstrual disturbance. The prevalence of amenorrhea in climbers is currently unknown. Thus, the aim of this novel study was to determine the prevalence of amenorrhea among elite competitive climbers.

Materials and methods

Survey tool

An online survey (Qualtrics XM 2021, Provo, UT) was administered to all female climbing competitors registered with the International Federation of Sport Climbing (IFSC). The survey was approved by the ethics committee at Northern Michigan University (IRB#HS21-1208) and distributed by the IFSC to 1,500 IFSC members *via* email. There were 57 Member Federations within the IFSC at the time this manuscript was submitted and the IFSC may add/delete Federations annually (i.e., Croatia and Puerto Rico were added for 2022).

The survey was open from June 21 through August 11, 2021. The survey contained 33 questions divided into five sections: (1) Informed consent, (2) Demographics, (3) Climbing experience, training volume, climbing discipline, and injury history, (4) Menstrual history, contraceptive use, and diagnosed medical conditions, and (5) Self-reported weight and weight changes, self-reported height, eating behavior and eating disorder history (see the Supplementary materials for the survey's complete question set).

Participants

Participation was optional, responses were collected anonymously without collecting personal identification. Inclusion criteria were self-identified and as follows: competition category identified as female, English was either their primary or secondary language, an IFSC registered athlete, and not pregnant or lactating within the past 12 months.

Menstrual cycle status

Climbers who answered all menstrual cycle questions were categorized as amenorrhoeic if they answered this way to all of the following criteria defining amenorrhea (De Souza and Williams, 2004; Torstveit and Sundgot-Borgen, 2005):

- No menstrual bleeding for at least three consecutive months in the past 12 months
- No menstrual bleeding in the past 90 days
- Had three or fewer menstrual cycles in the last 365 days
- No menstrual cycle during entire life
- Self-characterize menstrual cycles as irregular

Eumenorrhea, also listed as non-amenorrhea, was used to categorize climbers by their answers according to the following criteria (Torstveit and Sundgot-Borgen, 2005; De Souza et al., 2010):

- Had 10 or more menstrual cycles (period comes every 25–35 days consistently) in the past 12 months
- Had menstrual bleeding in the past 90 days
- Had eight or more menstrual cycles in the last 365 days
- Never longer than 35 days in between cycles
- Self-characterize menstrual cycles as regular

When answers were not congruent about menstrual cycle status or did not meet either criteria, climbers were categorized as unsure. We asked the same question in two different ways to attempt to check for consistent answers (one year = 12 months and 365 days).

To help determine how regular the participants felt that their cycles were, a slider bar with a drag and drop function with choices of 0.1 to 5.0 was employed to self-characterize their cycles within the past 12 months as regular (0.1 to 1.5) or irregular (3.5 to 5.0), and if they selected scores from 1.6 to 3.4 then these data did not contribute to the characterization of amenorrhea or eumenorrhea. Thirty-three climbers (29%) self-characterized their cycles as irregular.

Statistics

Results were computed using IBM SPSS Statistics for Windows, version 28.0 (IBM Corp., Armond, N.Y., USA). The data are presented using descriptive statistical summary

TABLE 2 Anthropometry and climber characteristics.

Characteristic (***n* = 114, unless otherwise noted**)	**Mean ± SD or percentage of athletes**
Age, y ($n = 112$)	22.9 ± 5.0
Height, cm ($n = 110$)	164.4 ± 5.9
Weight, kg	56.1 ± 6.9
BMI, kg/m^2 ($n = 110$)	20.7 ± 1.9
Competition country ($n = 113$)	Austria: 11.5%
30 countries were represented. The top 7 are	United States: 9.7%
indicated here. The remaining 23 countries	Germany: 8.8%
each represented 4.4% or less of the data	Switzerland: 6.2%
reported	Canada: 6.2%
	India: 6.2%
	Great Britain: 5.3%
Age at first climbing competition, y ($n = 113$)	12.9 ± 5.1
Financial sponsorship received in past 6	Yes: 45%
months	No: 55%
Current climbing competition category	Speed: 14%
could select all that apply	Lead: 35%
	Boulder: 53%
	Combined: 10%
	Have not competed in past
	year: 39%
Days trained per week, d	5.2 ± 1.7
Hours trained per train day, h ($n = 105$)	3.4 ± 1.2

measures (number of athletes), percentages, or means ± standard deviations.

Results

Survey tool results

During the time of inclusion, 229 attempts to enter the survey were recorded and 147 participants met the inclusion criteria and answered at least 6 questions. A total of 114 female climbers completed the majority of the climbing, eating behavior and menstrual cycle related questions, which were included in this publication.

Participant results

As it is unknown how many of the possible participants actually received the email with the survey link due to a variety of reasons (i.e., inactive email accounts, unopened email, filtered to junk mail), a response rate is unknown. There were 114 complete responses ($N = 114$). All participants were IFSC registered female sport climbers who represented 30 different countries with their anthropometrics and climbing training and competition characteristics are reported in Table 2. The climbers mean age was 22.4 ± 4.8 years. The overall average BMI of the group ($n = 110$) was 20.7 ± 1.9 kg/m^2. Three climbers in the eumenorrhea group did not report their height and one climber in the amenorrhea group did not report their weight, thus BMI could not be calculated for 4 climbers.

Nine athletes reported that they were not currently training, but those that were training averaged 3.4 ± 1.2 h per training day and 5.2 ± 1.7 days per week. Of the athletes that indicated that they had more than one training session within the same day, 17.5% had double trainings one day per week, 27.2% had double trainings two days per week, 9.2% had double trainings three days per week, 7.0% had double trainings four days per week, and 2.6% indicated that five days a week they had double training sessions within the same day.

In the past 6 months, 39% of the athletes had not competed. Of those who had, 61% competed in more than one discipline (speed, lead, boulder), and 10% had competed in a combined event (scores tallied in two or more disciplines within the same competition). Additionally, 45% of the athletes received financial sponsorship within the past 6 months.

Table 3 reflects body weight manipulation and eating characteristics of the athletes. Nearly half of the athletes reported that they attempt to change their body weight for competition through various methods including reduced food intake or increased training. Only 17% do not consciously restrict food intake while 23% report daily restriction of food intake. Additionally, of the athletes classified as eumenorrheic, 13.4% revealed they currently struggle with an eating disorder, while 22.2% of the athletes classified as amenorrhoeic revealed they currently struggle with an eating disorder.

Menstrual cycle status results

Athletes with amenorrhea

Within the past 90 days, 13.2% ($n = 15$) had not had a menstrual cycle and 14% ($n = 16$) had no menstrual cycles for 3 consecutive months or more during the past 12 months, and 9.7% ($n = 11$) had 3 or fewer menstrual cycles in the last 365 days. One athlete (21 y) indicated they had never had a menstrual cycle, which was confirmed with a consistent, "never menstruated" response for all menstrual cycle questions.

By consistently answering all questions indicative of an amenorrhea diagnosis, the prevalence of current amenorrhea (past 12 months) in these IFSC competitive climbers was 15.8% ($n = 18$), one climber with primary amenorrhea and 17 with secondary amenorrhea. Table 4 displays the menstrual cycle characteristics of the athletes. Their average BMI was 19.9 ± 2.4 kg/m^2. Within the past 12 months, 1 participant with amenorrhea used a hormonal implant, indicated she used it for birth control and to reduce bleeding, and had been diagnosed with or treated for polycystic ovary syndrome (PCOS). One

TABLE 3 Body weight manipulation and eating characteristics.

Characteristic ($n = 114$, unless otherwise noted)	Percentage of athletes
Attempt to change training weight ($n = 105$)	Yes: 23%
	No: 77%
Attempt to change competition weight ($n = 105$)	Yes: 45%
	No: 55%
Consciously restrict food intake	Never: 17%
	Rarely, a few times/yr: 13%
	Occasionally, maybe twice/mos: 21%
	Yes, at least 3–4 times/mos: 11%
	Yes, at least once per wk: 9%
	Yes, several days per wk: 6%
	Yes, daily: 23%
Injury during past 12 months	Yes: 53.5%
	No: 46.5%
Relationship with food ($n = 59$)	Sometimes struggle: 37%
	Like my relationship: 49%
	Dislike my relationship: 14%
Currently struggle with this eating disorder (yes to any; $n = 17$) *could select all that apply*	Anorexia nervosa: 2%
	Bulimia nervosa: 2%
	Binge eating disorder: 3%
	Orthorexia nervosa: 1%
	Night eating syndrome: 3%
	Avoidant/restrictive food intake disorder: 5%
	Eating disorder not otherwise specified: 3%
	Have disordered eating patterns: 25%
	Never had any of the above: 64%
	Unsure: 5%
At any time, diagnosed with or believed to have had this eating disorder (yes to any; $n = 32$) *could select all that apply*	Anorexia nervosa: 14%
	Bulimia nervosa: 6%
	Binge eating disorder: 8%
	Orthorexia nervosa: 2%
	Night eating syndrome: 3%
	Avoidant/restrictive food intake disorder: 8%
	Eating disorder not otherwise specified: 8%
	Have disordered eating patterns: 26%
	Never had any of the above: 53%
	Unsure: 6%

other athlete with amenorrhea used oral contraceptives for birth control reasons only.

The number of climbers with amenorrhea also reported some characteristics that may have contributed to this menstrual status and are listed in Table 5. The use of oral contraception and/or hormonal treatment (11.1%), a low BMI (22.2%), increased training volume (33.3%), and/or restricting food (50%), or have an eating disorder (38.9%) may alter menses in athletes individually or when some or all of these issues coexist.

Athletes with eumenorrhea

The majority of participants were categorized with eumenorrhea, 72.0% ($n = 82$). During the past 12 months, 62.3% had 10 or more menstrual cycles (i.e., had a period every 25–35 days consistently) and 85.1% indicated that they had a period within the past 90 days. 61.4% had 8 or more menstrual cycles in the last 365 days and 43.0% indicated they had never had more than 35 days in between their cycles. Forty-nine athletes self-characterize their menstrual cycles as regular. Their average BMI was 20.8 ± 1.8 kg/m^2. Twenty-three eumenorrheic athletes reported using a form of oral or hormonal contraception (13 oral, 3 hormone ring, 3 implant, 1 coil, and 3 non-descriptive) with the majority of these athletes ($n = 18$) using it for birth control purposes. However, 10 athletes with eumenorrhea declared they also used it to regulate their cycles in relation to performance.

Athletes unsure of menstrual status

An additional 12.3% ($n = 14$) of the athletes had answers to menstrual cycle questions that were not congruent or not known to the athlete and therefore, menstrual status could not be determined. For example, 20.5% of these athletes indicated that their cycles were somewhere in between regular and irregular on the menstrual cycle characterization scale, 17.5% were unaware of the number of cycles that had occurred in the past 365 days and 10.5% were unaware of the number of cycles that had occurred over the past 12 months. Thus, these participants were categorized as unsure. Their average BMI was 20.9 ± 2.1 kg/m^2. Two of these athletes used oral contraceptives, 4 used hormonal treatment or contraception and all six selected birth control as a reason. In addition, 4 of these 6 athletes with unsure menstrual status also selected the reason for using it was to reduce menstrual pain and to reduce bleeding. One of these athletes selected four reasons for use: to regulate my cycle in relation to performances, birth control, to reduce pain and to reduce bleeding.

Discussion

The purpose of this study was to determine the prevalence of amenorrhea among elite level competition sport climbers and, to the authors' knowledge, it was the first study to do so.

The overall prevalence of amenorrhea in our sample was 15.8%. When compared with other studies surveying elite athletes, our results are similar to volleyball players at 17% (Beals, 2002), lower than elite Norwegian athletes in leanness

TABLE 4 Menstrual cycle characteristics.

Characteristic (***n*** **= 114, unless otherwise noted**)	**Percentage of athletes**
Age at menarche, y	11 or younger: 8%
	12–14: 61%
	15–16: 24%
	17+: 4%
	Never menstruated: 1%
	Don't remember: 2%
Track period with calendar or app	Yes: 59%
	No: 30%
	Not menstruating: 10%
	Never menstruated: 1%
Perceived regularity of menstrual cycle ($n = 102$)	Regular: 48%
	Irregular: 31%
Menstrual Status Category	Primary Amenorrhea: 1%
	Secondary Amenorrhea: 15%
	Eumenorrhea: 72%
	Unsure: 12%
Used oral contraceptives or received hormonal treatment/contraceptives in past 12 months *could select all that apply*	Yes, oral contraceptives: 14%
	Yes, hormonal treatment (included medical treatment and/or hormonal intrauterine device-IUD): 6%
	Yes, hormonal contraceptives: 10%
	None of these were used during the past 12 months: 73%
	Yes, hormonal ring: 3%
	Yes, hormonal coil: 3%
	Yes, hormonal implant: 4%
Reason for oral or hormonal contraceptives/treatment *could select all that apply*	Birth control: 23%
	Reduce menstrual pain: 10%
	Reduce bleeding: 10.5%
	Regulate in relation to performance: 10.5%
	Otherwise menstruation stops: 2%
	None of the options explain the reason: 3%
Experienced changes to cycle with increased training intensity, frequency or duration	Yes: 32.5%
	No: 36%
	Unsure: 30%
Changes to cycle due to increased training *could select all that apply*	I don't bleed at all: 15%
	I bleed less over the same number of days: 22%
	I bleed fewer days: 15%
	I bleed more over the same number of days: 4%
	I bleed more days: 4%
	No changes happen to my menstrual cycle when my training increases: 4%
	I am unsure: 19%
Experienced changes to cycle with restricted or reduced food intake	Yes: 22%
	No: 49%
	Unsure: 29%
Changes to cycle due to restricted or reduced food intake *could select all that apply*	I don't bleed at all: 13%
	I bleed less over the same number of days: 10.5%
	I bleed fewer days: 11%
	I bleed more over the same number of days: 1%
	I bleed more days: 1%
	No changes happen to my menstrual cycle when I restrict my food intake: 4%
	I am unsure: 19%

TABLE 5 Plausible causes of amenorrhea.

Cause	Climbers with amenorrhea ($n = 18$) and potential contributing characteristics
Primary amenorrhea	1
Oral or hormonal contraception/treatment use	2
Low BMI (IFSC critical margins $\leq$18.0 kg/m^2)	4
Increased training volume report no bleeding at all	6
With food restriction reported no bleeding at all	9
Eating disorder	7
Medical reason (PCOS)	2

sports at 24.8% (Torstveit and Sundgot-Borgen, 2005), and lower than Swedish track and field athletes at 25% (Otis, 1992). Table 1 compares additional studies examining prevalence of menstrual dysfunction in athletes. Furthermore, one review estimated the prevalence of secondary amenorrhea in athletes at 3–66% compared with 2–5% in the general population (Sas-Nowosielski and Wycislik, 2019).

Similar to our findings, Cobb et al. (2003) reported that disordered eating was strongly correlated with menstrual disturbances in female distance runners (Cobb et al., 2003). Torstveit and Sundgot-Borgen (2005), Nichols et al. (2007), and Beals and Hill (2006) also noted that competing in a sport that emphasizes thinness, or a strength-to-weight characteristic, increased the prevalence of menstrual disturbances (Beals, 2002; Torstveit and Sundgot-Borgen, 2005; Nichols et al., 2007). In the present study, only 4 of the 18 climbers with amenorrhea had a low BMI, $\leq$18.0 kg/m^2. The IFSC uses BMI critical margin values to help screen athletes at competitions that may have compromised health and during the time of this research (2021), the BMI critical margins were set at 18.0 kg/m^2 for female competitors during the World Cup sanctioned events. BMI screenings were arranged at every Boulder and Lead semi-finals done by competition doctors or Medical Commission members. However, the consequences for athletes that fall below these BMI critical margins follow a fairly flexible process. National Climbing Federations with critical cases receive a letter from the IFSC Medical Commission requesting an explanation on the specific athlete(s) and then may also receive support from IFSC Medical Commission members. Only seven climbers of the 114 in the present study had BMI values at or below these critical margins, four of which had amenorrhea. The other 14 climbers with amenorrhea had higher BMI values, which supports that using BMI criteria alone is not indicative of menstrual function.

This suggests that BMI should not be the only parameter used to decide the health status, nutritional status, or competition status of a climber. A low BMI may indicate further health assessment in a climber, but a BMI above 18 kg/m^2 does not suggest that the climber is ensured to be healthy. Another tool applied by the IFSC is the Mass Index, which considers a long torso or long legs by using a formula with the sitting height or leg length to help adjust for body type differences. We did not include this measure in the present study. Currently, the International Olympic Committee has a working group researching the current status of body composition assessment in health and performance and an update on their previous report (Sundgot-Borgen et al., 2013) is hopefully forthcoming.

The aim of this study was to assess prevalence of amenorrhea and describe plausible causes for such, and not to assess nutritional status nor correlate any data with climbing performance. However, it is useful to draw on other studies that examined anthropometric data in female climbers. Giles et al. (2021) found that there was no significant difference in their female climber cohort between advanced and elite climbers for height, body mass, BMI, or skinfold thickness (Giles et al., 2021). The BMI for their elite climbers was 21.2 ± 2.0 kg/m^2, which is slightly higher than those with amenorrhea in our present study. This may be relevant for practitioners to understand BMI in context of the whole athlete.

Assessing full nutritional and medical status is recommended by the IFSC for all athletes, particularly those that may report altering calorie or food intake to control weight, disordered eating, or history of disordered eating. In our cohort, 44% with amenorrhea altered their calories/food intake in order to cut weight for competition and 22% reported they currently had an eating disorder and 39% reported yes to having had an ED at any time during their life. Among a few other reasons listed in Table 5, these energy related reasons are plausible causes of amenorrhea.

These issues are consistent within the RED-S framework, which places athletes at a higher risk for amenorrhea when weight or energy intake is inadequate to support training and normal body function. It is noted that the IFSC sets and revises standards for a yearly sports medical examination to help ensure the health of its licensed athletes. This recommended sports medicine examination includes a complete sports physical that includes the climber's weight, height, BMI, Mass Index, body fat, flexibility, spiroergometry, standard blood/urine lab tests, electrocardiography, echocardiography, vaccinations, psychological stability, and nutrition screening. Although all of these are recommended by the IFSC, it is often up to each National Federation to health screen their athletes which may vary in rigor.

Some of the limitations and strengths of the present research must be highlighted. This study was cross-sectional and data were collected using an online survey written in English only, which narrows the representation of all competitive elite climbers. The survey tool used to assess prevalence of current amenorrhea was not a validated instrument. It was modeled off the Low Energy Availability in Females Questionnaire (LEAF-Q) (Melin et al., 2014), but was slightly modified to better serve the purpose of our study and ensure relevance to our population (see the Supplementary materials for the survey's complete question set). Furthermore, medical professionals and experts researching amenorrhea in athletes were consulted and their advice guided our survey development.

The lack of control of whether or not the emails that were sent out actually were received and whether or not the decision of not taking part was an active decline or was a result of not opening or receiving the email is another issue that must be addressed. Perhaps construed as a low response rate if 1,500 female climbers are registered with the IFSC and only 7.6% of them responded to all pertinent questions. This methodology issue does occur with online based surveys and must be taken into consideration when the results are interpreted and used. This preliminary data suggests further investigations with more objective measures, such as multiple sample hormone testing over several months, are required to truly determine amenorrhea prevalence of any given population. The surveyed prevalence value helps us to learn that this population is still vulnerable to reproductive health issues and that 16% is not a value to ignore. Instead, we need to focus more attention on placing proper screening within each National Climbing Federation and reproductive health education to support this population.

In addition, the timing of the survey may have had an impact on the reported body weight because the survey was open during the 3 months while most respondents were in the midst of the international competitive season. Finally, some participants may have purposefully lowered their weight for competition and the self-reported data collected may not have reflected their usual body weight, although the survey did ask participants about whether or not they altered their training body weight vs. competition body weight and how they went about it.

A strength of the study is that all participants were international elite climbers. Performing research with a specific group of athletes makes the results easier to interpret and use to develop medical screening guidelines, education and injury prevention strategies specifically targeted to this population. To the authors' knowledge, menstrual disturbance research among athletes from multiple countries has never before been published.

This study has captured scientific evidence on female climbers competing at the elite level, which indeed supports that this population is susceptible to menstrual dysfunction, eating disorders and disordered eating patterns. Future research should include a more comprehensive examination of the causes of amenorrhea and menstrual irregularity in climbing populations, energy availability assessment in competitive climbers and its correlation with performance and health and injury risk. This will facilitate the development of medical screenings and protocols within competitive climbing organizations to ensure female athletes are safe for competition with their health protected. Also, it will help to shape a safer team atmosphere with proper eating behaviors that support athletic endeavors and reproductive function. With more scientific evidence in this area practitioners will be better equipped to educate athletes and coaches with evidence-based health recommendations.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study involved human participants which was reviewed and approved by the Internal Review Board of Northern Michigan University. Written informed consent to participate in this study was provided by the participant and all minors' legal guardian/next of kin.

Author contributions

LJ, AL, GG, and MM designed the study. LJ, AW, AL, GG, MM, VS, and EB designed the survey tool. LJ, VS, and EB collected the data. LJ and GG performed the data analyses. LJ, AW, GG, and MM wrote the manuscript. All authors read, contributed to, and approved the final manuscript.

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Conflict of interest

Author MM is self-employed by Real Nutrition, LLC and serves on the USA Climbing Medical Committee. She assisted with the survey question development and is not currently associated with a university, but has specific expertise in climbing nutrition, eating disorders, and female health.

The remaining 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.895588/full#supplementary-material

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