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Injuries, injury prevention and training in climbing

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Injuries, injury prevention and training in climbing

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Editorial: Injuries, injury prevention and training in climbing

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Editorial on the Research Topic
Injuries, injury prevention and training in climbing

Centuries ago, climbing pioneers began exploring mountains and high peaks. With the introduction of indoor climbing centers, climbing as an activity has evolved into a sport. The 2024 Olympics in Paris will feature individual climbing competitions in bouldering, lead climbing, and speed climbing (1). New climbing gyms are opening every year in every major city. With growing popularity and increasing performance levels, a need for evidence-based knowledge on injury prevention, testing, and training has emerged (2, 3). In particular, climbing research is in its infancy, but the literature is expanding rapidly (4–7). However, there remains a need to improve knowledge about injury prevention strategies, injury epidemiology, and sports medicine, including systematic training approaches for returning to climbing post-injury. Therefore, the Research Topic "Injuries, Injury Prevention, and Training in Climbing" aims to advance scientific understanding in these areas.

Sixty-four authors from Europe and the Americas contributed to the 12 papers published in this Research Topic. Notably, half of the papers include authors from multiple countries, highlighting the importance of collaboration in filling knowledge gaps. The manuscripts vary in methodology: three studies utilized surveys, three conducted training or rehabilitation interventions, two were systematic reviews, and four used a cross-sectional design. Of note, four studies involved competitive or elite climbers, a group almost entirely absent from the scientific literature and whose inclusion has been called for. The interdisciplinary evidence of this Research Topic has multiple applications: (a) chronic injury prevalence rates, low back pain, (b) eating disorders, amenorrhea, and nutritional knowledge among competitive climbers, (c) the development of new training methods to potentially reduce injury rates, (d) finger diagnostics, (e) the testing and measurement of climbing performance, and (f) recovery and fatigue states after climbing.

Injury prevention is a part of all sports. Chronic injuries are often the result of high intensity over an extended period of time without adequate rest or recovery strategies. Carraro et al. examined the prevalence of low back pain in 180 competitive climbers aged 13–19 years. Over the previous 12 months, 74% had reported low back complaints, most of which were classified as low-intensity to low-disability (63%). Concerns over non-traumatic, overuse injuries in climbing have been previously addressed but not in a systematic review that examines potential risk factors and injury prevention strategies. Quarmby et al. included 34 studies in their review and identified higher climbing intensity, bouldering, reduced finger strength, use of the crimp grip, and previous injuries as risk factors for overuse injuries. However, findings related to gender, climbing experience, and training volume were inconsistent, while body weight/BMI, stretching, and warm-up/cool-down routines were not associated with an increased risk of injury. Concerning the potential for an exaggerated focus on body weight in climbing, injuries, amenorrhea, and eating disorders were assessed among 114 elite female competitive climbers (Grønhaug et al.). More than 53% reported injuries in the previous 12 months, with shoulders (38%) and fingers (34%) being the most common injury locations. BMI did not show an increased odds ratio for injury, but those with an eating disorder had twice the odds of being injured. In a study of 50 competitive boulderers in the UK, nutritional knowledge scores were average, with considerable individual variation (Gibson-Smith et al.). Moreover, 38% of female athletes and 46% of male athletes reported intentional weight loss, with 76% engaging in concerning practices. It is, therefore, crucial that trainers and professionals remain vigilant in identifying athletes at risk for problematic behaviors early, addressing the issue, and establishing appropriate specialist services.

Finger injuries are the most common affliction among climbers (8). Therefore, Grønhaug et al. compared finger cartilage composition using MRI between 13 climbers and ten non-climbers and found no significant difference in T2 values between the groups. Additionally, Bayer et al. examined the clinical management of finger joint capsulitis/synovitis in rock climbing through a case study. Following a 6-week comprehensive rehabilitation program that focused on unloading affected tissues, increasing mobility, correcting climbing movements, and improving muscle performance, pain levels decreased from 5.5 to 1.5 on the 0–10 analog pain scale. Furthermore, Devise et al. implemented a 4-week, twice-weekly hangboard training program and divided 52 experienced climbers into four groups. The study found that only the extensor-based training significantly improved finger extensor strength.

Exel et al. demonstrated that performing a dead hang with the arms fully extended placed less stress on the elbow and shoulder joints compared to elbow flexion at 90 and 135°. Moreover, Javorsky et al. compared two 5-week periods of low-volume blood flow restriction (BFR) training with high-intensity resistance training in intermediate climbers. The results showed that low-intensity BFR training (30% of maximum) yielded similar climbing-specific strength and endurance outcomes as high-intensity resistance training (60% of maximum), suggesting that BFR may be an effective alternative for reducing mechanical stress on the fingers.

In their systematic review, Langer et al. sought to provide an overview of the diagnostic tests and performance measurements in climbing. From 148 studies, 63 different tests were identified, indicating a lack of uniform or standard procedures for evaluating climbing performance. Assessment of recovery markers associated with climbing could potentially reduce the incidence of overuse injuries. Gasparie et al. analyzed a range of recovery markers 4 min post-competition, and 12, 24, 48, and 60 h following a national bouldering competition. They found that forearm strength and pain returned to pre-competition levels within 24 h, but climbing readiness was still compromised 48 h after the competition. In a separate study, Yu et al. reported that 24 h of continuous rock climbing led to a 15% reduction in mean grip strength and a 71% reduction in dead hang endurance in 36 climbers.

As we conclude this Research Topic, we are confident that we have addressed numerous gaps in evidence-based knowledge and significantly advanced the understanding of injury, injury prevention, and training in climbing. We trust that this compilation of studies will provide valuable and practical insights for both recreational and competitive climbers, as well as coaches. We also encourage researchers around the world to add to the body of evidence-based climbing literature.

Author contributions

AS: Writing – original draft, Writing – review & editing. VS: Writing – original draft, Writing – review & editing. AS: Writing – original draft, Writing – review & editing. GG: Writing – original draft, Writing – review & editing.

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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References

1. Lutter C, Tischer T, Schoffl VR. Olympic competition climbing: the beginning of a new era-a narrative review. *Br J Sports Med*. (2021) 55(15):857–64. doi: 10.1136/bjsports-2020-102035

2. Saeterbakken AH, Stien N, Pedersen H, Langer K, Scott S, Michailov ML, et al. The connection between resistance training, climbing performance, and injury prevention. *Sports Med Open*. (2024) 10(1):10. doi: 10.1186/s40798-024-00677-w

3. Winkler M, Kunzell S, Augste C. The load structure in international competitive climbing. *Front Sports Act Living*. (2022) 4:790336. doi: 10.3389/fspor.2022.790336

4. Draper N, Giles D, Taylor N, Vigouroux L, Espana-Romero V, Balas J, et al. Performance assessment for rock climbers: the international rock climbing research association sport-specific test battery. *Int J Sports Physiol Perform*. (2021) 16 (9):1242–52. doi: 10.1123/ijspp.2020-0672

5. Gronhaug G, Norberg M. First overview on chronic injuries in sport climbing: proposal for a change in reporting of injuries in climbing. *BMJ Open Sport Exerc Med*. (2016) 2(1):e000083. doi: 10.1136/bmjsem-2015-000083

6. Langer K, Simon C, Wiemeyer J. Strength training in climbing: a systematic review. *J Strength Cond Res*. (2023) 37(3):751–67. doi: 10.1519/JSC.0000000000004286

7. Stien N, Saeterbakken AH, Andersen V. Tests and procedures for measuring endurance, strength, and power in climbing-a mini-review. *Front Sports Act Living*. (2022) 4:847447. doi: 10.3389/fspor.2022.847447

8. Gronhaug G, Saeterbakken A. No pain no gain: a survey of use of healthcare and reasons not to seek healthcare by Norwegian climbers with chronic injuries. *BMJ Open Sport Exerc Med*. (2019) 5(1):e000513. doi: 10.1136/bmjsem-2019-000513

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Physical performance testing in climbing—A systematic review

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Due to the increasing popularity of climbing, the corresponding diagnostics are gaining in importance for both science and practice. This review aims to give an overview of the quality of different diagnostic testing- and measurement methods for performance, strength, endurance, and flexibility in climbing. A systematic literature search for studies including quantitative methods and tests for measuring different forms of strength, endurance, flexibility, or performance in climbing and bouldering was conducted on PubMed and SPORT Discus. Studies and abstracts were included if they a) worked with a representative sample of human boulderers and/or climbers, b) included detailed information on at least one test, and c) were randomized-controlled-, cohort-, cross-over-, intervention-, or case studies. 156 studies were included into the review. Data regarding subject characteristics, as well as the implementation and quality of all relevant tests were extracted from the studies. Tests with similar exercises were grouped and the information on a) measured value, b) unit, c) subject characteristics (sex and ability level), and d) quality criteria (objectivity, reliability, validity) were bundled and displayed in standardized tables. In total, 63 different tests were identified, of which some comprised different ways of implementation. This clearly shows that there are no uniform or standard procedures in climbing diagnostics, for tests on strength, endurance or flexibility. Furthermore, only few studies report data on test quality and detailed information on sample characteristics. This not only makes it difficult to compare test results, but at the same time makes it impossible to give precise test recommendations. Nevertheless, this overview of the current state of research contributes to the creation of more uniform test batteries in the future.

KEYWORDS

performance, strength, endurance, flexibility, bouldering, testing, measuring

1. Introduction

Climbing (lead climbing, speed climbing, bouldering) has become an increasingly popular sport attracting a growing number of researchers around the world. This has led to a constantly growing database with many insights into the performance-determining factors of climbing. A broad overview of this is given in **Figure 1**.

It has been shown that performance in climbing and bouldering depends on psychological, skill-related, anthropometric, tactical-cognitive, and on conditional factors (1). As shown by MacLeod et al. (2), Grant et al. (3), Laffaye et al. (4), and Saul et al. (1), one of the most important conditional factors in climbing is finger strength. Moreover, MacLeod et al. (2) found greater finger endurance in intermittent tests in climbers compared to non-climbers, and Saul et al. (1) emphasized the importance of aerobic forearm capacities and hand grip endurance. In addition to these factors, mental endurance, and anthropometric factors explained 77% of climbing ability in a study conducted by Magiera et al. (5). Laffaye et al. (4) found that 64% of the total variance in

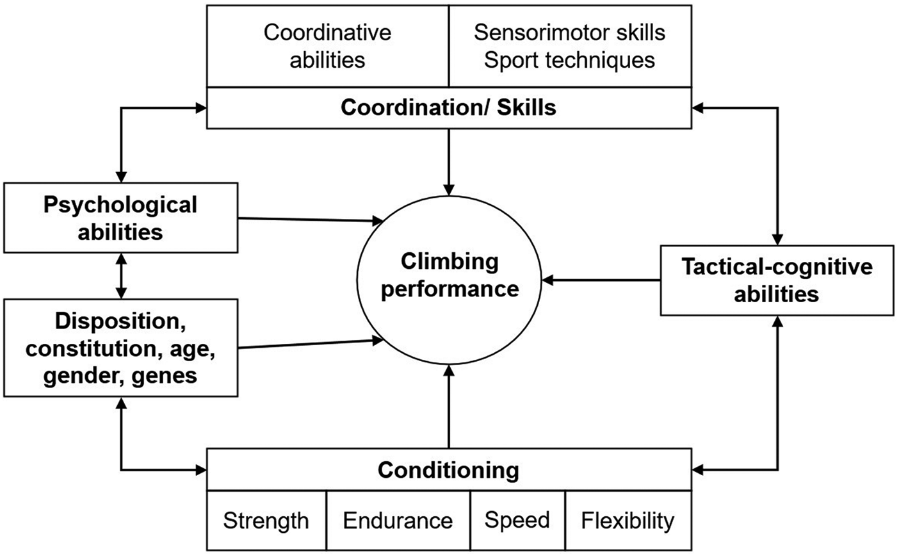

FIGURE 1
Performance structure of climbing (own figure).

climbing ability could be explained by trainable variables such as upper limb and finger strength and anthropometric variables such as body composition and biacromial breadth. Trainable variables including upper limb and finger strength, lower limb power, as well as shoulder and knee flexibility according to Mermier et al. (6) explained 58.9% of the total variance in climbing ability. In addition, Grant et al. (3) found greater shoulder girdle endurance and hip flexibility in advanced climbers compared to both recreational climbers and non-climbers, and Saul et al. (1) emphasized the importance of postural stability and selected anthropometric factors such as a low body fat percentage and large forearm volume for climbing ability. Furthermore, they described climbers as having high mental endurance and low in tension, depression, anger, and confusion. Although differences in the weighting of the various factors were found between the different climbing disciplines (4, 7–10), the overall requirements for the disciplines formally correspond to the same categories.

Based on the findings on performance requirements in climbing, research in the field of training to improve climbing ability has been increasing. Performance diagnostics in climbing have therefore become increasingly important in order to determine performance deficits and measure training effects. However, the diagnostic tests lack consistency and only few studies include quality assessments for the tests used.

Within this review climbing performance as an empirical indicator is defined as a measurable variable represented by a test score. Climbing ability on the other hand is defined as the potential to achieve high climbing performance and refers to the theoretical construct which all variables are set in relation to. It is assessed individually through self-reporting of ability level with the help of (inter-)national grading systems in each study.

The most important criteria for test quality are validity and reliability. Validity "refers to the degree to which evidence and theory support the interpretations of test scores for proposed uses of tests" (11). Therefore, validity is not a feature of the test itself but rather of test interpretation. Different subcategories of validity can be distinguished. This review especially addresses construct and criterion validity as two closely related concepts. Construct validity refers to "the concept or characteristic that a test is designed to measure" (11). Regarding physical climbing diagnostics, test interpretations have high construct validity when there is evidence that test scores represent theoretical components of climbing ability or tests show a predefined/theoretical factor structure; for example, correlation with self-estimated climbing ability or Cohen's d as a measure of the difference between different ability groups is an indicator of construct validity. Criterion validity refers to the correlation between a test score and a measured criterion variable (11), which in this case is climbing performance. For example, Spearman's and Pearson's correlation coefficients between test scores and climbing performance were used for assessing criterion validity.

High validity requires high reliability. Reliability refers to measurement consistency or in other words an acceptable measurement error allowing effective practical use of the measurement (12). In this review we will differentiate between intra-session and inter-session reliability referring to measurement consistency within and between sessions, respectively. The prerequisites for measurement consistency are a high conformity across raters (inter-rater reliability) and within the ratings of a single rater (intra-rater reliability) (12). Reliability can be measured with different tools. In this review intra-class correlation coefficient (ICC), concordance correlation coefficient (CCC), Spearman's and Pearson's correlation coefficient were considered. In addition, the coefficient of variation (CV) and the standard error of mean (SEM) were considered as indicators of reliability.

The heterogeneity of the tests and the lack of reports on test quality can lead to problems when comparing the effects of different training interventions (13). In addition, researchers, coaches, and athletes find it difficult to select appropriate tests for their diagnostic test batteries. Approaches to create and validate a sport-specific test battery for climbing revealed low construct validity in relation to climbing ability for most of the selected tests, as well as tests that only allowed differentiation between specific performance groups (14, 15).

The aim of this review was therefore to give an overview of the tests for performance, strength, endurance and flexibility in climbing and their quality in order to identify strengths and weaknesses of existing tests and to support more homogeneous test batteries for future performance assessments and quantification of training effects.

2. Methods

2.1. Search strategy and data sources

The literature research and analysis followed the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines (16), and the study selection process described by Meline (17).

A systematic literature search on PubMed and SPORTDiscus was performed in June 2022. Additionally, the retrieved articles were manually searched for additional articles possibly fulfilling the inclusion criteria. The search was conducted with the following terms: "performance", "strength", "force", "power", "endurance", "aerobic capacity", "anaerobic capacity", "flexibility", "agility", "boulder", "climb", "assess", "measur", "hand dynamomet", "test", "diagnostic". The wildcard symbol "*" and Boolean operators (OR and AND) were included to maximize and optimize the search.

2.2. Inclusion and exclusion criteria

To be included, studies had to be published in either English or in German. All studies including detailed information on at least one quantitative method of testing or measuring forms a) strength, b) endurance, c) flexibility, or d) performance in climbing and/or bouldering were included into the review. As we were interested in the quality of the tests in climbing and bouldering, only studies examining a representative sample of human boulderers and/or climbers were considered. In addition, studies had to contain detailed information on the subjects (age, sex, discipline, and experience) and report climbing ability levels using a recognized national or international scale. Randomized-controlled, cohort-, cross-over-, intervention- and case(-control) studies were included into the review. Publication types included were journal publications, dissertations, abstracts, and articles published in conference proceedings. Qualitative, explorative, and anecdotal research were not included into the review as they do not allow a quantitative analysis of the tests and measurements used.

2.3. Data extraction

The data on the diagnostic tests was extracted using a standardized form including sample characteristics (sample size, sex, discipline, ability level, age, experience, health), and variables related to each test and measuring method reported in the studies (test design, exercise, device, measured value, unit, reliability, validity). Reported grades for climbing and bouldering performance were standardized according to the International Rock Climbing Research Association (IRCRA) reporting scale (18).

2.4. Test classification and quality analysis

In a next step, the tests were sorted according to the exercises the subjects had to perform. For example, all tests in which the subjects had to do pull-ups were grouped together. Subsequently, the tests within each test group were classified according to a) measured values, b) exercise intensity (edge depth, percentage of MVC), c) exercise duration (time under tension/work time), d) involved body parts (fingers, upper limbs, lower limbs, core), and e) test execution (continuous or intermittent; isometric or dynamic). The quality of all tests within each test group in combination with sex and ability level of the respective subjects was then sorted according to the respective classification in a respective table. In a last step, the reliability and validity ranges for each test group were determined and summarized depending on the muscle groups (upper limbs, lower limbs, core, fingers) and the variable tested (strength, endurance, flexibility, or climbing performance). Regarding strength, a distinction was made between maximum strength, explosive strength (power), and strength endurance. In addition, strength endurance was divided into three subcategories. High intensity strength endurance was defined as maximum strength endurance (intensity: 90%–100%), submaximal strength endurance was defined as muscular endurance (intensity: 40%–80%) and explosive contractions to failure were defined as explosive strength endurance (intensity: 30%–60%, maximal power or rate of force development). Furthermore, static and dynamic flexibility as well as anaerobic and aerobic endurance were distinguished.

Correlations, effect sizes, and coefficients were rated as proposed by Akoglu (19), Koo and Li (20), Cohen (21), and Reed et al. (22) (**Table 1**). To facilitate understanding the different scales were transformed to a common three-point scale: low—middle-sized—high. In addition, we transformed r^2 values to r values in order to apply the three categories. SEM was evaluated for each study individually according to the recommendations by Denegar and Ball (23).

3. Results

3.1. Study selection and characteristics

A total of 1,128 studies were identified by searching PubMed and Sport DISCUS. By manually searching the reference lists of these articles, 51 further studies were identified. After the removal of the duplicates and 463 studies, which did not fulfill the content or language requirements, 187 full texts were assessed for eligibility. Due to different reasons such as insufficient content relevance or inadequate study design,

TABLE 1 Ratings of correlations, effect sizes, and coefficients.

Parameter	Grading	
ICC	<0.5	– Poor
	0.5–0.75	– Moderate
	0.76–0.89	– Good
	≥0.9	
CCC	<0.90	– Poor
	0.9–0.95	– Moderate
	0.96–0.98	– Substantial
	≥0.99	– Almost perfect
Pearson's and Spearman's r	0	– No correlation
	0.1–0.3	– Weak
	0.4–0.6	– Moderate
	0.7–0.9	– Strong
	1	– Excellent
Cohen's d	< 0.2	– Negligible
	0.2-<0.5	– Small
	0.5-<0.8	– Medium
	≥0.8	– Large
CV	≤ 20%	– Acceptable
	>20%	– Poor
Own terminology		
No correlation, negligible	– No correlation	
Poor, weak, small	– Low	
Moderate, medium	– Middle-sized	
Good, substantial, strong, large	– High	
Excellent, almost perfect	– Very high	
Acceptable	– Acceptable	
Poor	– Poor	

ICC, intraclass correlation coefficient; CCC, concordance correlation coefficient.

31 studies were excluded. In the case of six studies (24–29), the abstract was found to provide sufficient information to include the conducted tests into the study. Ultimately, 156 studies were included in the review (Figure 2).

Figure 3 shows the climbing ability of the various samples investigated in the studies according to the IRCRA reporting scale (18). It also gives an overview of the number of studies focusing on similar sample characteristics regarding climbing ability. While 32 studies included advanced to elite climbers, 27 focused on intermediate to advanced athletes. Only one study exclusively included higher elite climbers while four studies each included lower grade to higher elite and elite to higher elite climbers. Three studies focused on intermediate to higher elite and two on advanced to higher elite climbers. Thirteen and ten studies dealt with climbers from the intermediate and lower levels to the elite, respectively. In seven, five, and six studies only lower grade, advanced, intermediate and elite climbers were considered, respectively. Four studies each included lower grade to intermediate and lower grade to advanced climbers. Nineteen studies did not report the climbing ability of their sample.

Within the studies a total of 429 strength, endurance, flexibility and performance tests were identified. 53% of the studies included upper limb and finger strength tests, 23% included climbing performance tests, 7% included lower limb flexibility tests, 5% each included core strength and lower limb strength tests, 3% each included upper and lower limb endurance tests, and 1% included upper limb flexibility tests (Figure 4).

3.2. Findings

A total of 66 test groups were identified. For many of these, many different ways of implementation of the respective tests were found. Seven tests measuring tactics, technique, hip flexibility, core strength endurance, and upper limb and finger strength endurance and maximum strength, were not included into the analysis as the studies did not include enough

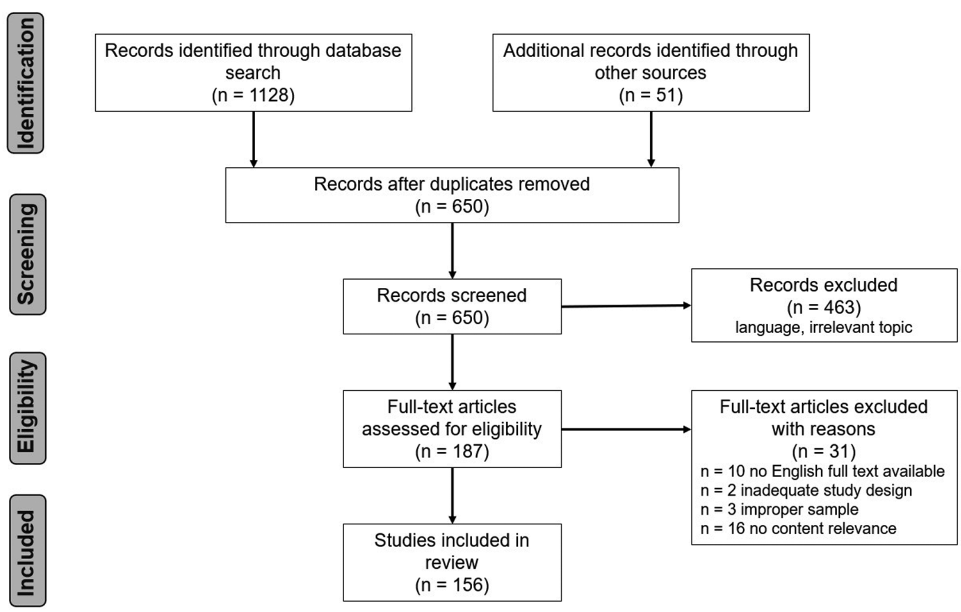

FIGURE 2
PRISMA flow diagram.

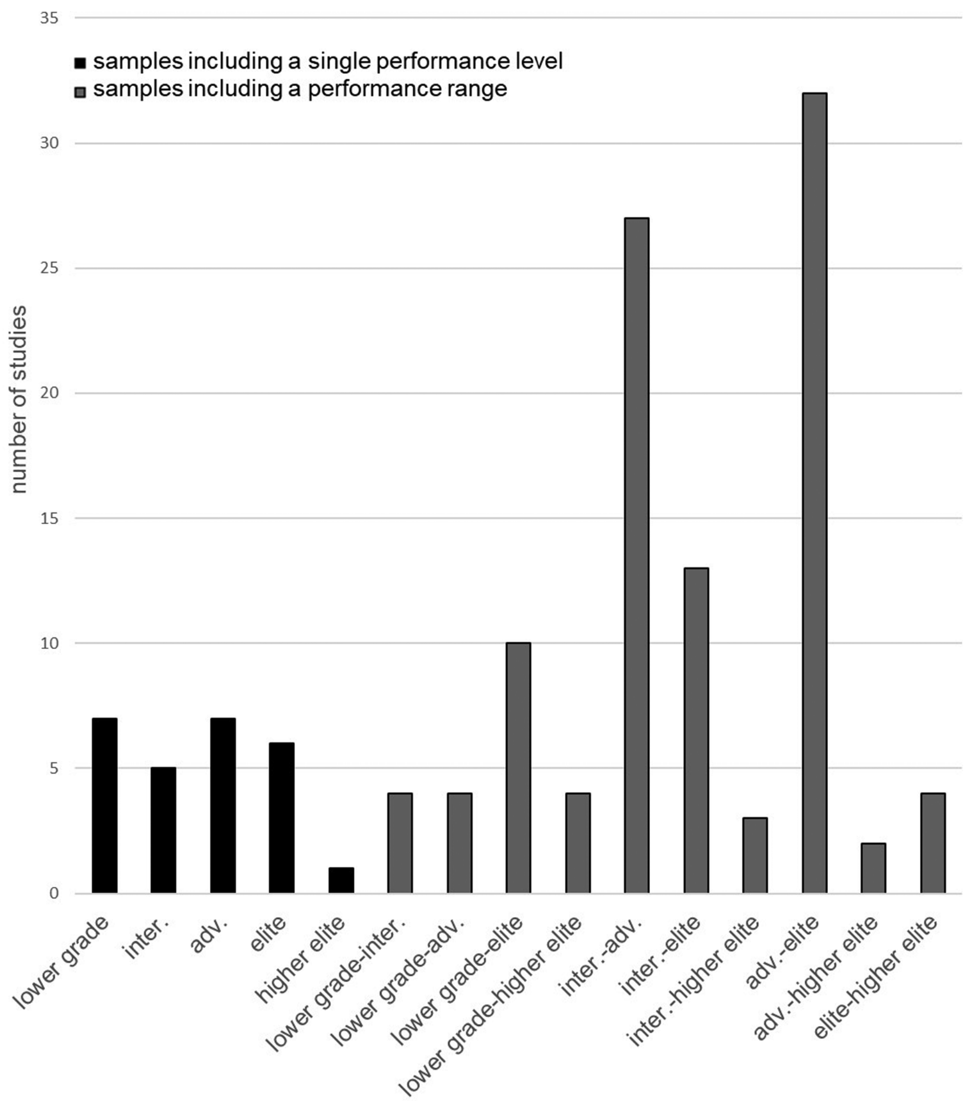

FIGURE 3
Overview of the samples in the included studies.

information on the test execution (5, 30, 31). One test examining route reading skills conducted by two studies (15, 32) was also not included into the analysis as it does not relate to physical climbing skills. One study conducted a 100-metre run (33). This test was also not included into the analysis due to its lack of specificity.

The tables presenting the quality of all tests within a test group in combination with sex and ability grading of the respective subjects can be found in the supplementary material (**Supplementary Material Tables S1–66**). **Tables 2**–**9** sum up the reliability and validity ranges for each test group.

3.2.1. Climbing performance

Climbing performance tests (**Table 2**) take on a special position. This is due to the fact that the measured value through the following tests highly depends on the design of the climbing wall:

- *P*epeated ascent of one boulder
- *B*ouldering in a circuit
- *T*readwall climbing
- *T*raverse bouldering
- *T*op-rope and/or lead climbing
- *B*ouldering

Other tests work with a standardized wall design:

- *P*ock over climbing test
- ne speed climbing run
- Speed climbing start

Medernach et al. (34) reported a high inter-session reliability and a high correlation between climbing ability and the test results for the repeated ascent of one boulder. Deyhle et al. (36) asked their subjects to boulder in a circuit following the rhythm of a metronome until exhaustion while Limmer et al. (26) only state

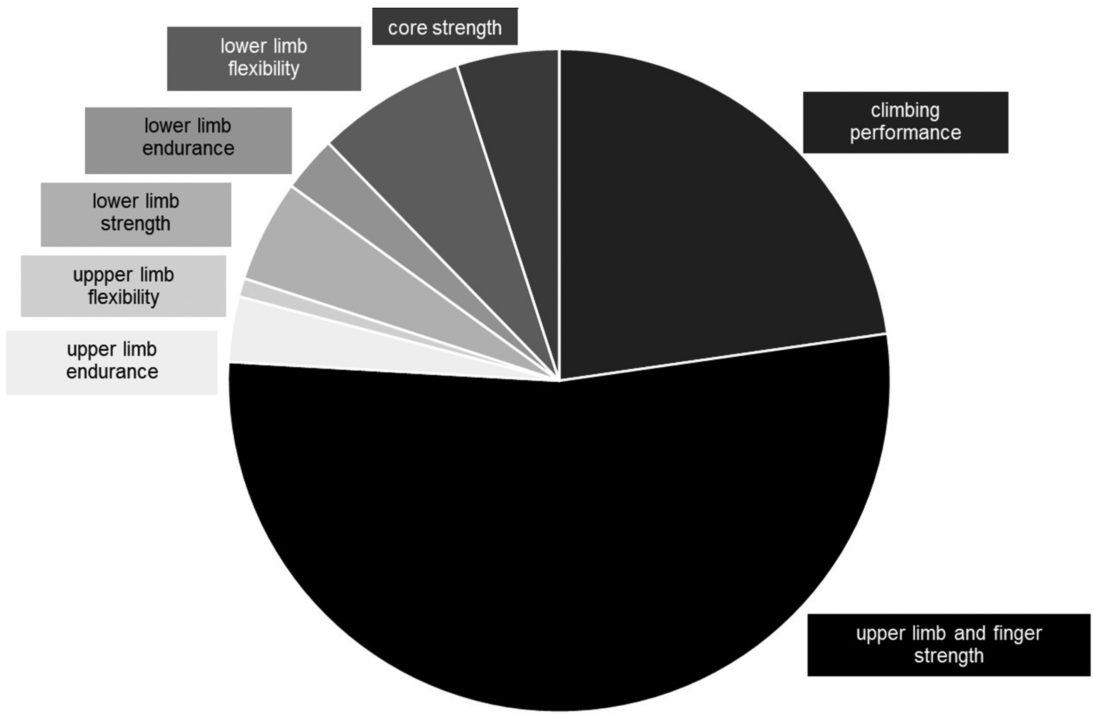

FIGURE 4
Overview of the distribution of tests within the identified studies.

TABLE 2 Reliability and validity measures for climbing and bouldering performance tests.

Bouldering/climbing	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Repeated ascent of 1 boulder (34, 35)	*Bouldering/climbing E*	Inter session: *r* = .99 (34)	*r* = .87 (34)
Boulder in a circuit (26, 36, 37)	*Bouldering/climbing E*	–	*r* = -.84 –.43 (37); *r* = .88 (37)
Boulder traverse (38, 39)	*Bouldering/climbing E*	–	*r* = .52 –.94 (38)
Treadwall climbing (40–47)	*Bouldering/climbing E*	Inter-session: *r* = .99 (40)	*r* = .81 –.91 (41, 42); *r* = -.66—−0.28 (43); d = .02–1.46 (41)
Top-rope and lead climbing combined (28, 48)	*Climbing E*	–	–
Outdoor climbing (49)	*Climbing E*	–	–
Rock over climbing test (50)	*Bouldering/climbing ability*	Inter-session: ICC = .90 (50)	–
Bouldering (7, 51–55)	*Bouldering ability*	–	*r* = -.47 –.39 (52)
Top-rope climbing (24, 56–71)	*Climbing E/ability/speed*	Inter-session: ICC = .97 (59); *r* = 0.10–0.48 (62); d = 0.69 (62)	–
	Climbing kinematics	Inter-rater: *r* = .88 (70)	*r* = .99 (68)
	Climbing dynamics	–	–
Lead climbing (6, 7, 28, 72–77)	*Climbing E/ability*	Inter-session: *r* = .81 (6)	*r* = .45 –.69 (73); *r* = .77 (6)
	Climbing kinematics	Inter session: *r* = .71 –.92 (74) Inter-rater: r > .81 (74)	–
	Climbing dynamics	–	–
Speed climbing start (78)	*Speed climbing dynamics*	–	–
1 speed climbing run (33, 79)	*Speed climbing ability*	–	–

E, Endurance.

that their subjects had to do some lap climbing. Both do not report any test quality data.

Both Michailov et al. (38) and Sas-Nowosielski et al. (39) tried to assess climbing performance through a boulder traverse. Sas-Nowosielski et al. (39) included a hard traverse with crimp and half-crimp holds and an easy traverse with pinch holds which the subjects had to climb back and forth until exhaustion. Michailov et al. (38) also included two routes, one of which had holds with an inclined contact surface and the other holds with a horizontal contact surface. Sas-Nowosielski et al. (39) did not provide test quality data. Michailov et al. (38) on the other hand report a high correlation between time to failure and climbing ability for the hard traverse and a middle-sized correlation for the easy traverse.

Treadwall climbing was used as a diagnostic tool by Schoeffl et al. (40) who report a high inter-session reliability. They had asked their subjects to climb a given route on a treadwall at constant speed and inclination until exhaustion. Studies by Baláš et al. (41) and Limonta et al. (42) report high to very high correlations between treadwall peak angle, systemic $\dot{V}O_2$ from submaximal climbing, local muscle tissue oxygen saturation (StO_2) from submaximal climbing, and muscle oxygenation breakpoint and climbing ability. Baláš et al. (41) conducted a test in which the subjects started at an inclination of 0° and had to climb until exhaustion, with the inclination of the treadwall increasing by 5° every minute. They also found low to high differences between intermediate and elite climbers regarding Treadwall peak angle. In another study Baláš et al. (43) conducted a similar test starting at +6° and an increasing angle of inclination of -3° per minute to identify the critical angle and multiple exhaustive tests at various fixed angles to estimate the critical angle. While the peak angle reached during the incremental test showed middle-sized correlations to both climbing and bouldering ability, the estimated critical angle showed only low correlations to climbing and bouldering ability.

Limonta et al. (42) conducted a discontinuous test in which the subjects started with 5 min of baseline measurements followed by the same two workloads, controlled over the speed, for all participants and three more workloads, each lasting 4 min, with 5 min of rest in between according to individual cardiorespiratory response to reach peak aerobic power in 5 workloads. Booth et al. (44) conducted a test with a similar protocol including three trials at increasing velocity and 20 min rest between the trials. Fryer et al. (45), Potter et al. (46), Booth et al. (44), and España -Romero et al. (47) do not report quality data. While Fryer et al. (45) and España -Romero et al. both conducted an incremental test, Fryer et al. (45) gradually increased the inclination of the wall, with the subjects starting at different angles according to their climbing ability, whereas España-Romero et al. (47) gradually increased the climbing speed. Potter et al. (46) asked their subjects to do three self-paced climbs on the treadwall until exhaustion. Baláš et al. (37) measured mean oxygen consumption and heart rate during bouldering in a circuit until exhaustion with an increase in wall inclination by 10° every three minutes. They reported a high negative correlation between mean oxygen consumption and climbing ability and a middle-sized negative correlation between heart rate and climbing ability. Additionally, they found a high correlation between climbing ability and the wall inclination at the moment of exhaustion. Deyhle at al (36). and Limmer et al. (26) did not provide any quality data.

Top-rope climbing was used in several different ways to assess multiple different factors of climbing performance. Jurrens (56) and Kingsley (57) provided 12 climbing routes with various levels of difficulty and awarded points for each handhold reached by the participants. Barton (58), and McNamee and Steffen (59) conducted a similar test. The subjects started with a route of their choice. If they reached the top, they continued with the next more difficult route. If they did not reach the top, they continued with an easier route. At the end, the highest grip reached on the most difficult route was counted if the next easier route was topped. Fraser (60) determined the highest hold achieved on the most difficult route attempted. Heyman et al. (61) asked their subjects to climb a route twice to volitional exhaustion. If they reached the top they immediately started again from the bottom. The test conducted by Limmer et al. (62) is very similar. Their subjects were asked to climb a route as often as possible with no rest in between the attempts. Hermans et al. (63) and Hermans (64) assessed the point of failure of each subject in a route they were asked to climb to failure once. While the participants in the study of Valenzuela et al. (65) had to cover as much distance as possible in one route within two minutes, Bertuzzi et al. (66) assessed the distance climbed up and down a route in three minutes. Sanchez et al. (67), Seifert et al. (68, 69), Jones et al. (70), and Mitchell et al. (24) assessed different factors while their subjects climbed one to three routes at their own pace. The participants of a study by Baláš et al. (71) however, climbed a route up and down twice at a given pace. Vertical reaction force under each foot was assessed. McNamee and Steffen (59) reported a very high inter-session reliability for their test for climbing ability. Limmer et al. (62) reported low to middle-sized correlation between test trails for time to failure and post activity lactate levels. Additionally, they reported middle-sized differences for post activity lactate levels between trials. Jones et al. (70) assessed climbing kinematics through the score on an observer scale and found a high correlation between the ratings by different experts. No further quality data were reported on top-rope climbing tests.

Lead climbing was also used as a diagnostic tool to assess climbing ability, endurance, kinematics, and dynamics. Multiple authors (6, 7, 72–74) have asked their subjects to climb one or two routes until failure. Magiera et al. (75) have assessed mean climbing difficulty through the performance of the subjects on multiple routes. Assessing performance during a competition is a tool used by Sanchez et al. (76) and Fuss et al. (77). Magiera et al. (75) reported a high correlation between the climber's performance on different routes. Middle-sized to high correlations were found by Taylor et al. (74) for the expert ratings between sessions and high correlations between the ratings of various experts regarding technical and tactical factors. The only data on test validity for lead climbing are reported by Gajewski et al. (73) and Mermier et al. (6). The former found a middle-sized correlation between climbing ability and post-exercise lactate recovery. The latter report a high correlation between the trainable variable in climbing, including climbing rating, and multiple power, and flexibility measurements, and climbing ability. Few studies assessed climbing endurance through a mixture of top-rope and lead climbing, or outdoor climbing, but did not provide data on the quality of the tests (28, 48, 49).

Brent et al. (50) have tried to assess bouldering or climbing ability through a complex test called the rock over climbing test.

They reported a high inter-session reliability but did not provide any data on the correlation with climbing ability.

Numerous studies have investigated bouldering ability through bouldering itself, using different approaches. White and Olsen (51) conducted a competition-like bouldering test with five 5 boulder problems for which the participants had six minutes each to solve and another six minutes rest in between. Zemtsova and Vavaev (52) observed the performance of their participants at the world championships 2018 in Innsbruck and 2019 in Hachioji including five boulder problems. The participants of the study by Frauman had to solve three boulder problems within five minutes each and five minutes rest in between. Stien et al. (7, 53) included three and four boulder problems respectively and gave the subjects four minutes to solve each of them and a three-minute rest between the boulder problems. Nichols et al. (54) also included three boulder problems. The only study reporting quality data were Zemtsova and Vavaev (52). They report middle-sized negative to middle-sized positive correlations between the test outcomes and climbing ability for multiple factors assessed (number of attempts per top and zone, number of grips, attempt time, recovery time, climbing time, and viewing time).

Speed climbing ability and speed climbing dynamics were assessed through the time taken for one speed climbing run (33, 79) and the directions of the mean forces during the speed climbing start (78). All three studies did not provide any information on the reliability of the tests or the correlation of their outcomes with (speed-) climbing ability.

In summary, climbing performance was assessed through nine different tests differentiating between climbing endurance, ability, kinematics, and dynamics. No study reported both reliability and validity data for any of the tests. However, the repeated ascent of one boulder, treadwall climbing, the rock over climbing tests, and top-rope climbing were shown to be highly reliable. The highest correlation with climbing ability was reported for the repeated ascent of one boulder.

3.2.2. Upper limb and finger strength

The following tests were used to assess upper limb and finger strength (**Table 3**):

- Dead hang
- *B*ent arm hang
- Pull-up
- Push-up
- Campus board performance test
- *B*ench press
- Pull down
- *T*raction test
- *M*edicine ball throw
- Shoulder strength tests
- *B*iceps strength test
- *E*lbow strength tests
- Power-slap test
- *A*rm jump test
- Gripping a dynamometer
- *A*pplying force on a hold
- Pinching a dynamometer

The dead hang was used to assess finger isometric muscular endurance in continuous and intermittent tests. It was also used to assess finger isometric maximum strength by holding maximum weight for 3–7 s. A mixture of muscular endurance and maximum strength was assessed by hanging to failure on very narrow edges or the one-arm dead hang. The implementation of the test varies substantially in terms of the grip type, the edge depth and the grip width used. High to very high inter-session reliability is reported for the tests on finger isometric intermittent muscular endurance and finger isometric maximum strength. Medernach et al. (34, 80) worked with a hang to rest ratio of 8:4 s on a 30 mm edge with open crimp. Bergua et al. (81) used a 40 mm edge and let their participants (advanced to elite males and females) choose between open- and half crimp, whereas López-Rivera and Gonzáles-Badillo (82) used a 15 mm edge when testing elite climbers and allowed half crimp only. The reliability of the dead hang tests to assess sustained isometric muscular endurance of the fingers is reported to be very high by Bergua et al. (14 mm or 25 mm edge with open- or half crimp) (81), Draper et al. (14) (30 mm edge with self-chosen grip), and López-Rivera and Gonzáles-Badillo (11 mm edge with half crimp) (82). Ozimek et al. (83) used a metal bar instead of an edge and reported a low to high inter-session reliability for elite male climbers. No reliability data is provided for tests combining muscular endurance and maximum finger strength. Validity data is reported for the sustained muscular endurance tests. The correlations between the test results and climbing ability cover a wide range. Bergua et al. (81) report high negative correlations for the minimum edge depth the participants could hang from for 40 s. Baláš et al. (84) and Kitaoka et al. (27) report high to very high positive correlations for maximum hangtime and post exercise lactate concentrations, respectively. Middle-sized to high correlations are reported between finger isometric maximum strength test results and climbing ability.

Like the dead hang, the bent arm hang was implemented with various grip types, edge depths and shoulder widths. Time to failure was assessed during a unilateral or a bilateral bent arm hang. Augste et al. (15) also assessed maximum weight held for 3 s in a unilateral bent arm hang. Thus, through different implementations, the bent arm hang can be used to assess upper limb isometric muscular endurance and maximum strength. If small holds are used, finger isometric maximum strength or muscular endurance also play a role in this test. Studies providing data on inter-session reliability, report very high ratings, including acceptable CV values, for the test design used in the IRCRA test-battery (14) and very high correlations between sessions for the maximum weight held for 3s in a one arm bent arm hang (15). Low to high correlations between test results and climbing ability were reported. Additionally, Mermier et al. (6) report a high correlation between the strength and the endurance component, including other strength and endurance tests, and climbing performance tested on multiple routes.

TABLE 3 Reliability and validity measures for upper limb and finger strength tests.

Upper limb and finger strength	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Dead hang (14, 15, 25, 27, 31–34, 54, 62–64, 80–93)	*Finger iso. ME*	Inter-session: ICC = .13—>.99 (14, 81–83), CV% = 18.0 (14), CV% = 23.4–29.9 (83), CV% = 12.8 (82)	*r* = -.26 –.87 (27, 62, 81, 83, 85, 87, 88); *r* = .90 –.93 (84)
	Finger iso. inter. ME	Inter-session: ICC = .97 (80); *r* = .86 (34)	–
	Finger iso. MS	inter-session: ICC = .93 –.99 (81, 82), CV% = 7.8 (82)	*r* = .58 –.84 (81, 83)
	Finger iso. ME/MS	–	–
Bent arm hang (3, 6, 14, 15, 30, 31, 46, 54, 63, 64, 82, 84, 94–99)	*Upper limb + finger iso. SE/MS*	Inter-session: ICC = .89, CV% = 15.0 (14); *r* = .97 –.99 (15)	*r* = .23—>.80 (15, 84, 94, 99) *r* = .77 (6)+
Pull-up (3, 7, 14, 31, 33, 46, 53, 54, 83, 85, 87, 89, 94, 95, 97, 100–106)	*Upper limb con. MS*	Inter-session: ICC = .84 –.99, CV% = 1.0–6.62 (100)	–
	Upper limb ESE	–	–
	Upper limb con.-ecc. ME	Intra-session: ICC = .97, CV% = 14.0 (14) Inter-session: ICC = .96 –.99 (14, 102), CV% = 14.0 (14)	*r* = .08 –.72 (83, 94)
	Upper limb + finger con.-ecc. MSE	–	–
	Upper limb + finger iso. MS	–	–
	Upper limb iso. ES and Upper limb + finger MS	Intra-session: ICC = .88 –.99, CV% = 9.1–12.9 (103)	*r* = .61 –.77 (85)
Pinch a dynamometer (3, 6, 24, 94, 95, 97, 102, 107–110)	*Pinch/pincer iso. MS*	Intra-session: r > .99 (108)	*r* = .22 –.59 (94, 109, 110); *r* = .77 (6, 95); CCC = .99 (107) *r* = .77 (6)+ (performance on multiple routes combined)
Grip a hand dynamometer (3, 4, 6, 24, 34, 38, 45–47, 49, 56, 57, 61, 62, 65, 73, 75, 80, 83–85, 94–97, 99, 109, 111–129)	*Hand iso. MS*	Intra-session: ICC≤.97 (4, 117), CV% = 3.2 (4) Inter-session: ICC = .91 –.98 (80, 112) Intra-rater: ICC = .88 (118)	*r* = -.96 –.72 (24, 73, 94, 95, 99, 121, 123) *r* = .77 (6)+; *r* = -.97—-.88 (24)+; *r* = .11 (121)+
	Hand iso. ES	–	–
	Hand iso. MS + ES	Intra-session: ICC = .94 –.99, CV% = 3.79–22.96 (115) Inter-session: ICC = .83 –.98, CV% = 4–6 (119)	–
	Hand iso. ME	–	*r* = .76 (6)+
	Hand inter. iso. MSE	Inter-session: ICC = .93, CV% = 3.2 (4)	*r* = -.60 (62)
Apply force on hold (2, 7–9, 14, 15, 24, 29, 32, 35, 38, 41, 47, 54, 90, 93, 96, 99, 101, 105, 106, 109, 110, 117, 122, 130–155)	*Finger iso. ES + MS*	Intra-session: ICC = .21 –.99 (130, 140), CV% = 2.64–28.34 (140) Inter-session: ICC = .40 –.94 (130); 0.60 < *r* < 0.80 (140)	*r* = .65-.76 (130)
	Finger iso. (inter.) ME	Intra-session (sus + inter): ICC = .85 –.92 (138) Inter session (inter): ICC = .29–91 (130, 142), CV% <2.5 (142)	Sus: *r* = -.26 –.72 (110, 138, 156); d = .44–1.47 (41); *r* = .76 (41) Inter: *r* = —27 –.19 (156); d = .07 –.33 (41); *r* = .65 (41)
	Finger iso. (inter.) MSE/CF	Intra-session (sus): ICC = .85 –.92 (138) Inter session (sus): ICC = .92 –.94 (130); (inter):.87 –.96 (132)	Sus: *r* = 80 –.82 (138, 156); *r* = .65–73 (130) Inter: *r* = .60 (99); *r* = .51 –.78 (132)
	Finger iso. (inter.) MS	Inter-session (sus): ICC = .88 –.92 (96, 130, 144), CV % = 2.2 (96); *r* = .88 –.99 (136, 143) Intra-session (sus): ICC = .97 –.98 (117); *r* = .88 –.95 (136, 138); Cronbach's alpha = .99 (110)	Sus: *r* = -.96 –.81 (2, 24, 99, 110, 136, 138, 144, 156); *r* = .04 –.92 (41, 95, 130, 131, 134, 147) *r* = -.94—-.77 (24)+, *r* = .43 –.67 (131)+
	Finger + wrist con.-ecc. MS	–	*r* = .57 (133)
Power-slap test (4, 14, 31, 32, 53, 54, 112, 134, 157, 158)	*Upper limb con. ES*	Intra-session: ICC = .98, CV%<4.89 (157) Inter-session: ICC = .95 –.98 (14, 112, 157, 158), CV% <4.89 (157), CV%=7.0 (14)	*r* = .69 –.73 (14, 157, 158)
	Upper limb con. ESE	–	–
Medicine ball throw (31, 112)	*Upper limb ES*	Inter-session: ICC = .96 (112)	–
Elbow strength tests (159)	*Upper limb MS*	–	*r* = .51 –.63 (159)
Biceps strength test (95)	*Biceps MS*	–	*r* = .29 –.45 (95)
Shoulder strength test (6, 160)	*Shoulder con.-ecc. MS*	–	–
	Shoulder con. MS	–	*r* = 0.77 (6)+
Push-ups (31)	*Upper limb ESE*	–	–
Campus board performance (39, 53)	*Upper limb ESE*	–	–
Arm jump test (161)	*Upper limb (ecc.)-con. ES*	–	–
Bench press (4)	*Upper limb con. ES + MS*	–	–

(*continued*)

TABLE 3 Continued

Upper limb and finger strength	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Pull down (63, 64)	*Upper limb con.-ecc. MSE*	–	–
Traction test (139)	*Upper limb con. ES*	–	–
	Upper limb con.-ecc. ME	–	–

CF, critical force; MS, maximum strength; ME, muscular endurance; ES, explosive strength; MSE, maximum strength endurance; ESE, explosive strength endurance; iso., isometric; con., concentric; ecc., eccentric; sus, sustained contraction; inter, intermittent contraction; CV, coefficient of variation; +, criterion validity (correlation with climbing performance test scores).

The pull-up was used to assess upper limb explosive strength (endurance) (33, 100, 101) and muscular endurance (14, 83, 94, 102). Furthermore, it was used to measure upper limb and finger maximum strength (endurance) (31). The isometric pull-up was implemented to assess upper limb isometric explosive strength (85, 103) as well as upper limb maximum strength and finger maximum strength (if small holds were used). Inter- and intra-session reliability measures, ranging between high and very high, were reported for multiple different pull-up variations (14, 102, 103, 111). Muscular endurance measures through the number of pull-ups performed show no to middle-sized correlation to climbing ability (83, 94). Middle-sized correlations were also found for peak force, and rate of force development (RFD) measured during an isometric pull-up by Vereide et al. (85).

Multiple tests such as push-ups, campus board performance, bench press, pull down and a traction test were used to assess upper limb explosive strength (endurance) and maximum strength (endurance). However, no quality data on any of these tests were reported.

Upper limb explosive strength was also assessed by measuring the maximum distance of a medicine ball throw. While no data on the correlation of the test measures with climbing ability were reported, Cochrane and Hawke (112) report a very high inter-session reliability.

For a test implemented by Mermier et al. (6) to assess shoulder concentric maximum strength, no quality data are being reported, except for a high correlation between shoulder strength and other strength and endurance tests, and climbing performance, measured on multiple routes. Wong (160), who tested eccentric and concentric strength of the shoulders did not provide any test quality data.

The only test implemented to specifically measure biceps maximum strength was conducted by MacKenzie et al. (95) who report a low to middle-sized correlation to climbing ability.

Augustsson et al. (159) were the only ones to examine elbow maximum strength in four tests including elbow flexion, extension, pronation, and supination. While no data on test reliability was reported, middle sized correlations to bouldering ability were reported.

The power-slap test is one of the most common tests used to assess upper limb explosive strength in climbers. Authors have measured the maximum height slapped with one hand or both hands at the same time and the highest rung reached and held for two seconds with one hand, respectively. Very high inter- and intra-session reliability were reported for the maximum height slapped with both one and two hands by multiple studies. However, no correlations with climbing ability were reported. The same is the case for quality data on the measurement of the fatigue index during multiple power-slaps to assess explosive strength endurance as conducted by Laffaye et al. (4).

Abreu et al. (161) asked their participants to perform an arm-jump test. This test is similar to the power slap test with both hands but instead of slapping the wall, the subjects are asked to reach and hold the highest possible rung. No quality data on measuring upper limb explosive strength through this test are reported.

Force parameters of the hand and fingers were assessed in multiple different ways. Three groups of tests were identified.

Firstly, hand dynamometers were used to measure hand force, which requires the use of the opposing thumb. Various different arm positions (shoulder flexion, elbow flexion, shoulder ab-/adduction), hand position (supination), and body positions (sitting or standing) were applied. In addition, the forearm was supported in some studies. Isometric maximum hand strength was assessed by measuring (mean) maximum force. Intra-rater reliability was reported to be high. In addition, intra-and inter-session reliability were reported to be very high. A very high negative correlation between the test results and top rope climbing time was reported by Mitchell et al. (24), while other authors have reported low to high positive correlations with top rope climbing time and self-reported climbing ability. Hand isometric explosive strength was assessed measuring RFD. No quality data are reported for these tests. Few studies measured both maximum strength and explosive strength during one test. Middle-sized correlations to climbing ability are reported for these tests and they show a very high intra- and inter-session reliability. Hand isometric muscular endurance was also tested through handheld dynamometry. Subjects were asked to maintain 50 or 80% of their MVC for as long as possible. While no data on the reliability of these tests are reported, Mermier et al. (6) report a high correlation between a group of strength and endurance tests including a handheld dynamometry test at 50% of MVC until exhaustion, and climbing ability. Moreover, hand intermittent isometric maximum strength endurance was assessed by measuring maximum force and fatigue index during repeated MVCs. A very high inter-session reliability and a middle-sized negative correlation with climbing ability are reported.

Secondly, finger strength without an opposing thumb was conducted by applying force on holds. Different hold types, hold depths, and various finger positions (slope crimp, half crimp, open crimp, pinch, jug, and sloper) were used. Furthermore, different arm positions (shoulder flexion, elbow flexion, shoulder ab-/adduction), and body positions (sitting, standing, hanging, crouching or leaning over a table) were applied. The forearm was supported during the tests in some studies. A combination of finger isometric explosive and maximum strength was assessed through one explosive MVC. Intra- and inter-session reliability were reported as low to very high. The test results explained 65% to 73% of the variability in climbing ability as reported by Michailov et al. (130). Finger isometric muscular endurance was assessed in both sustained and intermittent tests. Intra-session reliability for both variants was reported as high to very high. Inter-session reliability was only reported for the intermittent tests and ranged from low to very high. The correlation between the results from the sustained tests with climbing ability ranged from low negative to high positive. As reported by Baláš et al. (41), the test results were able to explain 56% of the variability in climbing ability. Furthermore, they found significant low to high differences between the test results of intermediate and advanced climbers. The correlation between the results from the intermittent tests with climbing ability ranged from low negative to low positive. As reported by Baláš et al. (41), the test results explained 43% of the variability in climbing ability. Furthermore, they found low but significant differences between the test results of intermediate and advanced climbers. In addition, Wall et al. (131) and Mitchell et al. (24) report high negative to middle-sized positive correlations with climbing performance on multiple routes and top-rope climbing time, respectively.

Finger maximum strength endurance and finger flexor critical force (132) were assessed through sustained and intermittent MVCs until failure, respectively. Intra-session reliability was reported to range between high and very high for the sustained tests. Inter-session reliability was reported to be very high for the sustained tests and high to very high for the intermittent tests. While high correlations to climbing ability were reported for the sustained tests, middle-sized correlations were reported for the intermittent tests. Tests assessing solely finger isometric maximum strength through intermittent and sustained contractions are reported to have a very high intra- and inter-session reliability. The correlation between the test results ranges from highly negative as reported by Mitchell et al. (24) to highly positive. One study by Schweizer and Furrer (133) assessed finger and wrist concentric-eccentric maximum strength with an especially designed apparatus. They reported a middle-sized correlation to climbing ability.

Thirdly, isometric pinch or pincer (only thumb and index finger) maximum strength were also assessed with a dynamometer. Depending on the study, different body positions were applied during the test. This includes shoulder and elbow flexion, body position (standing or sitting) and the fingers included into the pinch (I/II | I/III | I/II-III | I/II-IV | I/II-V). Studies report a high inter-session correlation and low to middle-sized correlation with climbing ability. Mundry et al. (107) report a high correlation with climbing ability. They had asked their participants to pinch a dynamometer while sitting on a chair with the upper arm leant on the thorax, the elbow at a 90° angle and the hand in a pronated position.

TABLE 4 Reliability and validity measures for upper limb endurance tests.

Upper limb endurance	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Rowing ergometry (162–164)	*Con.-ecc. E*	–	$r = .85$ (162)
	Con. MS	Inter-session: ICC = .79 –.85 (163)	$r = .72$ –.73 (163)
Arm crank ergometry (30, 49, 95, 165)	*Con.-ecc. E*		$r = .20$ –.56 (95)

MS, maximum strength; E, endurance; con., concentric; ecc., eccentric.

In summary, a total of sixteen tests for assessing upper limb and finger strength in climbing were identified. Several tests were used in multiple ways to assess different types of strength (maximum strength, muscular endurance, explosive strength, explosive/maximum strength endurance). Furthermore, test implementation varied greatly between the different studies. It was found that most tests still lack reliability assessment and validation. Few tests were reported to be highly reliable. This includes dead hang, bent arm hang, pull up, pinching a dynamometer, applying force on a hold, and the power-slap test. Due to the variety of test implementations, correlation ranges are large for most of the tests. Some of the highest correlations with climbing ability were reported for applying force on a hold or pinching a dynamometer.

3.2.3. Upper limb endurance

Upper limb endurance was assessed by two tests (**Table 4**):

- Arm crank ergometry
- Rowing ergometry

Arm crank ergometry was used in several studies and different values such as maximum and average power, maximum force, maximum oxygen uptake, time to failure, and heart rate were measured. No data on the reliability of arm crank ergometry are reported and while Pires et al. (165) found significant differences between climbers and non-climbers regarding VO_2-peak, the correlation with climbing ability was reported to be only low to middle-sized (95).

A high correlation with climbing ability was, however, found for maximum oxygen uptake during rowing ergometry by Michailov et al. (162). Marino et al. (163) used rowing ergometry to assess upper limb concentric maximum strength. The measurement through the one repetition maximum indicates a high reliability and a high correlation with climbing ability.

In summary, two tests were used to assess upper limb endurance in climbing but only few validity and reliability measures have been reported to this date.

3.2.4. Upper limb flexibility

Upper limb flexibility was tested through two tests (**Table 5**):

- Shoulder abduction and flexion
- Shoulder flexibility test

TABLE 5 Reliability and validity measures for upper limb flexibility tests.

Upper limb flexibility	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Shoulder flexibility test (6, 134)	*Shoulder active dynamic FLEX (overhead)*	–	–
Shoulder abduction and flexion (6)	*Shoulder active static FLEX (range of motion)*	–	r = .14 (6)+

FLEX, flexibility; +, criterion validity (correlation with climbing performance test scores).

Mermier et al. (6) assessed shoulder abduction and flexion through a test for the maximum active range of motion while standing with palms facing inward. Giles et al. (134) instead assessed the minimum distance between both hands gripping the same wooden stick that allowed for a full overhead rotation of the said stick without bending the arms. None of the two studies reported reliability measures. Validity measures were only reported by Mermier et al. (6) who found a low correlation between the flexibility component, including shoulder and lower limb flexibility, and climbing performance.

In summary, two tests assessing upper limb flexibility were implemented in climbing research, with only little data reported on test quality.

3.2.5. Lower limb strength

Several tests used to assess lower limb strength were identified (**Table 6**):

- Squat jump
- Standing long jump
- Jump with high foot
- Counter movement jump (CMJ)
- Vertical jump
- One legged squat
- Unnamed lower limb strength test

While no study reported both reliability and validity data on any of the tests, Mermier et al. (6) report a high correlation between the strength and endurance component including the lower limb strength test and other strength and endurance tests, and climbing performance in climbers.

Augste et al. (15) specified a high intra-session and an unacceptable inter-session reliability for the test jump with high foot.

According to Augste et al. (32), the CMJ proved to be relevant to speed climbing and bouldering. In addition, Krawczyk et al. (79) found a high negative correlation between height and power for the CMJ and climbing time in speed climbing. Both España-Romero et al. (47) and Giles et al. (134), however, found no significant differences between climbers of different ability levels.

The squat jump was used in studies by España -Romero et al. (47), Augste et al. (15) and Arazi et al. (94). The latter could identify a low correlation between jump height and climbing ability in both males and females.

For the standing long jump used by Kozina et al. (33) and Stancović et al. (31), the vertical jump conducted by Nichols et al. (54), and the one legged squat applied by Čular et al. (113), no data on test quality is provided.

In summary, six different tests were used to measure lower limb strength in climbing research. While only very little quality data was reported, research points toward squat jump, and CMJ measurements as possible indicators of climbing-specific lower limb strength.

3.2.6. Lower limb endurance

Lower limb endurance was tested through two tests (**Table 7**):

- Treadmill running
- Cycle ergometry

Only five studies used the cycle ergometer to conduct a discontinuous incremental test (42, 166–168) and the Wingate test protocol (6). Unfortunately, no data on the reliability or validity of the test were reported by Limonta et al. (42). However, the authors stated that they could not find any difference in maximum oxygen uptake between climbing and cycling. Mermier et al. (6) report a high correlation between the strength and endurance component including other upper- and lower limb endurance and strength test, and climbing performance.

MacKenzie et al. (95) found that aerobic capacity during a treadmill test with progressive inclination until volitional exhaustion shows a low correlation with climbing ability of both males and females. Michailov et al. (162) and Fryer et al. (45) on the other hand found no significant correlation between exhaustive treadmill running (continuous test with progressive

TABLE 6 Reliability and validity measures for lower limb strength tests.

Lower limb strength	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Lower limb strength test (6)	*Con. MS*	–	r =0.77 (6)+
jump with high foot (15, 32)	*Con. ES*	Intra-session: r = .76–92 (15)	–
Counter movement jump (32, 47, 79, 134)	*Ecc.-con. ES*	–	r =.79 (79)
Squat jump (32, 47, 94)	*Con. ES*	–	r =.23 –.33 (94)
Standing long jump (31, 33)	*Ecc.-conc. ES*	–	–
Vertical jump (54)	*(Ecc.-)con. ES*	–	–
One legged squats (113)	*Con.-ecc. ME*	–	–

MS, maximum strength; ES, explosive strength; ME, muscular endurance; con., concentric; ecc., eccentric; +, criterion validity (correlation with climbing performance test scores).

TABLE 7 Reliability and validity measures for lower limb endurance tests.

Lower limb endurance	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Treadmill running (37, 41, 45, 95, 162)	*E*	–	d = .17 –.43 (41); *r* = .17-.28 (95), ns (162)
Cycle ergometry (6, 42, 166–168)	*E*	–	–

E, Endurance; ns, non-significant.

speed and progressive speed and inclination respectively) and climbing performance. Baláš et al. (37) conducted a treadmill running test with progressive speed at constant inclination (5%) until exhaustion but did not report any reliability or validity data. Baláš et al. (41) found low differences between intermediate and advanced climbers during a treadmill running test with progressive inclination (%) to failure regarding time to failure, slope, tidal volume, respiratory exchange rate and heart rate.

In summary, two tests were established to measure lower limb endurance in climbing. No significant correlations were found between oxygen uptake during cycling and climbing, and treadmill running showed little or no correlation with climbing ability.

3.2.7. Lower limb flexibility

Lower limb flexibility was assessed through multiple tests (**Table 8**). While some tests are also known in other sports, more climbing specific tests were developed:

- Sit and reach
- Lateral foot reach
- Grant foot raise
- Climbing specific foot raise
- Hip abduction test
- Draga test
- Hip slide test
- Foot loading flexibility test
- Asymmetry in reach test
- Froggies
- Straddle test
- Hip flexion and rotation
- Leg flexion

The sit and reach test as a test for low back and hamstring active static flexibility was used in multiple studies. Except for one study by Siegel et al. (114), who conducted the back saver sit and reach test, all studies conducted the sit and reach test with both legs. The only authors reporting reliability data are Draper et al. (169), who report a very high inter-session reliability. MacKenzie et al. (95) found a low and middle-sized correlation with climbing ability in males and females respectively.

Active static hip flexibility was assessed through several tests. Draper et al. (169) report a very high inter-session reliability but only a low correlation between test results and climbing ability for the lateral foot reach test.

A very high inter-session reliability is also reported for the Grant foot raise test by Draper et al. (169) for implementing the test both with and without lateral hip movement. However, only low to middle-sized correlations with climbing ability are reported for both males and females for all ways of

TABLE 8 Reliability and validity measures for lower limb flexibility tests.

Lower limb flexibility	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Sit and reach (3, 47, 95, 97, 114, 169)	*Low back + hamstring Active static FLEX*	Inter-session: ICC = .97 (169)	*r* = 0.17–0.42 (95)
Lateral foot reach (169)	*Hip active static FLEX*	Inter-session: ICC = .93 (169)	*r* = .24 –.30 (169)
Grant foot raise (3, 95, 97, 110, 169, 170)	*Hip active static FLEX*	Inter-session: ICC = .90 –.93 (169)	*r* = .20 –.34 (110, 169); *r* = .26 –.49 (95)
Climbing specific foot raise (14, 15, 32, 169)	*Hip active static FLEX*	Inter-session: ICC = .89 (169); *r* = .95 –.99 (15)	*r* = .53 –.95 (14, 15, 169)
Hip abduction test (6, 131)	*Hip active static FLEX*	–	*r* = .14 (6)+
Draga test (170)	*Hip active static FLEX*	–	–
Hip slide test (134)	*Hip active static FLEX*	–	–
Foot loading flexibility test (169)	*Hip active static FLEX/ Climbing ability*	Inter-session: ICC = .96 (169)	*r* = .56 –.65 (169)
Asymmetry in reach test (113)	*Hip active static FLEX/ Climbing ability*	Intra-session: ICC = .89—>.99, CV% = 1.31–35.20, SEM%=.09 –.61 (113), inter-session: ICC = .87 -.96, CV% = 4.96–41.98, SEM% = .07–1.57 (113)	–
Froggies (5, 30)	*Hip passive static FLEX*	–	–
Straddle test (3, 95, 97, 134, 170)	*Hip + lower limb passive Static FLEX*	–	*r* = -.48—-.41 (170); *r* = .16 –.57 (95)
Hip rotation and flexion (131)	*Hip active FLEX*	–	–
Leg flexion (131)	*Lower limb active FLEX*	–	–

FLEX, flexibility; CV, coefficient of variation; SEM, standard error of mean; +, criterion validity (correlation with climbing performance test scores).

implementation (with or without lateral hip movement and with a 23 cm or arm length distance to the wall).

The climbing specific foot raise test is very similar to the Grant foot raise test. The participants stand on footholds with their hands on a rung or handholds around head height. They then raise one foot as high as possible either with or without lateral rotation of the body to the wall. Draper et al. (169) found high inter-session reliability for the test without lateral rotation. Very high inter-session reliability was reported by Augste et al. (15). Middle-sized and high correlations were found between the test measures without and with rotation, respectively, and climbing ability.

Mermier et al. and Wall et al. (6, 131) conducted a hip abduction test. No test related quality data was reported. However, a low correlation between the flexibility component, including shoulder, and lower limb flexibility, and climbing performance on multiple routes was stated.

Two other tests that were used to assess active static hip flexibility are the Draga- and hip slide test by Draga et al. (170) and Giles et al. (134), respectively. No quality data were reported on either test.

The foot loading flexibility test conducted by Draper et al. (169) and the asymmetry in reach test conducted by Čular et al. (113) combine active static hip flexibility with a climbing movement and are thus more complex compared to tests focused solely on hip flexibility. The inter-session reliability of both tests is rated as high to very high. Čular et al. (113) additionally report an equally high intra-session reliability for the asymmetry in reach test. While they, however, do not report any correlations to climbing ability, Draper et al. (169) report a middle-sized correlation between the results from the foot loading flexibility test and climbing ability.

Two tests were used to assess passive static hip and lower limb flexibility. During the so called froggies, the participants are asked sit or stand with their feet placed together and to then spread their legs as far as possible to the sides. Both studies conducting this test did not provide any data on the test's quality (5, 30). The straddle test, which is also used in other sports, was implemented in three different ways. The implementations differ in the body position of the subjects (lying, sitting, standing) while spreading their legs as far as possible. No data on the reliability of the straddle test are reported. However, a middle-sized negative correlation between the test outcomes in a sitting position and climbing ability was reported by Draga et al. (170). MacKenzie et al. (95) on the other hand report no correlation with climbing ability for males and a low correlation for females.

Wall et al. (131) conducted three different tests to assess frontal hip flexion, hip rotation and leg flexion but did not report any data on test quality.

In summary, fourteen different tests for the assessment of lower limb flexibility in climbing were identified. While high to very high inter-session reliability was reported for six of these tests, mainly low to middle-sized correlations with climbing ability were reported. Only the climbing specific foot raise was reported to highly correlate with climbing ability.

3.2.8. Core strength

The following core strength tests were identified (**Table 9**):

- Super-man
- Momentum absorption
- Core rotation test
- Body lock off
- Plank
- Sorensen test
- Kraus Weber test battery
- Sit-ups
- Curl-ups
- Fishing kicks
- Leg raise

No quality data are provided for the following tests: core rotation test, plank, Sorensen test, Kraus Weber test battery, sit-ups, and curl-ups. During the fishing kicks tests, participants held on to a bar attached to a 60-degrees overhanging wall. They were then asked to touch a foot plate on the wall with each foot for one second, starting in a vertical position and without swinging their legs. The test was repeated until the plate had not been loaded on three consecutive attempts. Augste et al. (15) reported low to moderate negative correlations to climbing ability. A similar test

TABLE 9 Reliability and validity measures for core strength tests.

Core strength	Measured variable	Reliability	Construct validity (correlation with self-reported climbing ability)
Super-man (86)	*Con.-ecc. MS*	Inter-session: ICC = 0.87 (86)	–
Momentum absorption (15, 32)	*Con. MS*	–	*r* = -.01 –.31 (15)
Core rotation test (86)	*Con. MS*	–	–
Body lock off (86)	*Iso. SE*	Inter-session: ICC = .79 (86)	–
Plank (14)	*Iso. SE*	–	–
Sorensen test (4, 96)	*Iso. SE*	–	–
Kraus Weber test battery (96)	*Iso. SE*	–	–
Sit-ups (31)	*Con.-ecc- SE*	–	–
Curl-ups (3, 97, 114)	*Con.-ecc- SE*	–	–
Fishing kicks (15, 32), (86)	*Con.-ecc. SE*	Inter-session: ICC = 0.91 (86)	*r* = -.42—-.12 (15)
Leg raise (14, 95, 96)	*Core + lower leg iso. SE*	–	*r* = .30 –.45 (95)

MS, maximum strength; ME, muscular endurance; iso., isometric; con., concentric; ecc, eccentric.

was conducted by Saeterbakken et al. (86) who report a very high inter-session reliability.

They also report high inter-session reliabilities for the super man and the body lock off test (86). During the super man test, participants adopted a push-up position with their hands on a slide board and their feet against a wall. They were then asked to slide their arms as far forward as possible so they could still return to the starting position. For the body lock off test, participants adopted a horizontal position with one foot on a campus rung and both hands on another. They were then asked to lift their second foot to the same height as the first and to lift their body so that shoulders, pelvis and ankle formed a horizontal line. They then had to hold the position for as long as possible. Augste et al. (15) reported low correlations between "momentum absorption" and climbing ability. For this test participants were asked to position both hands and feet on a 60-degrees overhanging wall. They then simultaneously released both feet and tried to allow as little back swing as possible. Whereas Draper et al. (14) as well as Macdonald and Callender (96) found no significant differences between climbers of different ability levels regarding leg raise measurements, MacKenzie et al. (95) found a low correlation to climbing ability in females and a middle-sized correlation in males.

In summary, eleven different tests were identified to assess core strength in climbing. For six of them no quality data are reported. High reliability measures were reported for body lock off, super-man, and fishing kicks. Low correlations with climbing ability are reported for leg raise and middle-sized to high correlations for "momentum absorption".

4. Discussion

The aim of this review was to give an overview over the quality of different test- and measurement methods for performance, strength, endurance, and flexibility in climbing. The type and frequency of the tests used (**Figure 3**) correspond to the performance structure of climbing shown in **Figure 1**. This shows that research is representing the conditional requirements of the climbing sport. Nonetheless, the climbing ability of most samples range across two or more ability levels (IRCRA) and only very few studies focused on specific ability levels. This leads to the fact that only broad assumptions within the field of climbing diagnostics can be made. In addition, all recommendations on testing need to be viewed in context of the population included in the respective study.

Based on current evidence, it is difficult to determine whether individual tests are superior to others in terms of reliability and validity. However, individual tests may be identified as particularly good based on multiple studies and quality checks, while others may need further exploration. Although a large number of studies and tests were included in this review, it should be noted that the majority of the studies (a total of 82 = 55,4%) did not provide data on test quality, which may have biased our analysis.

4.1. Performance tests

Climbing and bouldering performance were measured through several tests. Their high complexity and variability are both advantageous and disadvantageous at the same time. On the one hand they can be adapted to focus on various different performance factors such as endurance, strength, climbing ability, dynamics, and kinematics. Additionally, they can be implemented easily and most of them don't require expensive and unwieldy equipment. On the other hand, the fact that they are implemented in various different ways makes it hard to compare the results of different studies. Furthermore, the variability of the routes and walls used lead to substantial differences in the requirements needed to fulfil a test among different ability levels. For example, a test route designed to test climbing endurance in elite climbers might require more strength than endurance in intermediate and advanced climbers.

While there is little quality data reported on performance tests, the correlation between test scores and reported climbing ability is high or up to very high. Especially the repeated ascent of one boulder, and bouldering in a circuit stand out due to a high validity. Even though the test results might seem to be vague, due to the high complexity of the tests, various studies report very high inter-session reliability for top-rope, and treadwall climbing, as well as the rock over climbing test, and the repeated ascent of one boulder. Moreover, studies that evaluated climbing kinematics through expert ratings report high inter-rater reliability. A new attempt to measure climbing performance through climbing kinematics through the assessment of the jerk of the hip trajectory showed high correlations with climbing ability (68, 69). Tests that lack construct validity regarding climbing ability are traverse bouldering, bouldering and lead climbing.

One factor, researchers might criticize about tests that involve bouldering or climbing is the impact of route preview on the test results. While, according to Sanchez et al. (67), route preview does not lead to a climber being more likely to finish the ascent of a route, it is likely to influence the performance on the route itself. The ability to visually inspect a climb before its ascent or not may thus represent a key factor in performance testing (67).

Some climbing performance tests have been used to assess climbing specific endurance. While it was shown that both systemic and localized endurance are important in climbing ability and several tests are needed for a full picture of an athlete (171), there is still no consensus on the most appropriate tests.

In general, five climbing performance tests have not been validated and only eight studies report reliability data. Furthermore, the included population covers different ability levels, which is why no definitive recommendations for climbing performance tests can be given at present.

While we decided to classify the tests according to the exercises performed, another idea would be to classify them according to the intensity of the exercise. To our knowledge, no study has so far distinguished between exhaustive or submaximal tests which would be an interesting topic for future analyses.

4.2. Upper limb and finger strength

A total of 16 different test groups for upper limb and finger strength were identified. They were applied by 120 out of 156 studies included in this review. This represents the importance of upper limb and finger maximum strength, muscular endurance and explosive strength in climbing.

All tests conducted to measure finger strength are isometric tests, except for one test by Schweizer and Fuller (102) which is isokinetic. In total, four test groups were identified. However, these consist of almost 230 different ways of implementation regarding hold type, hold depth, arm- and body position, distance between the hands, force thresholds, contraction type, and work to rest ratios. Furthermore, the same tests were modified to assess not only finger isometric maximum strength but also isometric muscular endurance in both sustained and intermittent setups, explosive strength, and maximum strength endurance. The dead hang was reported to have very high reliability ratings by many studies. In addition, acceptable coefficients of variation were reported by Draper et al. (14) and López-Rivera and González-Badillo (82). Only Ozimek et al. (83) report poor CV values (23.4%–29.9%). Both gripping a hand dynamometer and applying force on a hold were also reported to be highly reliable. Acceptable CV-values are additionally reported by multiple studies (4, 96, 115–117, 135). The reliability for pinching a dynamometer has so far only been assessed by in one study (108) reporting very high intra-session reliability. Correlations with climbing ability were on the other hand studied less frequently reported. The dead hang seems to be a valid measure to assess finger isometric muscular endurance and maximum strength. New findings however show that the test is more likely to assess maximum strength rather than muscular endurance (171).

Both gripping and pinching a dynamometer for measuring finger maximum strength seem to be valid ways to assess finger isometric muscular endurance and maximum strength. Applying force on a hold might be a less valid procedure, however all these findings need to be treated with caution as test setups and included populations vary substantially.

One of the tests assessing maximum strength endurance of the fingers that has recently been introduced also assesses finger flexor critical force (132). This parameter is new to climbing research and holds great potential for further investigations of specific strength profiles of climbers and their correlation with climbing ability.

Both gripping a dynamometer and applying force on a hold have been reported to hold high and very high test reliability, respectively, and high levels of standardization in assessing hand strength (172, 173). While we cannot give a final answer to the question which arm- and body positions should be used for finger flexor strength testing, we are able to summarize the current findings in this field. One of the first studies investigating this question found that the most appropriate protocol seems to be to assess maximum grip strength in adolescents with the elbow extended rather than bent at 90 degrees (174). Whether this applies to adult climbers of different ability levels as well, remains to be investigated. Michailov et al. (130), state that, while finger strength testing with arm fixation is more reliable, tests without arm fixation are more related to climbing ability. Amca et al. (175) observed different forms of increase in force with increasing hold depth, depending on the grip technique. This points towards climbers adopting individual choices of body position while climbing according to the chosen grip technique. Consequently, some freedom of choice regarding the type of grip and body positioning during finger strength testing might lead to more reliable and valid results. Baláš et al. (136) assessed the differences between various grip types and report open grip and crimp grip as most closely related to self-reported climbing ability. Additionally, two finger grips might provide more detailed information on individual grip performance variations (136). Bourne et al. (137) assessed the effect of edge depth and found that finger strength measured on deep edges do not predict finger strength on shallow edges. In addition, individual anthropometric factors such as fingertip pulp may influence strength measurements. A recent study by van Bergen et al. (176) suggest to conduct finger strength testing and training with different holds and body positions.

Another factor that many tests differ on is the type of contraction (continuous or intermittent). It was shown that aerobic, alactic, and lactic relative energy contributions differ significantly between both test set ups (138). Researchers and coaches should thus choose the test set up according to the variable they wish to measure. Nonetheless, it remains unclear which work to rest ratio intermittent testing holds the highest correlation to climbing ability in different performance groups. Augste et al. (177) recently published a study aimed at optimizing the correlation of test performance in intermittent finger muscular endurance tests with climbing ability. They found the highest correlations for women and men when 9% and 6% deviation in required force and one second deviation in required pulling time were tolerated, respectively. This might be a good starting point for future research on intermittent finger strength testing.

Low to high reliability and middle-sized correlations to climbing ability have been reported for the assessment of finger flexors RFD. New findings suggest, that RFD plays an important role especially in high elite climbing (178, 179) and should therefore be considered in more detail in future.

As can already be seen form these findings, sex plays an important role in strength testing. Findings by Peterson et al. (180) indicate that relative grip strength measured with a hand dynamometer could be greater in males compared to females due to the decreased hand size of females in relation to males. This has to be taken into account when interpreting forces measured with a hand grip dynamometer.

Two isometric tests assessing upper limb strength were identified. The bent arm hang was used to measure upper limb muscular endurance. When conducted on small holds, however, finger maximum strength also played a role. It was reported to be a reliable test by multiple studies. In addition, diagnostic literature as identified the bent-arm hang as a test with a high level of standardization and a high reliability for young adults (181). Correlations to climbing ability covered a broad range from low to high. Again, the variety of implementations and within sample climbing ability levels is very high. The "best" way to implement this test can thus not be identified. However, it was reported to differentiate between climbers of different ability levels (3, 96, 97). The bent arm hang thus remains a valid test for upper limb strength in climbing. The same was found for the isometric pull up.

Although many dynamic tests to assess upper limb strength in climbing were identified, most of them were applied in only one or two studies (medicine ball throw (31, 112); elbow strength tests (159); biceps strength test (95); shoulder strength test (6, 160); push-ups (31), campus board performance (39, 53); arm jump test (161); bench press (4); pull down (63, 64); traction test (139)). In addition, quality data are only reported for medicine ball throw, the power-slap test and pull-ups. A very high inter-session reliability is reported for all of them by multiple studies. On top of that, Draper et al. (14), Levernier et al. (100), Stien et al. (103) and Laffaye et al. (157) report acceptable CV values for the power slap test and the pull up. While the correlation with climbing ability for these tests only ranges from low to middle-sized, the power-slap test was found to differentiate between different ability levels when assessing upper limb explosive strength and explosive strength endurance (4, 158). Furthermore, the pull up was found to differentiate between boulderers and climbers when assessing upper limb explosive strength (100, 101). In addition, Fetz and Kornexl (172) report a very high level of standardization and high reliability. A high level of standardization and high inter-rater reliability are also reported for the medicine ball throw when performed in a standing position by Bös and Schlenker (181). While no quality data was reported for push-ups, Bös and Schlenker (181), and Fetz and Kornexl (172) state a high level of standardization and high inter-session reliability for push-ups performed with a clap behind the back after every repetition. Augustsson et al. (159) were the only ones to report data on elbow strength. While this test seems to be a valid test especially in bouldering, further analysis need to be conducted.

This shows that even though climbing is often characterized as a series of isometric contractions, and dynamic tests are not often used, dynamic explosive strength of the shoulders and upper arms plays an important role in climbing and should thus be included into performance assessments in addition to isometric tests.

4.3. Upper limb endurance

Although upper limb endurance is an important factor in climbing, it was only investigated by a total of seven of the 156 included studies. Reliability measures for rowing ergometry are only reported by one study, while two report correlations to climbing ability. High correlations are reported for maximum strength assessed through the one repetition maximum and endurance assessed through maximum oxygen consumption. While no data on the reliability of arm crank ergometry are reported by the included studies, the test has been shown to hold a high inter-observer and inter-session reliability by Bulthuis et al. (182). However, only low to middle-sized correlations with climbing performance are reported by one study for arm crank ergometry.

These findings suggest that both tests could be valid for the assessment of upper limb endurance in climbing. However, more research by multiple studies is needed in this field (178).

4.4. Upper limb flexibility

While upper limb flexibility is reported to be one of the key factors of climbing (6), only two studies have assessed active dynamic shoulder flexibility. Additionally, only one study reports data regarding test quality (6). General diagnostic literature has already shown that shoulder flexibility assessed with a scaled rod moved over the head with straight arms is a measure with very high objectivity, and high intra-session reliability (183). However, more research regarding upper limb flexibility in climbing is needed to be able to provide test recommendations.

4.5. Lower limb strength

Lower limb strength was reported to be a key factor in climbing. In addition, coaches report an increasing importance of lower limb strength in modern bouldering and speed climbing (184). Nonetheless, very few studies included lower limb strength tests into their test batteries. The studies that did include lower limb strength tests mainly focus on lower limb explosive strength. Only one of the seven tests found focuses on maximum strength and one on lower limb muscular endurance. This is in line with the results of Mermier et al. (6) who found that lower body explosive strength plays an important role in climbing ability.

Nonetheless, hardly any data is reported on test quality. It can only be assumed that the jump with high foot (15), has high to very high inter-session reliability. The authors, however, emphasize that this test should only be included in a test battery if both angular position of the knee and test performance are closely monitored (15). All tests for which correlation values to climbing ability are reported, show low to high correlation with climbing ability. Nevertheless, this information should be taken with caution, as it is based only on the results of single studies and is therefore not conclusive. As shown by Krawczyk et al. (79) lower limb strength is a key factor, in speed climbing, and this relationship should thus be evaluated further. General sports diagnostics have shown that the standing long jump shows a very high level of standardization, and middle-sized to high inter-session reliability (172). In addition, both vertical jump and one legged squats have been shown to hold a high inter-session reliability in general strength testing (172, 181, 185) which is a good starting point for future climbing-specific assessments to provide valid test recommendations.

4.6. Lower limb endurance

Lower limb endurance was not reported to be a key factor of climbing. Nevertheless, six studies included treadmill running or cycle ergometry into their test batteries. The aim of the studies was to compare the respiratory requirements of running or cycling with those of climbing. While only three of the studies report low correlations with climbing ability, all indicate that climbing ability is not dependent on aerobic capacity as determined by a traditional treadmill analysis or cycle ergometry (37, 41, 42, 45, 95). In addition, no study reports reliability data, which shows another gap in climbing research. Nonetheless, it has been shown that incremental treadmill tests are a reliable tool for measuring lactate thresholds, blood lactate concentrations, and maximum oxygen consumption (186). It can be concluded that traditional lower limb endurance tests most probably do not directly contribute to climbing ability and should thus not be included in performance analysis.

4.7. Lower limb flexibility

As supported by multiple studies, lower limb flexibility is a key performance component of climbing (3, 6). However, the test battery included lower limb flexibility tests in only a few studies. For all tests for which inter-session or intra-session reliability data are reported, the reliability is very high. Additionally, Čular et al. (113) report an acceptable CV and SEM for the right and left hand individually, but not for the absolute values in the asymmetry in reach test. The high reliability of the flexibility tests is in line with diagnostic literature reporting high inter-rater and inter-session reliability for the sit and reach and the straddle test (172, 183). In contrast, the correlation to climbing ability ranges from middle-sized to high only for the climbing specific foot raise and the foot loading flexibility test and is low for the remaining tests. While researchers have emphasized that climbing specific flexibility tests are superior to less specific tests (169), our results show that both specific tests performed on a climbaflex board and existing tests used in many other sports only show low to middle-sized correlations with climbing ability. This could indicate that despite previous findings lower limb flexibility is a less important factor in climbing. Another possible explanation could be that due to their complexity these tests might not only refer to flexibility. The asymmetry in reach test for example might also include factors of shoulder strength. In addition, the current state of research may not be strong enough to support either position. As the samples of most studies focusing on lower limb flexibility range from lower level to elite or even to higher elite climbers, no ability group has specifically and thoroughly been investigated until now. More research in this area is thus needed and should thus focus on specific ability groups.

4.8. Core strength

Even though core strength was reported to be a key component of climbing, only 11 out of 156 studies conducted core maximum strength tests and muscular endurance tests of the core. Diagnostic literature reports high intra- and inter-tester, as well as high inter-session reliability for the Sorensen test, sit-ups, curl-ups, and leg raise (181, 185, 187). In climbing specific research, however, only one study reports reliability data and only two report on the validity of a single test each. While the inter-session reliability of the super-man, the body-lock, and fishing kicks are reported to range from high to very high, the correlations reported for the leg raise and "momentum absorption" range from low to high only. This again highlights the need for further research in the field of strength testing in climbing.

4.9. Practical applications

The large variety of tests used, and the large number of factors influencing the measured values (ability level, wall inclination, loads, test implementation, etc.), makes it hard to give concrete test recommendations to coaches and researchers. Our suggestions reflect the current state of evidence; we only recommend tests with high validity.

According to our findings, the most valid tests for bouldering endurance, climbing performance, and climbing kinematics are the repeated ascent of one boulder, lead climbing, and top-rope climbing, respectively. Finger maximum strength is best assessed through applying force on a hold, rather than using a hand dynamometer. Intermittent dead hang protocols are reliable and valid tests for finger muscular endurance. Upper limb maximum strength and strength can be measured through the bent arm hang and pull-ups. Isometric pull-ups additionally allow the assessment of explosive strength, for which the power-slap test can also be used. Regarding the lower limbs, currently no test can be recommended due to low or missing validity.

5. Conclusion

When creating a test battery and comparing and analyzing test results, researchers are almost overwhelmed by the multitude and variability of diagnostic options. To date, no between test correlation analysis or multiple regression analysis has been carried out to find out whether it might be sufficient to perform only few tests in order to successfully map climbing ability. Of course, this does not apply to diagnostics which aim to identify deficiencies or weaknesses. However, when evaluating training effects, for example, a reduced test battery could save a lot of time and work.

While some tests have been validated mainly in the area of upper limb and finger strength, especially the assessment of climbing performance, core strength, global endurance, and lower limb strength and flexibility lack valid and reliable testing methods. Standardized settings such as the moon or the kilter board have not been used to assess performance to this day and might hold potential for future examinations within performance testing.

This review might give the impression that in order to reach a "perfect test", authors should strive towards optimized reliability and validity measures. While low-complexity tests are not characterized by a particular proximity to climbing, they might, however, lead to significantly more reliable test results. This is why the aim of this review was not to find the test with the highest quality data reported. Instead, it was our aim to give an overview of the variety of tests and their current state of quality assessment. Researchers can use this information to create future test batteries or to further assess test quality.

In this context it also has to be kept in mind that the term "climbing specific" is not clearly defined to this day due to the great complexity and variability of the climbing movement. As already postulated by Stien et al. (188), further biomechanical analyses of the climbing movement need to be conducted to formulate concrete test recommendations. During the last years, for example, coaches have reported an increasing importance of lower limb coordination (184) in bouldering and speed climbing.

On top of that, we were able to confirm that discipline-specific tests do not exist in climbing to this date. Many studies did not include the discipline, the climbing ability, reported by the participants, was related to. This makes it hard to give coaches discipline-specific advice which is why we ask authors to specifically name the climbing discipline used to calculate correlations with the test results in future. Nonetheless, it has to be taken into account, that our goal was to conduct a generic review regarding diagnostics in climbing which is why our literature search might not have allowed us to identify some discipline-specific studies. Future research could focus on this topic.

As criticized by Stien et al. (188) and confirmed in this review, research on testing in climbing lacks data on test quality. Future research on strength, endurance and flexibility in climbers should thus aim to provide detailed information on the test reliability and validity. Furthermore, authors should strive to use similar tests in future studies to increase comparability of test results. First steps towards a uniform test battery have already been taken recently (14) and should be followed up in future as they are not only important for research. Test results should also form the basis for training organization (189) and are a key factor of injury prevention (184).

Furthermore, inadequate descriptions regarding the ability level, sex and main discipline of the subjects examined in the studies also posed a major challenge in the context of this review. The IRCRA scale (18), introduced a few years ago, has enabled a uniform assessment of performance. In addition, future research should include clear information on the subject's sex and main discipline.

Author contributions

All authors contributed to the design and conceptualization of the review. KL conducted the search, extracted, and analysed the data, and drafted the article. All remaining authors critically revised the draft.

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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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1130812/full#supplementary-material.

References

1. Saul D, Steinmetz G, Lehmann W, Schilling AF. Determinants for success in climbing: a systematic review. *J Exerc Sci & Fit*. (2019) 17:91–100. doi: 10.1016/j.jesf.2019.04.002

2. MacLeod D, Sutherland DL, Buntin L, Whitaker A, Aitchison T, Watt I, et al. Physiological determinants of climbing-specific finger endurance and sport rock climbing performance. *J Sports Sci*. (2007) 25:1433–43. doi: 10.1080/02640410600944550

3. Grant S, Hynes V, Whittaker A, Aitchison T. Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *J Sports Sci*. (1996) 14:301–9. doi: 10.1080/02640419608727715

4. Laffaye G, Levernier G, Collin J-M. Determinant factors in climbing ability: influence of strength, anthropometry, and neuromuscular fatigue. *Scand J Med Sci Sports*. (2016) 26:1151–9. doi: 10.1111/sms.12558

5. Magiera A, Roczniok R, Maszczyk A, Czuba M, Kantyka J, Kurek P. The structure of performance of a sport rock climber. *J Hum Kinet*. (2013) 36:107–17. doi: 10.2478/hukin-2013-0011

6. Mermier CM, Janot JM, Parker DL, Swan JG. Physiological and anthropometric determinants of sport climbing performance. *Br J Sports Med*. (2000) 34:359–65. doi: 10.1136/bjsm.34.5.359

7. Stien N, Frøysaker TF, Hermans E, Vereide VA, Andersen V, Saeterbakken AH. The effects of prioritizing lead or boulder climbing among intermediate climbers. *Front Sports Act Living*. (2021) 3:1–9. doi: 10.3389/fspor.2021.661167

8. Sveen J, Stone K, Fryer S. "Strength and forearm volume differences in boulderers and sport climbers,". In: Draper N, Drum S, Joubert L, Watts P, editors. *Proceedings of the 3rd international rock climbing research congress*. Telluride, Colorado (2016). p. 10–1.

9. Fanchini M, Violette F, Impellizzeri FM, Maffiuletti NA. Differences in climbing-specific strength between boulder and lead rock climbers. *J Strength Cond Res*. (2013) 27:310–4. doi: 10.1519/JSC.0b013e3182577026

10. Winkler M, Künzell S, Augste C. The load structure in international competitive climbing. *Front Sports Act Living*. (2022) 4:1–10. doi: 10.3389/fspor.2022.790336

11. American Educational Research Association. Standards for Educational and Psychological Testing. Washington DC: National Council on Measurement in Education (2014)).

12. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*. (1988) 26:217–38. doi: 10.2165/00007256-199826040-00002

13. Langer K, Simon C, Wiemeyer J. Strength training in climbing: a systematic review. *J Strength & Cond Res*. (2022) 37:751–67. doi: 10.1519/JSC.0000000000004286

14. Draper N, Giles D, Taylor N, Vigouroux L, España-Romero V, Baláš J, et al. Performance assessment for rock climbers: the international rock climbing research association sport-specific test battery. *Int J Sports Physiol Perform*. (2021) 16:1242–52. doi: 10.1123/ijspp.2020-0672

15. Augste C, Winkler M, Künzell S. *Entwicklung einer wissenschaftlich fundierten Leistungsdiagnostik im Sportklettern. Augsburg*. (2022) 1–31.

16. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JP, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *Br Med J*. (2009) 339:b2700. doi: 10.1136/bmj.b2700

17. Meline T. Selecting studies for systemic review: inclusion and exclusion criteria. *CICSD*. (2006) 33:21–7. doi: 10.1044/cicsd_33_S_21

18. Draper N, Giles D, Schöffl V, Konstantin Fuss F, Watts P, Wolf P, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: international rock climbing research association position statement. *Sports Technol*. (2015) 8:88–94. doi: 10.1080/19346182.2015.1107081

19. Akoglu H. User's guide to correlation coefficients. *Turkish J Emerg Med*. (2018) 18:91–3. doi: 10.1016/j.tjem.2018.08.001

20. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. (2016) 15:155–63. doi: 10.1016/j.jcm.2016.02.012

21. Cohen J. *Statistical power analysis for the behavioral sciences*. Abingdon, Oxon: Routledge (1988).

22. Reed GF, Lynn F, Meade BD. Use of coefficient of variation in assessing variability of quantitative assays. *Clin Diagn Lab Immunol*. (2002) 9:1235–9. doi: 10.1128/cdli.9.6.1235-1239.2002

23. Denegar CR, Ball DW. Assessing reliability and precision of measurement: an Introduction to intraclass correlation and standard error of measurement. *J Sport Rehabil*. (1993) 2:35–42. doi: 10.1123/jsr.2.1.35

24. Mitchell AC, Bowhay A, Pitts J. Relationship between anthropometric characteristics of indoor rock climbers and top roped climbing performance. *J Strength & Cond Res*. (2011) 25:S94–95. doi: 10.1097/01.JSC.0000395728.22365.7d

25. López-Rivera E, González-Badillo JJ, España-Romero V. Which is the most reliable edge depth to measure maximum hanging time in sport climbers? *Gait Posture*. (2022) 91:59–65. doi: 10.1016/j.gaitpost.2021.09.200

26. Limmer M, de Marées M, Roth R. "Compression sleeves in sports climbing_effects on muscular strength and endruance parameters of finger flexors in recreational climbers,". In: Espana-Romero V, Reed T, Giles D, Vigouroux L, Seifert L, Fryer S, et al., editors. *Proceedings of the 5th international rock climbing research congress*; Tokyo, Japan (2021). p. 146.

27. Kitaoka K. Evaluation method for sport climbing-specific forearm endurance by blood lactate concentration. *Adv in Exerc & Sports Physiol*. (2014) 20:121.

28. de Ghetaldi LR. *The effect of self-modeling on climber self-efficacy, motivation, actual and perceived rock climbing skills, and knowledge in beginning rock climbers*. Greeley, CO: Dissertation (1998).

29. España Romero V, López-Rivera E, Garrido-Palomino I. "Differences in maximal volunatry contraction, strength and enduracne, and neuromuscular function during half-crimp and slope grip positions in elite and expert rock climbers,". In: Espana-Romero V, Reed T, Giles D, Vigouroux L, Seifert L, Fryer S, et al., editors. *Proceedings of the 5th international rock climbing research congress*; Tokyo, Japan (2021). p. 58–9.

30. Magiera A, Roczniok R. The climbing preferences of advanced rock climbers. *Human Movement*. (2013) 14:254–64. doi: 10.2478/humo-2013-0031

31. Stanković D, Ignjatović M, Raković A, Puletić M, Hodžić S. The strength structure of sport climbers. *Facta Universitatis: Series Physical Education & Sport*. (2014) 12:11–8. UDC: 796.525.012.11.

32. Augste C, Winkler M, Künzell S. *Performance diagnostics in sport climbing—test manual. Augsburg*. (2022) 1–17.

33. Kozina Z, Ubarova N, Cieslicka M, Bejtka M, Jagiello M. Experimental substantiation of the program of the annual cycle of preparation of climbers 16-17 years to the competitive discipline "climbing combined". *J Phy Edu & Sport*. (2020) 20:1250–6. 10.7752/jpes.2020.s2174

34. Medernach JP, Kleinöder H, Lötzerich HH. Effect of interval bouldering on hanging and climbing time to exhaustion. *Sports Technol*. (2015) 8:76–82. doi: 10.1080/19346182.2015.1063643

35. Medernach J, Kleinöder H, Lötzerich H. "Vibration training in indoor bouldering: effects on strength and endurance,". In: Radmann A, Hedenborg S, Tsolakidis E, editors. *Proceedings of the 20th annual congress of the European college of sports science*; Malmö, Sweden (2015). p. 599.

36. Deyhle M, Hung-Sheng HS, Fairfield T, Cadez-Schmidt T, Gurney B, Mermier C. Relative importance of four muscle groups for indoor rock climbing performance. *J Strength & Cond Res*. (2015) 29:2006–14. doi: 10.1519/JSC.0000000000000823

37. Baláš J, Panáčková M, Strejcová B, Martin AJ, Cochrane DJ, Kaláb M, et al. The relationship between climbing ability and physiological responses to rock climbing. *Scientific World J*. (2014) 2014:678387. doi: 10.1155/2014/678387

38. Michailov M, Rokowski R, Regwelski T, Staszkiewicz R, Brown LE, Szygula Z. Physiological responses during two climbing tests with different hold types. *Int J Sports Sci Coach*. (2017) 12:276–83. doi: 10.1177/1747954117694740

39. Sas-Nowosielski K, Wyciślik J, Kaczka P. Beta-Alanine supplementation and sport climbing performance. *Int J Environ Res Public Health*. (2021) 10:18. doi: 10.3390/ijerph18105370

40. Schoeffl VR, Moeckel F, Koestermeyer G, Roloff I, Kuepper T. Development of a performance diagnosis of the anaerobic strength endurance of the forearm flexor muscles in sport climbing. *Int J Sports Med*. (2006) 27:205–11. doi: 10.1055/s-2005-837622

41. Baláš J, Gajdošík J, Giles D, Fryer S, Krupková D, Brtník T, et al. Isolated finger flexor vs. Exhaustive whole-body climbing tests? How to assess endurance in sport climbers? *Eur J Appl Physiol*. (2021) 121:1337–48. doi: 10.1007/s00421-021-04595-7

42. Limonta E, Brighenti A, Rampichini S, Cè E, Schena F, Esposito F. Cardiovascular and metabolic responses during indoor climbing and laboratory cycling exercise in advanced and élite climbers. *Eur J Appl Physiol*. (2018) 118:371–9. doi: 10.1007/s00421-017-3779-6

43. Baláš J, Gajdošík J, Giles D, Fryer S. The estimation of critical angle in climbing as a measure of maximal metabolic steady state. *Front Physiol*. (2021) 12:1–9. doi: 10.3389/fphys.2021.792376

44. Booth J, Marino F, Hill C, Gwinn T. Energy cost of sport rock climbing in elite performers. *Br J Sports Med*. (1999) 33:14–8. doi: 10.1136/bjsm.33.1.14

45. Fryer SM, Giles D, Palomino IG, de la O Puerta A, España-Romero V. Hemodynamic and cardiorespiratory predictors of sport rock climbing performance. *J Strength Cond Res*. (2018) 32:3534–41. doi: 10.1519/JSC.0000000000001860

46. Potter JA, Hodgson CI, Broadhurst M, Howell L, Gilbert J, Willems ME, et al. Effects of New Zealand blackcurrant extract on sport climbing performance. *Eur J Appl Physiol*. (2020) 120:67–75. doi: 10.1007/s00421-019-04226-2

47. España-Romero V, Ortega Porcel FB, Artero EG, Jiménez-Pavón D, Gutiérrez Sainz A, Castillo Garzón MJ, et al. Climbing time to exhaustion is a determinant of climbing performance in high-level sport climbers. *Eur J Appl Physiol*. (2009) 107:517–25. doi: 10.1007/s00421-009-1155-x

48. Rodio A, Quattrini FM, Fattorini L, Egidi F, Marchetti M. Physiological significance of efficiency in rock climbing. *Med Sport (Roma)*. (2006) 59:313–7. Available at: https://www.minervamedica.it/en/journals/medicina-dello-sport/article.php?cod=R26Y2006N03A0313.

49. Hardy L, Hutchinson A. Effects of performance anxiety on effort and performance in rock climbing: a test of processing efficiency theory. *Anxiety Stress Coping*. (2007) 20:147–61. doi: 10.1080/10615800701217035

50. Brent S, Draper N, Hodgson C, Blackwell G. Development of a performance assessment tool for rock climbers. *Eur J Sport Sci*. (2009) 9:159–67. doi: 10.1080/17461390902741132

51. White DJ, Olsen PD. A time motion analysis of bouldering style competitive rock climbing. *J Strength Cond Res*. (2010) 24:1356–60. doi: 10.1519/JSC.0b013e3181cf75bd

52. Zemtsova YS, Vavaev AV. "Video analysis of the men's Bouldering world climbing championship performance,". In: Espana-Romero V, Reed T, Giles D, Vigouroux L, Seifert L, Fryer S, et al., editors. *Proceedings of the 5th international rock climbing research congress*; Malmö, Sweden (2021). p. 149–54.

53. Stien N, Pedersen H, Vereide VA, Saeterbakken AH, Hermans E, Kalland J, et al. Effects of two vs. Four weekly campus board training sessions on bouldering performance and climbing-specific tests in advanced and elite climbers. *J Sports Sci Med*. (2021) 20:438–47. doi: 10.52082/jssm.2021.438

54. Nichols J, Wind D, Bellicini Z, Bates R, Hall D, Hall M, et al. Climbing-Specific fitness profiles and determinants of performance in youth rock climbers. *J Sports Sci*. (2018) 6:257–67. doi: 10.17265/2332-7839/2018.05

55. Frauman E. An Examination of Climbing Performance and its Relationship to Perceived Abilities and Experience among Boulderers,'. In: *Association of Outdoor Recreation & Education Conference Proceedings*. p. 32–5.

56. Jurrens JD. *The effects of hang board exercise on grip strength and climbing performance in college age male indoor rock climbers*. La-Crosse, WI: Masterthesis (1997).

57. Kingsley AM. *The effects of hangboard exercise on climbing performance and grip strength in college age female indoor rock climers*. La-Crosse, WI: Masterthesis (1997).

58. Barton K. *The effect of mental imagery on sport climbing performance of college students*. La-Crosse, WI: Masterthesis (1996).

59. McNamee J, Steffen J. The effect of performance cues on beginning indoor rock climbing performance. *Physical Educator*. (2007) 64:2–10. Available at: https://eric.ed.gov/?id=EJ768185.

60. Fraser RG. *The effect of relaxation training on sport climbing performance of college students*. La-Crosse, WI: Masterhesis (1998).

61. Heyman E, de Geus B, Mertens I, Meeusen R. Effects of four recovery methods on repeated maximal rock climbing performance. *Med Sci Sports Exerc*. (2009) 41:1303–10. doi: 10.1249/MSS.0b013e318195107d

62. Limmer M, Buck S, de Marées M, Roth R. Acute effects of kinesio taping on muscular strength and endurance parameters of the finger flexors in sport climbing: a randomised, controlled crossover trial. *Eur J Sport Sci*. (2020) 20:427–36. doi: 10.1080/17461391.2019.1633415

63. Hermans E, Andersen V, Saeterbakken AH. The effects of high resistance-few repetitions and low resistance-high repetitions resistance training on climbing performance. *Eur J Sport Sci*. (2017) 17:378–85. doi: 10.1080/17461391.2016.1248499

64. Hermans E. "Effect of maximal- and local muscular endurance strength training on climbing performance and climbing-specific strength in recreational climbers: a randomized controlled trial". In: Draper N, Drum S, Joubert L, Watts P, editors. *Proceedings of the 3rd international rock climbing research congress*. Telluride, Colorado (2016). p. 38–9.

65. Valenzuela PL, de La Villa P, Ferragut C. Effect of two types of active recovery on fatigue and climbing performance. *J Sports Sci Med*. (2015) 14:769–75. PMCID: PMC4657419.

66. Bertuzzi R, Franchini E, Tricoli V, Lima-Silva AE, Pires FD, Okuno NM, et al. Fit-climbing test: a field test for indoor rock climbing. *J Strength Cond Res*. (2012) 26:1558–63. doi: 10.1519/JSC.0b013e318231ab37

67. Sanchez X, Lambert P, Jones G, Llewellyn DJ. Efficacy of pre-ascent climbing route visual inspection in indoor sport climbing. *Scand J Med Sci Sports*. (2012) 22:67–72. doi: 10.1111/j.1600-0838.2010.01151.x

68. Seifert L, Orth D, Boulanger J, Dovgalecs V, Hérault R, Davids K. Climbing skill and complexity of climbing wall design: assessment of jerk as a novel indicator of performance fluency. *J Appl Biomech*. (2014) 30:619–25. doi: 10.1123/jab.2014-0052

69. Seifert L, Orth D, Davids K. Hold design supports learning and transfer of climbing fluency. *Sports Technol*. (2014) 7:159–65. doi: 10.1080/19346182.2014.968250

70. Jones MV, Bray SR, Mace RD, MacRae AW, Stockbridge C. The impact of motivational imagery on the emotional state and self-efficacy levels of novice climbers. *J Sport Behav*. (2002) 25:57. Available at: https://psycnet.apa.org/record/2002-00861-004

71. Baláš J, Panáčková M, Jandová S, Martin AJ, Strejcová B, Vomáčko L, et al. The effect of climbing ability and slope inclination on vertical foot loading using a novel force sensor instrumentation system. *J Hum Kinet*. (2014) 44:75–81. doi: 10.2478/hukin-2014-0112

72. Philippe M, Filzwieser I, Leichtfried V, Blank C, Haslinger S, Fleckenstein J, et al. The effects of 8 weeks of two different training methods on on-sight lead climbing performance. *J Sports Med Phys Fitness*. (2019) 59:561–8. doi: 10.23736/S0022-4707.18.08399-8

73. Gajewski J, Hübner-Woźniak E, Tomaszewski P, Sienkiewicz-Dianzenza E. Changes in handgrip force and blood lactate as response to simulated climbing competition. *Biol Sport*. (2009) 26:13–21. doi: 10.5604/20831862.890171

74. Taylor N, Giles D, Panáčková M, Mitchell J, Chidley J, Draper N. A novel tool for the assessment of sport Climbers' movement performance. *Int J Sports Physiol Perform*. (2020) 15:795–800. doi: 10.1123/ijspp.2019-0311

75. Magiera A, Roczniok R, Sadowska-Krępa E, Kempa K. Changes in performance and morning-measured responses in sport rock climbers. *J Hum Kinet*. (2019) 70:103–14. doi: 10.2478/hukin-2019-0050

76. Sanchez X, Boschker MS, Llewellyn DJ. Pre-performance psychological states and performance in an elite climbing competition. *Scand J Med Sci Sports*. (2010) 20:356–63. doi: 10.1111/j.1600-0838.2009.00904.x

77. Fuss FK. Instrumented climbing holds and performance analysis in sport climbing. *Sports Technol*. (2008) 1:301–13. doi: 10.1080/19346182.2008.9648487

78. Wolf P, Wittmann F, Scheuber P, Legreneur P. "Performance analysis in speed climbing: first insights into accelerating forces during starting phase,". In: Espana-Romero V, Reed T, Giles D, Vigouroux L, Seifert L, Fryer S, et al., editors. *Proceedings of the 5th international rock climbing research congress*; Malmö, Sweden (2021). p. 69–72.

79. Krawczyk M, Pociecha M, Ozimek M, Draga P. The force, velocity, and power of the lower limbs as determinants of speed climbing efficiency. *Trends in Sport Sci*. (2020) 27:219–24. doi: 10.23829/TSS.2020.27.4-5

80. Medernach JP, Kleinöder H, Lötzerich HH. Fingerboard in competitive bouldering: training effects on grip strength and endurance. *J Strength Cond Res*. (2015) 29:2286–95. doi: 10.1519/JSC.0000000000000873

81. Bergua P, Montero-Marin J, Gomez-Bruton A, Casajús JA. Hanging ability in climbing: an approach by finger hangs on adjusted depth edges in advanced and elite sport climbers. *Int J Perfor Analy in Sport*. (2018) 18(3):1–14. doi: 10.1080/24748668.2018.1486115

82. López-Rivera E, González-Badillo JJ. The effects of two maximum grip strength training methods using the same effort duration and different edge depth on grip endurance in elite climbers. *Sports Technol*. (2012) 5:100–10. doi: 10.1080/19346182.2012.716061

83. Ozimek M, Staszkiewicz R, Rokowski R, Stanula A. Analysis of tests evaluating sport Climbers' strength and isometric endurance. *J Hum Kinet*. (2016) 53:249–60. doi: 10.1515/hukin-2016-0027

84. Baláš J, Pecha O, Martin A, Cochrane D. Hand–arm strength and endurance as predictors of climbing performance. *Eur J Sport Sci*. (2012) 12:16–25. doi: 10.1080/17461391.2010.546431

85. Vereide V, Kalland J, Solbraa AK, Andersen V, Saeterbakken AH. "Correlation between relative peak-, isometric force and RFD and climbing performance,". In: Draper N, Drum S, Joubert L, Watts P, editors. *Proceedings of the 3rd international rock climbing research congress*. Telluride, Colorado (2016). p. 12–3.

86. Saeterbakken AH, Loken E, Scott S, Hermans E, Vereide VA, Andersen V. Effects of ten weeks dynamic or isometric core training on climbing performance among highly trained climbers. *PLoS One*. (2018) 13:e0203766. doi: 10.1371/journal.pone.0203766

87. Ozimek M, Rokowski R, Draga P, Ljakh V, Ambroży T, Krawczyk M, et al. The role of physique, strength and endurance in the achievements of elite climbers. *PLoS One*. (2017) 12:e0182026. doi: 10.1371/journal.pone.0182026

88. López-Rivera E, González-Badillo JJ. Comparison of the effects of three hangboard strength and endurance training programs on grip endurance in sport climbers. *J Hum Kinet*. (2019) 66:183–95. doi: 10.2478/hukin-2018-0057

89. Hermans E, Saeterbakken AH, Vereide V, Nord IS, Stien N, Andersen V. The effects of 10 weeks hangboard training on climbing specific maximal strength. Explosive strength, and finger endurance. *Front Sports Act Living*. (2022) 4:146. doi: 10.3389/fspor.2022.888158

90. Usaj A, Jereb B, Robi P, von Duvillard SP. The influence of strength-endurance training on the oxygenation of isometrically contracted forearm muscles. *Eur J Appl Physiol*. (2007) 100:685–92. doi: 10.1007/s00421-007-0461-4

91. López-Rivera E, González-Badillo JJ. "Comparison of the effects of three hangboard training programs on maximal finger strength in rock climbers,". In: Draper N, Drum S, Joubert L, Watts P, editors. *Proceedings of the 3rd international rock climbing research congress*. Telluride, Colorado (2016).

92. López-Rivera E, González-Badillo JJ. "The effects of a weighted dead-hang training program on grip strength and endurance in expert climbers with different levels of strength,". In: Draper N, España-Romero V, Fuss T, Schweizer A, Legreneur P, Seifert L, et al., editors. *Proceedings of the 4th international rock climbing research congress*; Chamonix, France (2018).

93. Giles D, Chidley JB, Taylor N, Torr O, Hadley J, Randall T, et al. The determination of finger-flexor critical force in rock climbers. *Int J Sports Physiol Perform*. (2019) 14:972–9. doi: 10.1123/ijspp.2018-0809

94. Arazi H, Rashidlamir A, Zahed Abolhasani M, Askari Hosaini S. Profiling and predicting performance of indoor rock climbers. *Rev Bras Cineantropom Desempenho Hum*. (2018) 20:82–94. doi: 10.5007/1980-0037.2018v20n1p82

95. MacKenzie R, Monaghan L, Masson RA, Werner AK, Caprez TS, Johnston L, et al. Physical and physiological determinants of rock climbing. *Int J Sports Physiol Perform*. (2020) 15:168–79. doi: 10.1123/ijspp.2018-0901

96. Macdonald JH, Callender N. Athletic profile of highly accomplished boulderers. *Wilderness and Environmental Medicine*. (2011) 22:140–3. doi: 10.1016/j.wem.2010.11.012

97. Grant S, Hasler T, Davies C, Aitchison TC, Wilson J, Whittaker A. A comparison of the anthropometric, strength, endurance and flexibility characteristics of female elite and recreational climbers and non-climbers. *J Sports Sci*. (2001) 19:499–505. doi: 10.1080/026404101750238953

98. Došla J, Meško J. The influence of strength abilities on sports performance in climbing. *J Human Sport & Exerc*. (2016) 11:S159–67. doi: 10.14198/jhse.2016.11.Proc1.06

99. Marcolin G, Faggian S, Muschietti M, Matteraglia L, Paoli A. Determinants of climbing performance: when finger flexor strength and endurance count. *J Strength Cond Res*. (2020) 36(4):1–6. doi: 10.1519/JSC.0000000000003545

100. Levernier G, Samozino P, Laffaye G. Force–velocity–power profile in high-elite boulder, lead, and speed climber competitors. *Int J Sports Physiol Perform*. (2020) 15:1012–8. doi: 10.1123/ijspp.2019-0437

101. Stien N, Saeterbakken AH, Hermans E, Vereide VA, Olsen E, Andersen V. Comparison of climbing-specific strength and endurance between lead and boulder climbers. *PLoS One*. (2019) 14:e0222529. doi: 10.1371/journal.pone.0222529

102. Bacon N, Ryan G, Wingo J, Richardson M, Pangallo T, Bishop P. Effect of magnesium carbonate use on repeated open-handed and pinch grip weight-assisted pull-ups. *Int J Exerc Sci*. (2018) 11:479–92. PMCID: PMC5841679.

103. Stien N, Vereide VA, Saeterbakken AH, Hermans E, Shaw MP, Andersen V. Upper body rate of force development and maximal strength discriminates performance levels in sport climbing. *PLoS One*. (2021) 16:e0249353. doi: 10.1371/journal.pone.0249353

104. Rokowski R, Tokarz R. Importance of motoric capabilities of energy ground in sport climbing in competition of on sight. *Antropomotoryka*. (2007) 17:81–91. GICID: 01.3001.0002.2203.

105. Saeterbakken AH, Andersen V, Stien N, Pedersen H, Solstad TE, Shaw MP, et al. The effects of acute blood flow restriction on climbing-specific tests. *Movement & Sport Sci/Sci & Motricité*. (2019) 109:1–8. doi: 10.1051/sm/2020004

106. Vigouroux L, Devise M, Cartier T, Aubert C, Berton E. Performing pull-ups with small climbing holds influences grip and biomechanical arm action. *J Sports Sci*. (2019) 37:886–94. doi: 10.1080/02640414.2018.1532546

107. Mundry S, Steinmetz G, Atkinson EJ, Schilling AF, Schöffl VR, Saul D. Hangboard training in advanced climbers: a randomized controlled trial. *Sci Rep*. (2021) 11:13530. doi: 10.1038/s41598-021-92898-2

108. Assmann M, Steinmetz G, Schilling AF, Saul D. Comparison of grip strength in recreational climbers and non-climbing athletes-A cross-sectional study. *Int J Environ Res Public Health*. (2020) 18:1–11. doi: 10.3390/ijerph18010129

109. Cutts A, Bollen SR. Grip strength and endurance in rock climbers. *Proc Inst Mech Eng H*. (1993) 207:87–92. doi: 10.1243/PIME_PROC_1993_207_275_02

110. Ezzy AC, Hagstrom AD, Shorter KA, Gray AJ. Anthropometric, strength, climbing and training characteristics that predict outdoor rock climbing performance. *J Austr Strength & Cond*. (2018) 26:7–15. Available at: https://strengthandconditioning.org/jasc-26-4/1991-original-scientific-research-study-anthropometric-strength-climbing-and-training-characteristics-that-predict-outdoor-rock-climbing-performance.

111. Limonta E, Cè E, Veicsteinas A, Esposito F. Force control during fatiguing contractions in elite rock climbers. *Sport Sci Health*. (2008) 4:37–42. doi: 10.1007/s11332-008-0065-3

112. Cochrane D, Hawke E. Effects of acute upper-body vibration on strength and power variables in climbers. *J Streng & Cond Res*. (2007) 21:527–31. doi: 10.1519/R-18505.1

113. Čular D, Dhahbi W, Kolak I, Dello Iacono A, Bešlija T, Laffaye G, et al. Reliability, sensitivity, and minimal detectable change of a new specific climbing test for assessing asymmetry in reach technique. *J Strength Cond Res*. (2021) 35:527–34. doi: 10.1519/JSC.0000000000002694

114. Siegel S, Robinson J, Jonston S, Lindley M, Pfeiffer K. Health-related fitness and energy expenditure in recreational youth rock climbers 8-16 years of age. *Int J Exerc Sci*. (2015) 8:174–83. Available at: https://digitalcommons.wku.edu/ijes/vol8/iss2/8.

115. Levernier G, Laffaye G. *The rate of force development a new biomechanical key factor in climbing* (2018) (cited 2023 Apr 04). Available at: https://www.semanticscholar.org/paper/The-rate-of-force-development-%3A-a-new-biomechanical-Levernier-Laffaye/027fa10111baefe8fae34f94887451f964920680

116. Gürer B, Yildiz M. Investigation of sport rock Climbers' handgrip strength. *Biology of Exercise*. (2015) 11:55–71. doi: 10.4127/jbe.2015.0092

117. Baláš J, Panáčková M, Kodejška J, Cochrane JD, Martin JA. The role of arm position during finger flexor strength measurement in sport climbers. *Int J Perform Analy in Sport*. (2014) 14:345–54. doi: 10.1080/24748668.2014.11868726

118. Matsouka O, Nani S, Papadimitriou K, Astrapellos K, Beneka A, Malliou P. Time course changes in hand grip strength performance and hand position sense in climbing. *J Human Sport & Exerc*. (2020) 15:23–33. doi: 10.14198/jhse.2020.151.03

119. Levernier G, Laffaye G. Four weeks of finger grip training increases the rate of force development and the maximal force in elite and top world-ranking climbers. *J Strength Cond Res*. (2019) 33:2471–80. doi: 10.1519/JSC.0000000000002230

120. Limonta E, Cè E, Gobbo M, Veicsteinas A, Orizio C, Esposito F. Motor unit activation strategy during a sustained isometric contraction of finger flexor muscles in elite climbers. *J Sports Sci*. (2016) 34:133–42. doi: 10.1080/02640414.2015.1035738

121. Smetanka RG, Armenta RF, Nessler JA, Newcomer SC. Heart rate response, duration, grip strength, and anthropometric characteristics in recreational indoor rock climbers. *J Streng & Cond Res*. (2022) 36:832–7. doi: 10.1519/JSC.0000000000003540

122. Michailov M, Mladenov L, Schöffl V. Anthropometric and strength characteristics of world-class boulderers. *Medicina Sportiva*. (2009) 13:231–8. doi: 10.2478/v10036-009-0036-z

123. Gajewski J, Jarosiewicz B. Post-exercise decrease in handgrip force following a single training session in male and female climbers. *Human Movement*. (2008) 9:121–3. doi: 10.2478/v10038-008-0015-6

124. Thompson EB, Farrow L, Hunt JE, Lewis MP, Ferguson RA. Brachial artery characteristics and micro-vascular filtration capacity in rock climbers. *Eur J Sport Sci*. (2015) 15:296–304. doi: 10.1080/17461391.2014.940560

125. Watts PB, Joubert LM, Lish AK, Mast JD, Wilkins B. Anthropometry of young competitive sport rock climbers. *Br J Sports Med*. (2003) 37:420–4. doi: 10.1136/bjsm.37.5.420

126. Watts PB, Martin DT, Durtschi S. Anthropometric profiles of elite male and female competitive sport rock climbers. *J Sports Sci*. (1993) 11:113–7. doi: 10.1080/02640419308729974

127. Watts PB, Daggett M, Gallagher P, Wilkins B. Metabolic response during sport rock climbing and the effects of active versus passive recovery. *Int J Sports Med*. (2000) 21:185–90. doi: 10.1055/s-2000-302

128. Green J, Stannard SR. Active recovery strategies and handgrip performance in trained vs. Untrained climbers. *J Streng & Cond Res*. (2010) 24:494–501. doi: 10.1519/JSC.0b013e3181c06af3

129. Watts PB, Jensen RL, Gannon E, Kobeinia R, Maynard J, Sansom J. Forearm EMG during rock climbing differs from EMG during handgrip dynamometry. *Int J Exerc Sci*. (2008) 1:4–13.

130. Michailov ML, Baláš J, Tanev SK, Andonov HS, Kodejška J, Brown L. Reliability and validity of finger strength and endurance measurements in rock climbing. *Res Q Exerc Sport*. (2018) 89:246–54. doi: 10.1080/02701367.2018.1441484

131. Wall C, Starek J, Fleck S, Byrnes W. Prediction of indoor climbing performance in women rock climbers. *J Streng & Cond Res*. (2004) 18:77–83. doi: 10.1519/1533-4287(2004)018<0077:poicpi>2.0.co;2

132. Giles D, Hartley C, Maslen H, Hadley J, Taylor N, Torr O, et al. An all-out test to determine finger flexor critical force in rock climbers. *Int J Sports Physiol Perform*. (2021) 16:942–9. doi: 10.1123/ijspp.2020-0637

133. Schweizer A, Furrer M. Correlation of forearm strength and sport climbing performance. *Isokinetics & Exerc Sci*. (2007) 15:211–6. doi: 10.3233/IES-2007-0275

134. Giles D, Barnes K, Taylor N, Chidley C, Chidley J, Mitchell J, et al. Anthropometry and performance characteristics of recreational advanced to elite female rock climbers. *J Sports Sci*. (2021) 39:48–56. doi: 10.1080/02640414.2020.1804784

135. Baláš J, Kodejška J, Krupková D, Hannsmann J, Fryer S. Reliability of near-infrared spectroscopy for measuring intermittent handgrip contractions in sport climbers. *J Strength Cond Res*. (2018) 32:494–501. doi: 10.1519/JSC.0000000000002341

136. Baláš J, MrskoČ J, Panáčková M, Draper N. Sport-specific finger flexor strength assessment using electronic scales in sport climbers. *Sports Technol*. (2014) 7:151–8. doi: 10.1080/19346182.2015.1012082

137. Bourne R, Halaki M, Vanwanseele B, Clarke J. Measuring lifting forces in rock climbing: effect of hold size and fingertip structure. *J Appl Biomech*. (2011) 27:40–6. doi: 10.1123/jab.27.1.40

138. Maciejczyk M, Michailov ML, Wiecek M, Szymura J, Rokowski R, Szygula Z, et al. Climbing-Specific exercise tests: energy system contributions and relationships with sport performance. *Front Physiol*. (2022) 12:787902. doi: 10.3389/fphys.2021.787902

139. Berrostegieta JI. "Relation between specific force tests and chained degree in high level sport climbers,". In: *Developments for disciplines: Proceedings of the ISEA* (2006), Munich, Germany. p. 275–80.

140. Levernier G, Laffaye G. Rate of force development and maximal force: reliability and difference between non-climbers, skilled and international climbers. *Sports Biomech*. (2021) 20:495–506. doi: 10.1080/14763141.2019.1584236

141. Fryer SM, Stoner LE, Dickson TG, Draper SB, Mccluskey MJ, Huges JD, et al. Oxygen recovery kinetics in the forearm flexors of multiple ability groups of rock climbers. *J Streng & Cond Res*. (2015) 29:1633–9. doi: 10.1519/JSC.0000000000000804

142. Phillips K, Noh B, Gage M, Yoon T. The effect of cold ambient temperatures on climbing-specific finger flexor performance. *Eur J Sport Sci*. (2017) 17:885–93. doi: 10.1080/17461391.2017.1328707

143. Morenas Martín J, Del Campo VL, Leyton Román M, Gómez-Valadés Horrillo JM, Gómez Navarrete JS. Description of the finger mechanical load of climbers of different levels during different hand grips in sport climbing. *J Sports Sci*. (2013) 31:1713–21. doi: 10.1080/02640414.2013.797592

144. Torr O, Randall T, Knowles R, Giles D, Atkins S. Reliability and validity of a method for the assessment of sport rock Climbers' isometric finger strength. *J Strength Cond Res*. (2020) 36(8):2277–82. doi: 10.1519/JSC.0000000000003548

145. Fryer S, Stoner L, Lucero A, Witter T, Scarrott C, Dickson T, et al. Haemodynamic kinetics and intermittent finger flexor performance in rock climbers. *Int J Sports Med*. (2015) 36:137–42. doi: 10.1055/s-0034-1385887

146. Watts PB, Jensen RL. Reliability of peak forces during a finger curl motion common in rock climbing. *Measurement in Phy Educ & Exerc Sci*. (2003) 7:263–7. doi: 10.1207/S15327841MPEE0704_4

147. Philippe M, Wegst D, Müller T, Raschner C, Burtscher M. Climbing-specific finger flexor performance and forearm muscle oxygenation in elite male and female sport climbers. *Eur J Appl Physiol*. (2012) 112:2839–47. doi: 10.1007/s00421-011-2260-1

148. Grant S, Shields C, Fitzpatrick V, Loh WM, Whitaker A, Watt I, et al. Climbing-specific finger endurance: a comparative study of intermediate rock climbers, rowers and aerobically trained individuals. *J Sports Sci*. (2003) 21:621–30. doi: 10.1080/0264041031000101953

149. Kodejška J, Michailov M, Baláš J. Forearm muscle oxygenation during sustained isometric contractions in rock climbers. *Acta Universitatis Carolinae: Kinanthropologica*. (2015) 51:48–55. doi: 10.14712/23366052.2015.31

150. Fryer S, Stone KJ, Sveen J, Dickson T, España-Romero V, Giles D, et al. Differences in forearm strength, endurance, and hemodynamic kinetics between male boulderers and lead rock climbers. *Eur J Sport Sci*. (2017) 17:1177–83. doi: 10.1080/17461391.2017.1353135

151. Kodejška J, Baláš J, Draper N. Effect of cold-water immersion on handgrip performance in rock climbers. *Int J Sports Physiol Perform*. (2018) 13:1097–9. doi: 10.1123/ijspp.2018-0012

152. Watts PB, Jensen RL, Agena SM, Majchrzak JA, Schellinger RA, Wubbels CS. Changes in EMG and finger force with repeated hangs form the hands in rock climbers. *Int J Exerc Sci*. (2008) 1:62–70. PMCID: PMC4739290.

153. López-Rivera E., España-Romero V. "Relationship between forearm pump and decreased force in expert and elite rock climbers,". In: Espana-Romero V, Reed T, Giles D, Vigouroux L, Seifert L, Fryer S, et al.. *Proceedings of the 5th international rock climbing research congress*; Tokyo, Japan (2021). p. 51–5.

154. Schoeffl VR, Einwag F, Strecker W, Schoeffl I. Strength measurement and clinical outcome after conservatively treated pulley ruptures in climbers. (abstract). *Sports Engineering (Springer Science & Business Media B.V.)*. (2006) 9:188–9. doi: 10.1249/01.mss.0000210199.87328.6a

155. Baláš J, Michailov M, Giles D, Kodejška J, Panáčková M, Fryer S. Active recovery of the finger flexors enhances intermittent handgrip performance in rock climbers. *Eur J Sport Sci*. (2016) 16:764–72. doi: 10.1080/17461391.2015.1119198

156. Rokowski R, Michailov M, Maciejczyk M, Więcek M, Szymura J, Draga P, et al. Muscle strength and endurance in high-level rock climbers. *Sports Biomech*. (2021):1–16. doi: 10.1080/14763141.2021.1916577

157. Laffaye G, Collin J-M, Levernier G, Padulo J. Upper-limb power test in rock-climbing. *Int J Sports Med*. (2014) 35:670–5. doi: 10.1055/s-0033-1358473

158. Draper N, Dickson T, Blackwell G, Priestley S, Fryer S, Marshall H, et al. Sport-specific power assessment for rock climbing. *J Sports Med Phys Fitness*. (2011) 51:417–25. PMID: 21904280.

159. Augustsson S, Frodi-Lundgren A, Svantesson U. Elbow strength profiles and performance level in Swedish climbers. *HSOA J Phy Med, Rehab and Disabil*. (2018) 26. doi: 10.24966/PMRD-8670/100026

160. Wong EK, Ng GY. Strength profiles of shoulder rotators in healthy sport climbers and nonclimbers. *J Athl Train*. (2009) 44:527–30. doi: 10.4085/1062-6050-44.5.527

161. Abreu E, Araújo SR, Da Cançado GH, Andrade AGPD, Chagas MH, Menzel H-JK. TEST-retest reliability of kinetic variables measured on campus board in sport climbers. *Sports Biomech*. (2019) 18:649–62. doi: 10.1080/14763141.2018.1456558

162. Michailov ML, Morrison A, Ketenliev MM, Pentcheva BP. A sport-specific upper-body ergometer test for evaluating submaximal and maximal parameters in elite rock climbers. *Int J Sports Physiol Perform*. (2015) 10:374–80. doi: 10.1123/ijspp.2014-0160

163. Marino TK, Coelho DB, Lima-Silva AE, Bertuzzi R. MBboard: validity and reliability of a new tool developed to evaluate specific strength in rock climbers. *J Hum Kinet*. (2021) 79:5–13. doi: 10.2478/hukin-2021-0060

164. Michailov M, Moritz EF, Haake S. "Evolvement and experimentation of a new interval method for strength endurance development". In: Moritz EF, editor. *Developments for disciplines*. The Engineering of Sport. New York, NY: Springer (2006). Vol. 6, p. 291–6.

165. Pires FO, Lima-Silva AE, Hammond J, Franchini E, Dal' Molin Kiss MA, Bertuzzi R. Aerobic profile of climbers during maximal arm test. *Int J Sports Med*. (2011) 32:122–5. doi: 10.1055/s-0030-1268007

166. Rodio A, Fattorini L, Rosponi A, Quattrini FM, Marchetti M. Physiological adaptation in noncompetitive rock climbers: good for aerobic fitness? *J Strength Cond Res*. (2008) 22:359–64. doi: 10.1519/JSC.0b013e3181635cd0

167. Sheel AW, Seddon N, Knight A, McKenzie DC, Warburton DE R. Physiological responses to indoor rock-climbing and their relationship to maximal cycle ergometry. *Med Sci Sports Exerc*. (2003) 35:1225–31. doi: 10.1249/01.MSS.0000074443.17247.05

168. Rosponi A, Schena F, Leonardi A, Tosi P. Influence of ascent speed on rock climbing economy. *Sport Sci Health*. (2012) 7:71–80. doi: 10.1007/s11332-012-0115-8

169. Draper N, Brent S, Hodgson C, Blackwell G. Flexibility assessment and the role of flexibility as a determinant of performance in rock climbing. *Int J Perform Analy in Sport*. (2009) 9:67–89. doi: 10.1080/24748668.2009.11868465

170. Draga P, Ozimek M, Krawczyk M, Rokowski R, Nowakowska M, Ochwat P, et al. Importance and diagnosis of flexibility preparation of male sport climbers. *Int J Environ Res Public Health*. (2020) 17:1–9. doi: 10.3390/ijerph17072512

171. Baláš J. "Endurance testing in sport climbing,". In: *Book of abstracts form 10th International Montain and Outdoor Sports Conference* (2022). p. 20).

172. Fetz F, Kornexl E. *Sportmotorische Tests. Wien: Pädagogischer Verlag* (1993) p. 20–77. ISBN: 3215113252.

173. Kellawan JM, Tschakovsky ME. The single-bout forearm critical force test: a new method to establish forearm aerobic metabolic exercise intensity and capacity. *PLoS One*. (2014) 9:e93481. doi: 10.1371/journal.pone.0093481

174. España-Romero V, Ortega FB, Vicente-Rodríguez G, Artero EG, Rey JP, Ruiz JR. Elbow position affects handgrip strength in adolescents: validity and reliability of jamar, DynEx, and TKK dynamometers. *J Strength Cond Res*. (2010) 24:272–7. doi: 10.1519/JSC.0b013e3181b296a5

175. Amca AM, Vigouroux L, Aritan S, Berton E. Effect of hold depth and grip technique on maximal finger forces in rock climbing. *J Sports Sci*. (2012) 30:669–77. doi: 10.1080/02640414.2012.658845

176. van Bergen NG, Soekarjo K, van der Kamp J, Orth D. Reliability and validity of functional grip strength measures across holds and body positions in climbers: associations with skill and climbing performance. *Res Q Exerc Sport*. (2022):1–11. doi: 10.1080/02701367.2022.2035662

177. Augste C, Winkler M, Künzell S. Optimization of an intermittent finger endurance test for climbers regarding gender and deviation in force and pulling time. *Front Sports Act Living*. (2022) 4:902521. doi: 10.3389/fspor.2022.902521

178. Michailov M. "Performance limiting factors in climbing,". In: *Book of abstracts form 10th International Montain and Outdoor Sports Conference* (2022). p. 25.

179. Vereide V, Andersen V, Hermans E, Kalland J, Saeterbakken AH, Stien N. Differences in upper-body peak force and rate of force development in male intermediate, advanced, and elite sport climbers. *Front Sports Act Living*. (2022) 4:888061. doi: 10.3389/fspor.2022.888061

180. Peterson E, Murray W, Hiebert JM. Effect of gender and exercise type on relative hand grip strength. *Journal of Strength & Conditioning Research*. (2010) 24:1. doi: 10.1097/01.JSC.0000367192.78257.72

181. Bös K, Schlenker L. "Testaufgaben zur erfassung von komponenten der motorischen leistungsfähigkeit: krafttests,". In: Bös K, editor. *Handbuch motorische tests: sportmotorische tests, motorische funktionstests, fragebögen zur körperlich-sportlichen aktivität und sportpsychologische diagnoseverfahren*. Göttingen: hogrefe (2017). p. 28–49.

182. Bulthuis Y, Drossaers-Bakker W, Oosterveld F, van der Palen J, van de Laar M. Arm crank ergometer is reliable and valid for measuring aerobic capacity during submaximal exercise. *J Strength Cond Res*. (2010) 24:2809–15. doi: 10.1519/JSC.0b013e3181e31242

183. Bös K, Schlenker L. "Testaufgaben zur erfassung von komponenten der motorischen leistungsfähigkeit: beweglichkeitstests,". In: Bös K, editor. *Handbuch motorische tests: sportmotorische tests, motorische funktionstests, fragebögen zur körperlich-sportlichen aktivität und sportpsychologische diagnoseverfahren*. Göttingen: hogrefe (2017). p. 82–90.

184. Ebenchoch F, Höllrigl L, Ebenbichler C, Krassnitzer F, Luchner R, Patterson C, et al. "Current performance testing in elite Austrian sport climbers,". In: *Book of abstracts form 10th International Montain and Outdoor Sports Conference* (2022). p. 23–4.

185. Grosser M, Starischka S. *Konditionstests: theorie und Praxis aller Sportarten. München: blv Sportwissen*. (1981) p. 8–106. ISBN: 3405122244.

186. Weltman A, Snead D, Stein P, Seip R, Schurrer R, Rutt R, et al. Reliability and validity of a continuous incremental treadmill protocol for the determination of lactate threshold, fixed blood lactate concentrations, and VO2max. *Int J Sports Med*. (1990) 11:26–32. doi: 10.1055/s-2007-1024757

187. Steib S, Streber R, Pfeifer K. "Motorische tests für bewegungsbezogene gesungheitsförderung: einzeltests zur erfassung motorischer grundfunktionen,". In: Bös K, editor. *Handbuch motorische tests: sportmotorische tests, motorische funktionstests, fragebögen zur körperlich-sportlichen aktivität und sportpsychologische diagnoseverfahren*. Göttingen: hogrefe (2017). p. 334–468.

188. Stien N, Saeterbakken AH, Andersen V. Tests and procedures for measuring endurance, strength, and power in climbing—a Mini-review. *Front Sports Act Living*. (2022) 4:43. doi: 10.3389/fspor.2022.847447

189. Müller E, Benko U, Raschner C, Schwameder H. Specific fitness training and testing in competitive sports. *Med Sci Sports Exerc*. (2000) 32:216–20. doi: 10.1097/00005768-200001000-00032

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Clinical management of finger joint capsulitis/synovitis in a rock climber

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This case study presents a 23-year-old male recreational rock climber, who climbed an average of 3–4 times per week and presented with finger joint capsulitis/synovitis after increasing his climbing intensity and training from moderate to high over 6 months, which led up to injury. During the exam, the diagnosis was ruled in with clinical orthopedic testing. Additional movement analyses revealed improper gripping mechanics contributing to asymmetric finger loading. A comprehensive rehabilitation program was developed based on the concept of a progressive framework that included unloading of the affected tissues, increasing mobility, improving muscle performance, and correcting suboptimal climbing movements. After 6 weeks, the climber's pain 24 h after climbing, which was rated on a visual analog pain scale (VAS), decreased from 5.5/10 to 1.5/10 and 0/10 at the 12-month follow-up. His patient-specific functional scale improved from 0% at the initial evaluation to 43% after 6 weeks and to 98% after 12 months. His sports-specific disabilities of the arm, shoulder, and hand improved from 69% to 34% to 6% during the initial evaluation, 6-week follow-up, and 12-month discharge. He made a full recovery to his previous grade of V8 bouldering. This is the first case study of its kind to provide a rehabilitation framework for the management of finger joint capsulitis/synovitis in a rock climber.

KEYWORDS

physical therapy, finger pain, joint capsulitis, joint synovitis, rock climbing

Introduction

Rock climbing is a sport that imposes considerable physical demands on the hands and fingers, which play a crucial role in gripping and holding onto the rock while climbing. As a result, the fingers are particularly susceptible to injuries due to the repeated stress and strain placed. Three of the most common finger injuries in rock climbers are injury to the finger flexor pulley system, flexor tendon tenosynovitis, and capsulitis/synovitis (1). Several studies have investigated the prevalence and nature of finger injuries in climbers with incidence rates ranging from 30% to 40% (2–4). A study by Schweizer et al. found that finger injuries accounted for over 38% of all acute and overuse climbing injuries (2). Another study by Schöffl et al. found that over 30% of climbing injuries reported occurred in the fingers (3). Similarly, a study by Grønhaug found that over 40% of climbers self-reported experiencing finger injuries (4). A critical review of the incidence and risk factors for finger injuries in rock climbing additionally identified that the fingers are the most common site of injury (5).

Capsulitis/synovitis accounts for approximately 6%–10% of all climbing injuries and is the second most common injury in the finger (3). Despite a few studies that have examined the epidemiology of hand and finger injuries in rock climbers, there is a lack of research on the management of these injuries, particularly capsulitis and synovitis. With capsulitis and synovitis being such common injuries among climbers, it is important to understand what the condition entails to develop effective management strategies.

Capsulitis is described as an inflammatory condition in a joint capsule. Histologic studies have shown chronic fibrosis of the capsule, with the predominant cells involved being fibroblasts and myofibroblasts (6). Synovitis describes the inflammatory histological changes that occur within an affected joint. This includes synovial lining hyperplasia, infiltration of macrophages and lymphocytes, neoangiogenesis, and fibrosis (7). In climbers, capsulitis/synovitis mostly affects the proximal (PIP) and distal interphalangeal joints (DIP) of the fingers. Capsulitis/synovitis in the PIP joint most often occurs from the high peak pressure within the finger PIP joints during the half or full crimp position (**Figures 1A,B**) (8). The crimp grip in climbing is used when contacting small holds. A half crimp involves flexion of the metacarpophalangeal joint (MCP) and the PIP joint and no hyperextension of the DIP joint (9). A full crimp involves flexion of the MCP and the PIP joint and hyperextension of the DIP joint (9). In addition to compression at the PIP joint during a half crimp, capsulitis/synovitis can occur as well at the DIP joints during full crimping secondary to high forces during DIP hyperextension (**Figure 1B**). In both cases, the stress on the finger joint is localized to one location rather than being spread across the entire joint surface. The onset of finger capsulitis/synovitis in climbers can be chronic and develop over time from repetitive microtraumas, such as climbing with increased volume or intensity or the increased use of the crimp grip. It can also occur secondary to acute trauma, such as twisting the fingers into a crack, losing footing, or hitting the knuckle against the rock wall. With either mechanism, the climber often presents with edema, stiffness, and a dull ache in the dorsal and/or lateral DIP or PIP joint. Symptoms typically decrease with warming-up and mid-range activity (such as ball squeezes or rice bucket finger curls) similar to clinical reports of osteoarthritis (10). However, although capsulitis/synovitis is commonly present during osteoarthritis, it can also occur in isolation and is typically a precursor to chronic osteoarthritis in climbers (8). The article aims to present a case study of a recreational rock climber with finger joint capsulitis/synovitis and provide a comprehensive rehabilitation program based on a progressive framework that resulted in a full recovery and could serve as a basis for future research and management of similar injuries in rock climbers.

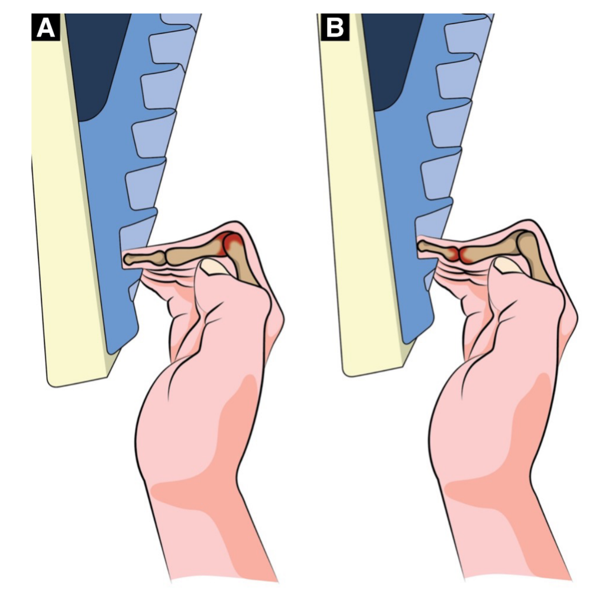

FIGURE 1
(A,B) Left to right. Half and full crimp with the red indicating the major stress regions of each type of crimp.

Methods

A 23-year-old male rock climber, who climbed an average of 3–4 times per week with a combination of indoor climbing during the week and outdoor climbing on the weekend, was evaluated for left fourth digit finger pain in the PIP region. He had 6.5 years of bouldering experience with a pre-injury grade of V8. He reported that, for the first 4–5 years of climbing, he would climb 3 days per week at a moderate intensity and supplement his climbing with core training, weighted pull-ups, shoulder strength exercises, and light training on a fingerboard (hanging bodyweight from the fingers on various depths of edges). The climber reported a history of pain in his finger on and off during that time. He then gradually began increasing the intensity of his climbing from moderate to high. He stopped performing supplemental training exercises but continued fingerboarding with a combination of moderate to maximal hangs (7 s hang followed by 1–3 min rest) and repeater hangs (7–10 s hang followed by 3–5 s rest). In the 6 months, his fingerboard sessions were becoming less structured, and he reported an increased intensity of climbing, which led up to his injury. Although he was feeling gradual discomfort in his finger, he did not fully notice it until during a fingerboard session where he was hanging his body weight on a small edge for 7 s. He discontinued the fingerboard session and attempted to climb the next day, but he still felt finger discomfort. He attempted self-care for several weeks that consisted of decreasing his climbing intensity and stretching his finger into flexion to relieve the pain, but it made the symptoms worse, so he scheduled a physical therapy appointment for an evaluation of the injury. During the evaluation, 2 months after the onset of the injury, he reported moderate finger pain with a severity of 5.5 out of 10 on the visual analog scale (VAS) scale 24 h after climbing with 0 being "no pain" and 10 being "pain as bad as it could possibly be." He also reported a chronic history of right-sided low back pain with increased intensity 8 weeks prior to the evaluation. Secondary to pain, he was limited to climbing to the grade of V5. He denied any radiating pain or numbness in the hand or fingers.

The clinical examination included finger joint range of motion with overpressure, joint compression/distraction, tissue

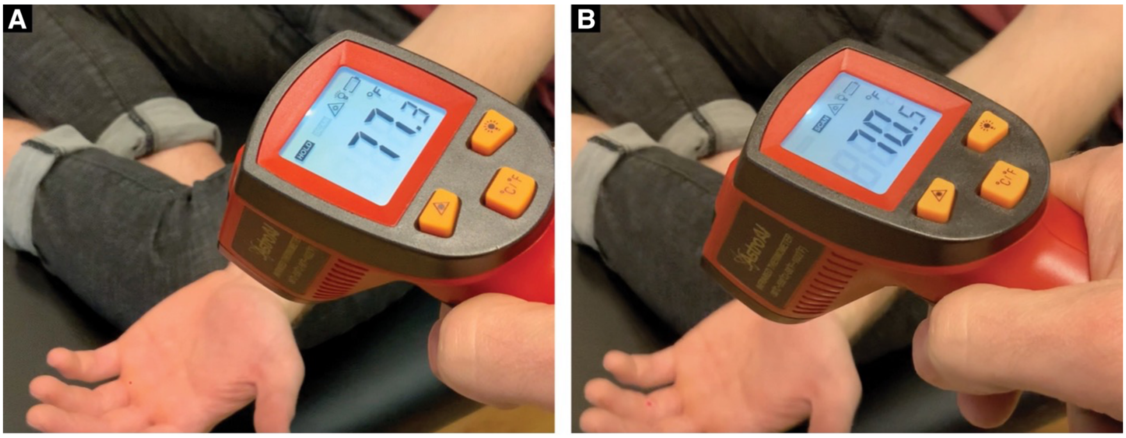

FIGURE 2
(A) Tissue temperature taken at the MCP joint. (B) Tissue temperature taken distal to the PIP joint.

temperature comparisons (AstroAI Infrared Thermometer) above and below the PIP joint (Figure 2), and movement observation of the climber hanging from their fingertips from a fingerboard (Figure 3). Imaging was not available to use for assessment, so the objective tests and measures were used to make a clinical diagnosis. Based on the subjective reports and objective data gathered, the climber 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 (11). Interventions consisted of unloading techniques for the first 2 weeks, icing the finger for 5 min (either in an ice bucket or with a cold compressive gel pack) once per day, wrapping the finger in a self-adherent compression bandage wrap or floss band, and performing active range of motion for three sets of 45 s daily (Figures 4A–C). Additionally, for the duration of 6 weeks, the climber was prescribed daily mobility exercises for three sets of 45 s each including oscillatory PIP joint mobilizations (using a finger trap to separate the joint surfaces and blocking the middle phalanx with the thumb), instrument-assisted soft tissue mobilization of the fingers with moderate pressure, and active straight fingers to hook fist range of motion (Figures 4D–F). The climber was also given strength exercises to be performed three times per week including rubber band flicks and palmer interosseous gripping exercises (Figures 4G–I). The climber was told after 6 weeks that he could reduce the frequency of the mobility and strength exercises from once per day to three times per week. The climber was instructed to refrain from climbing and training for a period of 2 weeks. After this time, he was advised to gradually resume their regular climbing and training schedule of 3–4 sessions per week by adjusting the intensity and volume of their sessions. Six weeks following the start of the program, the climber was given

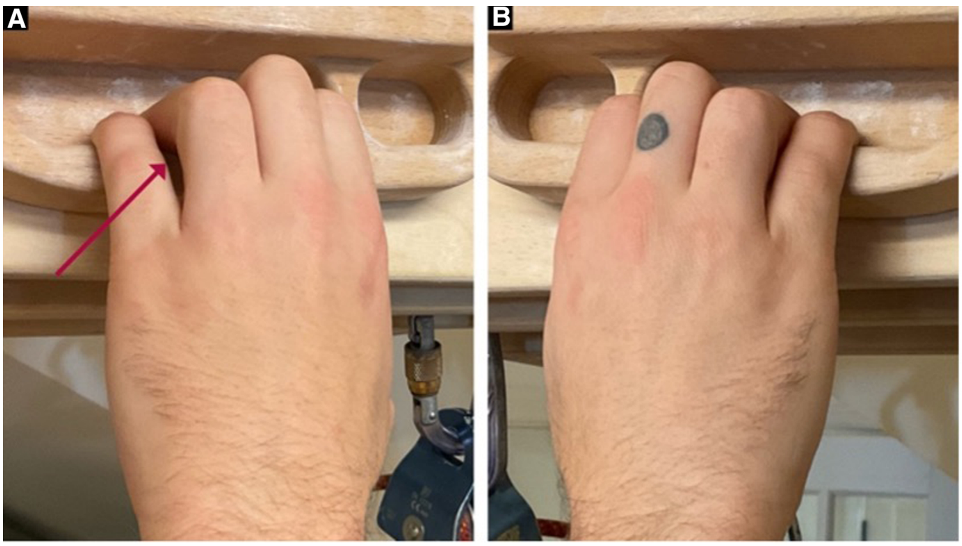

FIGURE 3
(A) Left hand hanging on a fingerboard with fifth digit abduction, MCP flexion, and PIP extension. (B) Right hand hanging on a fingerboard for comparison.

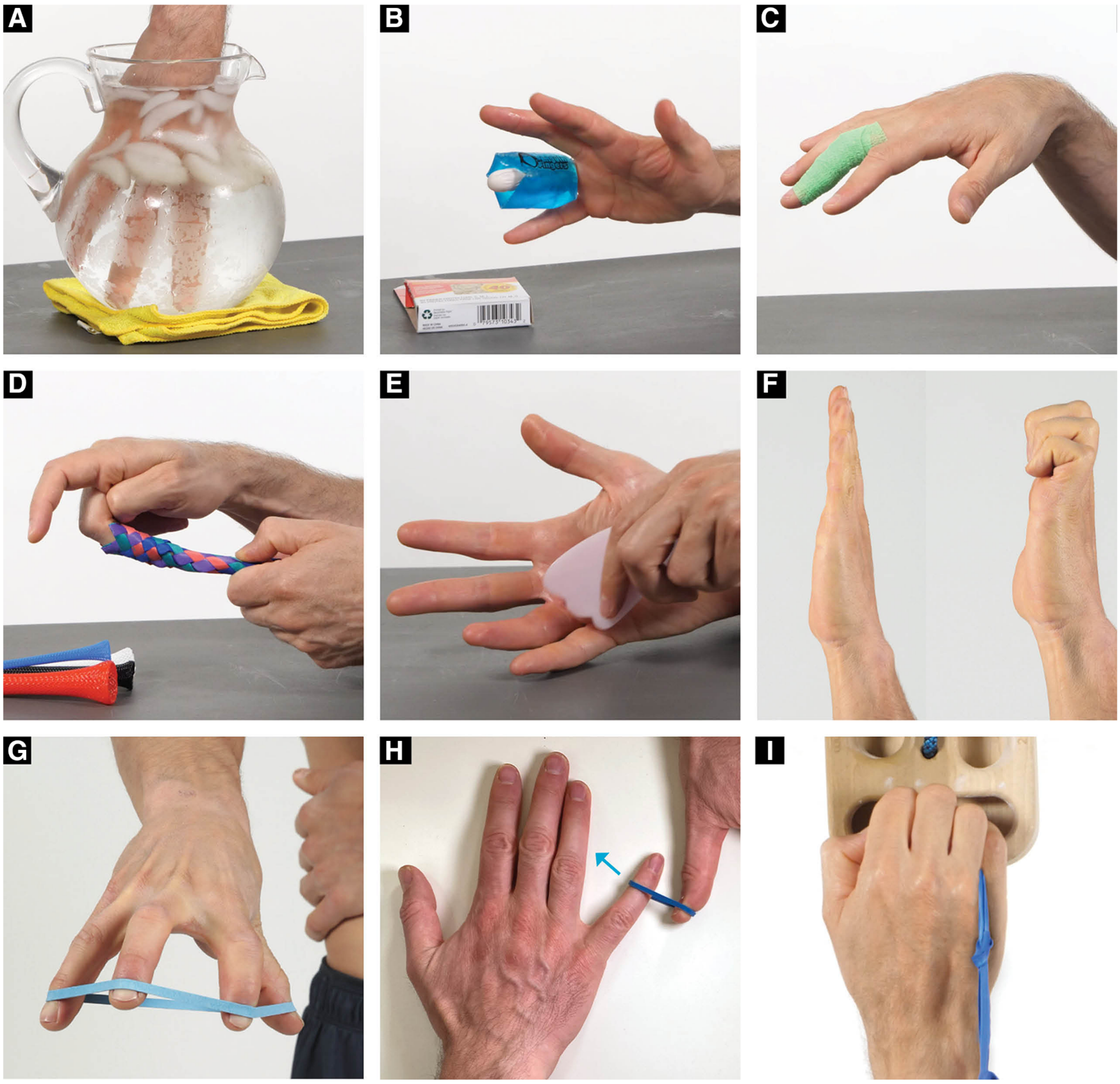

FIGURE 4
(A) Finger icing in water, (B) Finger icing with wrap, (C) Self-adherent compression bandage wrap range of motion, (D) Finger trap oscillations, (E) Instrument assisted soft tissue mobilization, (F) Hook fist active range of motion, (G) Resistance band flicks, (H) Open chain palmer interosseous resistance exercises, (I) closed chain gripping palmer interosseous resistance exercises.

permission to climb without restrictions but advised to self-regulate the volume and intensity of their climbing based on their level of comfort. The climber preferred a treatment structure that consisted of an initial session followed by a home exercise program to allow for self-management, rather than repeated sessions.

Exercises were reviewed during the initial evaluation with manual and verbal feedback, and correct exercise performance was confirmed. Detailed videos and written descriptions of the exercises were provided to the climber. During the first 6 weeks of the program, the climber demonstrated high adherence with almost full compliance, as assessed through a subjective report questionnaire that tracked the number of self-therapy sessions completed. However, as symptoms began to improve, the climber self-reported moderate adherence from week 6 to month 12, with no formal monitoring conducted during this period.

The VAS; sports-specific disabilities of the arm, shoulder, and hand (DASH); and patient-specific functional scale (PSFS) were used to monitor patient progress during the initial evaluation, 6-week follow-up, and 12-month discharge. The VAS was given prospectively, and the sports-specific DASH and PSFS were given retrospectively. The VAS scale, ranging from 0 to 10, was used to measure the patient's pain levels 24 h after climbing, providing a validated subjective measure for pain. The sports-specific DASH is a module within the DASH that was utilized to determine the impact of the injury on sports participation, consisting of four questions related to the injury's effects. The scores of each question were averaged to calculate the percentage of disability. The PSFS was used to identify three self-selected activity limitations, including the climber's ability to crimp on boulder problems, project boulder problems at 80% of maximum intensity, and complete a full training session without modification. Each limitation was scored from 1 to 5 based on the patient's ability to perform, and the scores were averaged to calculate a percentage of ability.

Results

The climber presented with reports of left ring finger pain (dorsal greater than volar) in the region of the PIP joint. He presented with a VAS of 5.5/10, a sports-specific DASH of 69%, and a PSFS score of 0%, 24 h after climbing. During clinical testing, the climber presented with mild swelling of the left fourth PIP joint. Joint overpressure into flexion and extension reproduced 4/10 symptoms and joint distraction decreased symptoms to 0/10 in end-range positions. The climber presented with a 6.8°F decrease in temperature distal to the affected PIP joint (**Figure 2**) on the left fourth digit and only a 3° change on the right hand. A negative Bunnell–Littler test was used to rule out the involvement of intrinsic muscle stiffness limiting the joint range of motion. Additionally, during movement analysis, it was discovered that when the climber hung from a fingerboard, the climber demonstrated an asymmetric position of the fingers on their left hand. The primary fault was excessive left fifth digit metacarpal phalangeal (MCP) flexion and PIP extension (**Figure 3**). The climber performed his home exercise program independently as prescribed for 6 weeks. At the 6-week follow-up, the climber presented with a VAS of 1.5/10, sports-specific DASH of 34%, and PSFS score of 43%, 24 h after climbing. He had returned to training and climbing pain-free at his previous grade of V8 cautiously but without restriction. At the 12-month discharge, his symptoms had decreased to 0/10 24 h after climbing, his sports-specific DASH was reduced to 6%, his PSFS improved to 98%, and his climbing ability improved from V5 with pain to V8 pain-free (**Table 1**).

Discussion

A comprehensive rehabilitation program was developed based on the concepts of a progressive framework that included unloading the affected tissues, increasing mobility, improving muscle performance, and addressing climbing movement and training (**Figure 5**) (9, 11).

The unloading techniques included two methods (ice and active compression) to reduce inflammation and improve mobility in the affected finger. Cold compression has been shown to be effective in decreasing pain and improving mobility in patients with inflammatory conditions such as arthritis (12). Additionally, the climber was told to wrap the digit with a self-adherent compression bandage wrap (less aggressive) or a floss band (more aggressive) and to perform finger flicks. It has been shown that floss band wrapping of peripheral joints can increase joint range of motion, manage pain, and reduce muscle tightness (13). This active compression method was chosen over the use of compression gloves since the research on the effectiveness of passive prolonged compression with gloves in cases of rheumatoid arthritis and hand osteoarthritis remains inconclusive (14).

The rationale behind the mobility techniques was to restore pain-free mobility and reduce joint capsule tissue tension in end-range positions. Finger traps were used during oscillations to allow the climber to obtain a better grip to mobilize the affected finger. The climber was instructed to place the finger in the resting position and to perform three sets of 45 s (15). Additionally, the climber was instructed to perform gentle instrument-assisted soft tissue mobilization to the fingers as this technique has been shown to be effective in improving pain and patient-reported function (16). After the climber improved their joint mobility with the finger trap oscillations and improved adjacent tissue mobility with instrument-assisted soft tissue mobilization, the climber was told to perform an active range of motion of the PIP joint from a straight hand to a hook fist to use the range of motion that they had just gained.

It has been shown in research that there is a deficit in finger extensor strength ratios to finger flexors in rock climbers when compared to non-climbers (17). It is proposed that climbers may benefit from finger extensor training to balance the strength of the muscles that move the fingers. Additionally, the finger extensor tendons (extensor digitorum communis extensor indices and extensor digiti minimi) play a role in micro-adjusting finger position while gripping. In particular, extensor digiti minimi can extend the fifth digit at the MCP joint while gripping to help the climber reduce the excessive MCP flexion of his fifth digit that was observed during fingerboarding. The climber also presented with decreased temperature in the affected finger distal to the PIP joint when compared to the other side which likely was a result of the decreased circulation distal to the PIP injury. While there are no standardized normative values for an acceptable tissue temperature difference to reflect decreased circulation, the fact that commercially available infrared thermometers have been validated for measuring skin surface temperature associated with deep and surrounding wound infections still makes the information useful in the context of the climber's presentation (18). For these reasons, rapid active finger movements into a rubber band (rather than isometric) were prescribed to strengthen the finger extensor tendons and improve finger circulation prior to climbing with the proposed mechanism of

TABLE 1 Subjective report questionnaire.

Questionnaire	Injury onset	6 weeks	1 year
VAS	5.5/10	1.5/10	0/10
Sports-specific DASH	69%	34%	6%
PSFS	0%	43%	98%
Climbing grade	V5	V8	V8

VAS, visual analog scale (from 0 to 10 reported 24 h after climbing); DASH, disabilities of the arm, shoulder, and hand; PSFS, patient-specific functional scale. Sports-specific DASH: The DASH module for assessing the impact of an injury on sports participation comprises four questions pertaining to the injury's effects, and the scores from each question are averaged to determine the percentage disability. PSFS: Three self-selected activity limitations were identified for the climber, which included crimping on boulder problems, projecting boulder problems at 80% of maximum intensity, and completing a full training session without modification. These limitations were scored on a scale of 1–5, based on the patient's ability to perform, and the scores were averaged to calculate a percentage of ability.

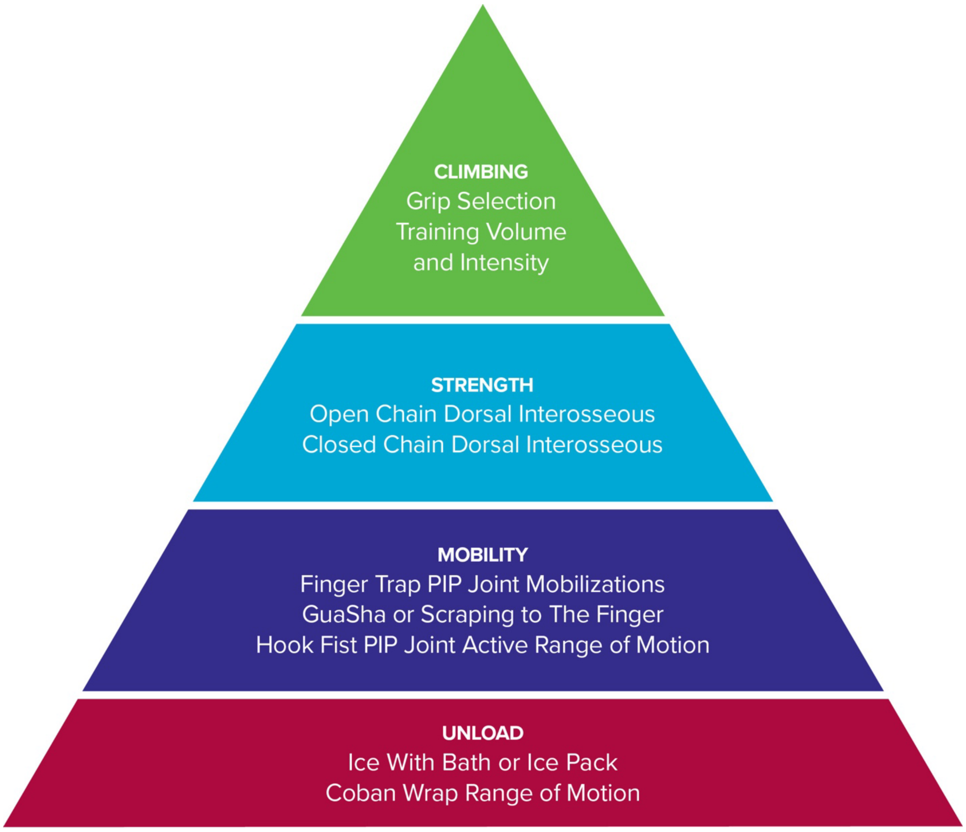

FIGURE 5
Organization of rehabilitation into a framework.

creating a muscle/tendon pump to promote increased tissue temperate through the arterial system and recirculation of the edema through the venous system.

Based on the climber's gripping on the fingerboard, additional exercises were added to improve open and closed kinetic chain finger positions with an emphasis in the fifth digit positioning.

FIGURE 6
Closed kinetic chain interossei exercise demonstrated between the third and fourth digit. The climber performed this same exercise but with the band between the fourth and fifth digit.

Since the climber's fifth digit was abducted, flexed at the MCP joint, and extended at the PIP joint, this can place greater amount of stress on the fourth digit secondary to the loss of lateral support from the pinky. Greater loads while crimping have been shown to increase joint forces and this can potentially lead to joint capsulitis/synovitis (8, 19). Based on this hypothesis, both open chain exercises for the palmar interosseous muscles (in particular the 3rd palmer interosseous) and closed kinetic chain exercises while gripping were given. Both open and closed kinetic chain finger exercises were hypothesized to improve muscle performance (open kinetic chain) and movement coordination (closed kinetic chain) during gripping to reduce joint torsion and PIP loading.

The open kinetic chain exercise was performed by having the climber press their pinky and/or ring finger into a resistance band. The closed kinetic chain exercise was a novel exercise that involved the climber placing a rubber band (connected to a 2 ft string or piece of climbing webbing) between the fourth and fifth digit and squeezing the band tightly as it is pulled downward while trying not to allow the band to slip (**Figure 6**).

Since the climber presented only with mild symptoms, they were recommended to discontinue climbing and training for 2 weeks, followed by a gradual return to full climbing and training intensity while using the crimp grip sparingly. He was encouraged during his return to full climbing and training to focus the movement modification of engaging the fifth digit while crimping. Additionally, since the climber showed signs of decreased temperature to the affected finger, he was given a comprehensive warm-up to perform prior to climbing to improve tissue temperature and prepare the fingers for loading.

Limitations of this case include a sample size of one and lack of imaging to confirm the diagnosis of synovitis/capsulitis. Moreover, there is a paucity of research on the average recovery time and timeline for return to sports following joint synovitis and capsulitis in rock climbers. Therefore, while the climber in this study made steady progress and was able to return to his pre-injury grade of climbing, the effectiveness of the described rehabilitation framework cannot be accurately evaluated or measured in this single study due to the absence of comparable data in the existing literature. The retrospective administration the sports-specific DASH and PSFS at the 12-month follow-up may have introduced recall bias in this study. However, the climber maintained meticulous weekly training logs and notes that were utilized during the evaluation process to minimize the impact of potential bias.

Conclusion

The results of this study suggest that the use of a progressive framework, which includes unloading, mobility, strength, and movement training, holds promise for rehabilitating early-stage finger joint capsulitis/synovitis in rock climbers over short-term (6 weeks) and long-term (1 year) periods. While this study cannot definitively conclude the effectiveness of the progressive framework without comparisons to other treatment approaches, the findings are encouraging and warrant further investigation in future research.

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

Ethical review and approval were 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.

Author contributions

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

Conflict of interest

The author declares 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.2023.1185653/full#supplementary-material.

References

1. Schöffl V, Popp D, Küpper T, Schöffl I. Injury trends in rock climbers: evaluation of a case series of 911 injuries between 2009 and 2012. *Wilderness Environ Med.* (2015) 26(1):62–7. doi: 10.1016/j.wem.2014.08.013

2. Schweizer A, Hudek R, Ruedi TP. Acute injuries and overuse syndromes in sport climbing and bouldering in Switzerland. *Schweizerische Zeitschrift fur Sportmedizin und Sporttraumatologie*. (2005) 53(4):130–6.

3. Schoffl V, Schoffl I, Frank L, Kupper T, Simon M, Lutter C. Tendon injuries in the hands in rock climbers: epidemiology, anatomy, biomechanics and treatment an update. *Muscles Ligaments Tendons J.* (2020) 10(02):233. doi: 10.32098/mltj.02.2020.08

4. Grønhaug G. Self-reported chronic injuries in climbing: who gets injured when? *BMJ Open Sport Exerc Med.* (2018) 4(1). doi: 10.1136/bmjsem-2018-000406

5. Jones G, Johnson MI. A critical review of the incidence and risk factors for finger injuries in rock climbing. *Curr Sports Med Rep.* (2016) 15(6):400–9. doi: 10.1249/jsr.0000000000000304

6. Bunker TD, Reilly J, Baird KS. Expression of growth factors, cytokines, and matrix metalloproteinases in frozen shoulder. *JBJS.* (2000) 82-B:768–73. doi: 10.1302/0301-620X.82B5.0820768

7. Scanzello CR, Goldring SR. The role of synovitis in osteoarthritis pathogenesis. *Bone.* (2012) 51(2):249–57. doi: 10.1016/j.bone.2012.02.012

8. Schöffl V, Schöffl I, Lutter C, Hochholzer T, editors. *Climbing medicine: a practical guide*. Springer Nature (2022).

9. Vagy J. *Climb injury-free*. Los Angeles, CA: The Climbing Doctor (2016).

10. Chow YY, Chin KY. The role of inflammation in the pathogenesis of osteoarthritis. *Mediat Inflamm.* (2020) 2020. doi: 10.1155/2020/8293921

11. Vagy J. Case report: using telehealth to treat triceps tendinopathy in a rock climber. *Front Sports Act Living.* (2022) 4. doi: 10.3389/fspor.2022.829480

12. Uludağ E, Kaşikçi KM. The effect of local cold compression upon pain and movement restriction among patients with knee osteoarthritis. *Austin J Nurs Health Care*. (2019) 6(1):1048. doi: 10.26420/austinjnurshealthcare.2019.1048

13. Jianhong G, Soon CC, Seng TJ, Zaremohzzabieh Z, Samsudin S. The effect of tissue flossing technique on sports and injury prevention and rehabilitation: a systematic review of recent research. *Int J Hum Mov Sports Sci.* (2021). doi: 10.13189/saj.2021.090611

14. Hammond A, Jones V, Prior Y. The effects of compression gloves on hand symptoms and hand function in rheumatoid arthritis and hand osteoarthritis: a systematic review. *Clin Rehabil*. (2016) 30(3):213–24. doi: 10.1177/0269215515578296

15. Kaltenborn FM. *Manual mobilization of the joints: vol I the extremities*. Olaf Norlis Bokhandel; OPTP (Orthopedic Physical Therapy Products) (2011).

16. Cheatham SW, Lee M, Cain M, Baker R. The efficacy of instrument assisted soft tissue mobilization: a systematic review. *J Can Chiropr Assoc*. (2016) 60(3):200.

17. Vigouroux L, Goislard de Monsabert B, Berton E. Estimation of hand and wrist muscle capacities in rock climbers. *Eur J Appl Physiol*. (2015) 115:947–57. doi: 10.1007/s00421-014-3076-6

18. Mufti A, Coutts P, Sibbald RG. Validation of commercially available infrared thermometers for measuring skin surface temperature associated with deep and surrounding wound infection. *Adv Skin Wound Care*. (2015) 28(1):11–6. doi: 10.1097/01.asw.0000459039.81701.b2

19. Schweizer A. Biomechanical properties of the crimp grip position in rock climbers. *J Biomech*. (2001) 34(2):217–23. doi: 10.1016/S0021-9290(00)00184-6

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Top of the podium, at what cost? injuries in female international elite climbers

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Objectives: Competitive sport climbing has made its way to the Olympic stage. This prestige has brought about route setting and training alterations which presumably affect injury epidemiology. Most of the climbing injury literature contains male climbers and lacks high performing athletes. Studies with both female and male climbers, rarely included separate analyses for performance level or sex. Therefore, injury concerns for elite female competitive climbers are impossible to discern. A former study examined the prevalence of amenorrhea in elite international female climbers ($n = 114$) and reported that 53.5% had at least one injury in the past 12 months, but injury details were excluded. This study's aim was to report these injury details and their associations with BMI, menstrual status and eating disorders of the cohort.
Methods: Online survey was emailed to competitive female climbers recruited through the IFSC database between June and August 2021. Data was analyzed using Mann–Whitney U, χ^2 and logistic regression.
Results: 229 registered IFSC climbers opened the questionnaire and 114 (49.7%) provided valid responses. Respondents (mean ± SD; age = 22.9 ± 5 year) represented 30 different countries and more than half (53.5%, $n = 61$) reported an injury in the prior 12 months with the majority in shoulders (37.7%, $n = 23$) and fingers (34.4%, $n = 21$). Injury prevalence in climbers with amenorrhea was 55.6% ($n = 10$). BMI was not a significant predictor of injury risk (OR = 1.082, 95% CI: 0.89, 1.3; $p = 0.440$) while accounting for current ED over the past 12 months. However, the odds ratio for having an injury was doubled for those with an ED (OR = 2.129, 95% CI: 0.905, 5.010; $p = 0.08$).
Conclusion: With over half reporting recent injuries (<12 months) mostly to shoulders and fingers, development of new strategies for injury prevention in competitive female climbers are warranted. In addition, climbers with disordered eating behaviors and/or menstrual disturbances might be more prone to injury. More research in this population is required. Suitable screening to prevent these health issues and proper monitoring of these athletes are paramount to long-term athlete success.

KEYWORDS

climbing, climbing injuries, BMI, eating disorders, sports injuries, sport medicine

1. Introduction

Climbing has gained momentum as a competitive sport, especially with its recent debut in the 2020 Tokyo Olympic Games. With the required Olympic climbing format, which currently (Paris 2024) includes two medals for each sex: one medal for a combination of boulder + lead (combined) and one for speed, it's expected that more task-specific training strategies will be employed (1–5). It is likely that these objectives will create higher injury susceptibility to these competitive climbers. Additionally, climbers with lower abilities and route setters at commercial gyms tend to look to the elite for inspiration. Thus, the anticipated augmented volume-overload training in elite climbers may create higher injury susceptibility at the pre-Olympic level and most likely will impact injury rates in climbers of all abilities.

In general, chronic injuries in sports result from repetitive movement with high stress including either excessive loading, insufficient recovery and/or inadequate energy intake (6–10). Previous studies have demonstrated that fingers, elbows, and shoulders are the most prevalent site of injury in climbing (11–14). Most studies examining injury rates of climbers that include females and males do not report their injury rates or injury sites between these two sexes (15–21). Climbing style (i.e., top rope, bouldering, speed) (22, 23), performance level (i.e., beginner, advanced, elite) and competitiveness (local gym, national, international) were also not often distinguished within the climbing injury literature (15–21). Lutter et al. (24) presented a narrative review of the literature on injuries in competition climbing and concluded that data was scarce, of low quality and only one study included a sex-specific analysis (25). Furthermore, the majority of data collected on competitive climbers has been dominated by male participants ranging from 60%–100% (24). One study that collected injury survey data on athletes (312 females, 262 males) competing in a variety of sports found sex differences occurred for injury location as well as in type of sport and were somewhat explained by the differences in training hours (26). Therefore, more research is needed on female climbers, especially in high-level competitors and their rates of injury, location and their etiology.

Thus, the aim of this paper was to report the injury data collected in a previously published study that examined the prevalence of amenorrhea in elite-level female climbers registered with the International Federation of Sport Climbing (IFSC) (27). Additionally, we conducted an exploratory analysis to understand whether factors such as body mass index (BMI), eating disorders (ED) or menstrual status were associated with the number of injuries in this cohort.

2. Methods

An electronic survey was developed in Qualtrics (Qualtrics XM 2021, Provo UT) and consisted of a total of 33 questions. The survey was distributed by the IFSC to competition climbers with an international license. A total of 229 climbers registered in the IFSC database opened the questionnaire and 114 participants (49.7%) completed the questions in full. The survey included questions developed by the researchers related to the following sections: (1) demographics and anthropometrics (e.g., height, weight), (2) climbing resume (e.g., training volume, discipline), (3) behaviors related to changing body weight, (4) eating behaviors, (5) injuries and (6) menstrual history. Questions were formatted for responses that were multiple choice (i.e., select one answer and select all that apply), sliding scale, and text-entry/open-ended. Injury-related questions asked about the number of injuries and location of injury (e.g., finger, arm, calf). Participants also self-reported whether they thought their injury was classified as acute (e.g., an injury with a sudden onset) or chronic/overuse (e.g., an on-going issue).

Climbers were recruited through the IFSC database between June and August 2021. All climbers were required to be licensed with one of the 57 IFSC federations (28, 3) if competing in IFSC sanctioned events prior to a competition for the calendar year. Survey links were dispersed to all IFSC licensed members via email with consent collected after opening the survey and advancing to the second page. Due to this recruitment process, the researchers were unable to track how many female athletes received this email and/or opened it. The major outcome variable of the study, injury prevalence, was defined as the number of participants that responded yes to having at least one injury within the past 12 months. Factors hypothesized to influence injury rate that were explored included: body mass index (BMI; kg/m^2), menstrual status (i.e., amenorrhea, no amenorrhea), and eating disorder prominence (i.e., eating disorder, no eating disorder).

BMI was classified as followed: <18.5 kg/m^2, underweight; 18.5–24.9 kg/m^2, healthy; 25.0–29.9 kg/m^2, overweight, and ≥30.0 kg/m^2, obese.

Eating disorder status (i.e., eating disorder, no eating disorder) was determined according to how respondents replied to prompt 31 on the survey. A "no eating disorder" classification was assigned if any of these 3 were checked "I have disordered eating patterns", "I don't have any of the above issues currently" or "I am unsure". Further detail on the methods has been previously reported (29).

2.1. Statistics

For descriptive statistics, categorical data is reported as *n* (%) and continuous data is reported as mean ± standard deviation.

For exploratory analyses, a Mann-Whitney U independent samples test was used to determine whether there was a statistical difference between the overall number of self-reported injuries between climbers meeting criteria for amenorrhea compared to non-amenorrhea. Effect size for the Mann–Whitney *U* tests was calculated as $r = z/\sqrt{n}$ and defined as: small effect, $r = .1$; medium effect, $r = .3$, and large effect, $r = .5$ (29).

A χ^2 test was used to determine if there was a statistical difference between the prevalence of injury within the past 12 months between climbers who met criteria for amenorrhea compared to those who did not meet criteria for amenorrhea. Lastly, a logistic regression was used to assess whether BMI was associated with higher odds of self-reported injury (0 = no injury, 1 = injury), accounting for eating disorder status (0 = no eating disorder, 1 = eating disorder) in the model. Results were computed using IBM SPSS Statistics for Windows, version 28.0 (IBM Corp., Armonk, N.Y., USA). Statistical significance was defined as $p < 0.05$.

3. Results

3.1. Demographic and training variables

On average, the sample of 114 respondents included female climbers from 30 different countries, were aged 22.9 ± 5 years spanning from 16 to 40 years. Participants reported partaking in their first competition at the age of 12.9 ± 5.1 years and ranged from 6 to 30 years. The average BMI (range 15.4–27.2) of the participants ($n = 110$) was classified as healthy at 20.7 ± 1.9 kg/m^2. Three climbers did not report their height and one climber did not report weight, thus BMI could not be calculated for 4 climbers. A total of 18 climbers (15.8%) were identified as meeting criteria for amenorrhea and 37 (32.4%) indicated they had least one eating disorder. Of the 18 climbers classified with amenorrhea 10 (55.6%) reported at least one injury the past 12 months.

The respondents reported training for an average of 3.4 ± 1.2 h per training day and 5.2 ± 1.7 days per week (9 athletes reported that they were not currently training) with the majority of climbers (82; 78%) training at least 5 days per week. Of those training, 20 (17.5%) athletes had double trainings one day per week, 31 (27.2%) had double trainings two days per week, 11 (9.2%) had double trainings three days per week, 8 (7.0%) had double trainings four days per week, and 3 (2.6%) indicated that five days a week they had double training sessions within the same day. In the past 6 months, 17 (14.9%) competed in speed, 60 (52.6%) competed in bouldering, and 40 (35.1%) in lead. Only 11 (10%) had competed in a combined event (scores tallied in two or more disciplines within the same competition). Almost half of the athletes, 51 (45%) received financial sponsorship for sport climbing within the past 6 months.

3.2. Self-reported injury prevalence

Of the respondents, 61 (53.5%) reported they had experienced at least one injury in the past 12 months. The majority of the injured climbers experienced only one (21.9%, $n = 25$) or two (21.9%, $n = 25$) injuries. Only a few climbers reported three injuries (7%, $n = 8$) or four (2.6%, $n = 3$) injuries and there were no climbers who reported five or more injuries within the past 12 months. The majority of the injuries were to the shoulder (37.7%, $n = 23$) and finger(s) (34.4%, $n = 21$) followed by ankle/foot (32.8%, $n = 20$) and knee (27.9%, $n = 17$). All athletes who reported an injury stated that they sought a health professional for treatment for the injury.

3.3. Exploratory analyses of factors associated with self-reported injury

The prevalence of injury in those who met criteria for amenorrhea was 55.6% ($n = 10$). On average, there was no difference ($U = 241.5$, $z = -0.284$, $p = 0.78$, $r = -0.04$) in the number of injuries self-reported by climbers who met criteria for amenorrhea ($n = 10$, 1.70 ± 0.68, median = 2) compared to those who did not meet criteria for amenorrhea ($n = 51$, 1.84 ± 0.88, median = 2). The proportion of climbers self-reporting an injury within the last 12 months who met criteria for amenorrhea was not different between the climbers who did not meet criteria for amenorrhea [Chi square (χ^2) = 0.036, $p = 0.85$]. Body mass index was not a significant predictor of injury risk (OR = 1.082, 95% CI: 0.89, 1.3; $p = 0.440$) while accounting for current eating disorders over the past 12 months. Although not statistically significant, the odds ratio for having an injury was doubled for participants indicating they had an eating disorder (OR = 2.129, 95% CI: 0.905, 5.010; $p = 0.08$).

4. Discussion

To the best of our knowledge the present study is the first to focus on injuries among international elite competitive female climbers. The main finding was that 53.5% of the athletes reported at least one injury within the past year, mostly injured shoulders and fingers. Compared to other individual sports, the rate of injuries in climbers, whether chronic or acute, is almost twice as high (30). Additionally, in many sports, elite athletes experience more injuries than lower-level athletes, and individual sports have fewer injuries than team sports (31). Although the findings of the present study with elite-level female climbers presents an injury rate greater than what is expected when comparing with other sports (31), it is still in line with a previous study of elite competitive climbers (32). Furthermore, compared with female artistic gymnasts the rate of shoulder injuries were similar (33) suggesting that the load to the shoulders in climbing is comparable to gymnastics. Comparing the present study with previous studies is difficult as most do not report sex-specific analyses. Still, the rate of injuries has been more or less the same for more than a decade and the one previous study that reported sex-specific analyses found similar injury rates in elite female climbers (13, 34).

4.1. Injuries

Injuries among climbers at a high level of performance has been assessed in 11 studies (24) reporting injury rates from 50% (13) to 61% (34). Thus, the present findings are in line with or slightly lower than previous studies. Still, comparisons between

TABLE 1 Number of injuries ($n = 132$) self-reported in the IFSC female athletes who experienced an injury ($n = 61$) during the year prior to June-August 2021.

Injury site	Shoulder	Finger	Foot/ankle	Knee	Elbow	Low back	Wrist	Hip	Neck	Thigh	Toe	Head
Acute	11	11	16	8	5	5	1	3	2	1	2	0
Chronic	12	10	4	9	10	9	6	3	2	1	0	1
Total number of injuries	23	21	20	17	15	14	7	6	4	2	2	1

studies is challenging due to differences in the populations studied and the difference in the definition of an "elite" or "competitive" athlete. In the present study we included only those who were registered as competing in international level events organized or recognized by the IFSC. Thus, the present study is the first to present analyses on injuries in an elite group of female climbers.

Lutter et al. (24) speculated that a change in the onset of injury site may come as a consequence of new route setting techniques and/or sizes of holds or volumes on indoor walls and competitive settings (24). If such a change is to come it is likely to occur first among the high performing athletes who initiate new trends in route setting and training. Route setting on climbing walls and in competitions are to climbing what course setting is to ski racing. The ski race course design influences skier injuries in ski racing, which has been widely debated and studied for several years (35, 36). These reports have guided stakeholders to minimize the risk for injuries by changing the ski course and by developing injury prevention training programs for both the elite and recreational athletes (37). Minimizing injury risks by analyzing and interpreting movement patterns and setting climbing routes accordingly might help climbers like it has helped skiers.

Previous studies on injuries in climbing have found the fingers to be injured more often than any other anatomical site (18, 25, 34, 15, 17). The present study is the first to show more injuries to the shoulders than the fingers (**Table 1**) in a climbing population. When compared to the only other sex-specific analysis from 2018 (34) there is a change from fingers being most prevalent in the previous study (29.8% fingers vs. 21.9% shoulders) to shoulders in the present study (38% shoulders vs. 34% fingers).

This possible change in the most prevalent site of injuries for the female climber from the fingers to the shoulders might be a sign of how the change in route setting has evolved over the last decade. Climbing routes have transformed from being slightly overhanging walls to severely overhung that involve several no-feet jumps. However, it must be noted that the difference in number of injuries in the present study between the shoulders and fingers were small (23 vs. 21 cases or 38% vs. 34%). Further studies are needed before we can conclude if this is a matter of the present study focusing on elite level female climbers or if the findings in this study are the first to document a shift in the epidemiology of injuries in climbing.

The findings in the present study showed a higher prevalence of injuries to the knees and ankles than in one other study including injuries of female climbers (34). Combined with the shoulders as the most prevalent site of injury in climbing in the present study, the finding of more injuries to the knees further strengthens the anticipation that there is a shift in terms of where and how often climbers are injured.

Most chronic injuries may be prevented with appropriate action by athletes, stakeholders and organizers of the sport. Similar to competitive skiing, some climbing injuries might be prevented by adjusting training and resting protocols, and/or changing the competition rules or routes.

Regardless whether the current study premiers a shift in injury site or not, more focus is clearly needed on climbing shoulder injuries in terms of potential diagnosis, treatment and return to sport protocols.

4.2. BMI/injuries

There is a dearth of research looking at possible interaction between BMI and injuries in climbers. One previous study (38) used an univariable general linear model to assess a potential association of higher BMI and injuries and found none. In the present study, BMI was not a significant predictor of injury risk (OR = 1.082, 95% CI: 0.89, 1.3; $p = 0.440$) while accounting for current eating disorders over the past 12 months. Although not statistically significant, the odds ratio for having an injury was doubled for participants indicating they had an eating disorder (OR = 2.129, 95% CI: 0.905, 5.010; $p = 0.08$). Still with a 2.1 odds ratio, it raises awareness and skepticism to the practical use of BMI as a tool for health monitoring in climbing. This supports the conclusion of Joubert et al. (39) that there is a need for better health monitoring for athletes and inclusion of education for both trainers and athletes to avoid injuries related to having a low BMI, eating disorders or disordered eating behaviors. While not all cases of low BMI are a result of low energy availability, any climber may be in an energy deficit at any given time. If that time of energy deficit coincides with high loads of training or an injury, recovery will most likely take longer than when compared with recovery with adequate dietary energy intake.

4.3. Medical aid

All of the climbers in the present study who reported an injury sought medical aid (**Table 2**) from a health professional. This is contradictory to the other studies that assessed the use of health care among injured climbers (40, 41). Grønhaug & Saeterbakken (41) reported that although the majority of climbers did not seek

TABLE 2 Overview of injuries and use of health care.

	Yes		No	
	n	%	*n*	%
Injury past 12 months	61	53.5	53	46.5
Number of injuries				
1	25	21.9		
2	25	21.9		
3	8	7		
4	3	2.6		
Did you seek health care?				
	61	100		

health care, the female climbers were more likely to seek medical aid than their male counterparts (41.7% vs. 27.3%).

As all the respondents in the present study sought medical aid, it is most likely an accessibility benefit to the climbers in the present study, since each team within the IFSC is required to have a medical commission. Additionally, the use of health care might be more about whether or not the climbers believe that the health personnel is capable to help with their injury. The female international elite climbers are all part of national teams within their own federations accompanied by health personnel that presumably are knowledgeable to treat climbing specific injuries.

4.4. Strengths and limitations

This study was a cross-sectional open on-line survey where injury prevalence was only a portion of the questions asked. It is very likely that some IFSC registered climbers with injuries may have been reluctant to take part in an online survey that included questions about menstrual health and eating behaviors.

The survey was open during the three months while most participants were in the midst of the international competitive season. This timing may have influenced their responses on questions regarding body weight. This may have been a prime time for these athletes to lower their weight to competition weight and the self-reported data collected may not have reflected their usual body weight.

A weakness of the study was absence of a medical examination on the reported injuries. Although the questionnaire specified that the study inquired about injuries, it is not guaranteed that the respondents reported the correct number of injuries within the past 12 months, or simply reported a sensation of pain that may or may not have been a true injury. Also, the survey neglected to ask if the injury occurred during climbing. Still, this is a weakness of all self-reported studies on the prevalence of injuries in sports.

A strength of the study was that all participants were international elite climbers. Performing research on a specific group of athletes makes the results easier to interpret and thereby increases the likelihood that the results may be used to develop medical screening guidelines, education and injury prevention strategies specifically targeted to this population.

5. Conclusion

With our cohort majority reporting injuries (<12 months) mostly to shoulders and fingers, this calls for development of new strategies for injury prevention to reduce injury susceptibility in female climbers. In addition, although this research did not make a strong case for this, climbers with disordered eating behaviors and/or menstrual disturbances might be more prone to injuries and require medical care interventions to attenuate injuries and protect health. More research on female competitive climbers is clearly needed. Health monitoring and injury prevention are paramount to long-term athlete success in other sports and climbing should be no exception.

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 ethics committee at Northern Michigan University (IRB#HS21-1208). Written informed consent to participate in this study was provided by the participant and all minors' legal guardian/next of kin.

Author contributions

Contributorship GG, LMJ, MCN: developed the questionnaire. MCN: provided the statistics GG, LMJ, AHS, SND, MCN: all contributed writing the manuscript. 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1121831/full#supplementary-material.

SUPPLEMENTARY TABLE 1
Full overview of survey questions.

References

1. IFSC. IFSC. 11 29, (2022). Available at: https://www.ifsc-climbing.org/index.php/news/804-boulder-lead-ifsc-officially-launches-paris-2024-olympic-format#:~:text=There%20will%20be%20four%20Boulder,for%20athlete%20and%20spectator%20clarity

2. Kozina Z, Uvarova N, Cieslicka M, Bejtka M, Jagielo M. Experimental substantion of the program of the annual cycle of preparation of climbers 16–17 years to the compeive discipline "climbing combined". *J Phys Educ Sport*. (2020) 20:1250–7. doi: 10.7752/jpes.2020.s2174

3. Lutter C, Tischer T, Cooper C, Frank L, Lenz R, Schöffl V. Mechanisms of acute knee injuries in bouldering and rock climbing. *Am J Sports Med*. (2020) 48:730–8. doi: 10.1177/0363546519899931

4. Shunko A, Kravchuk X. Competitive modelling in speed climbing. *J Phys Educ Sport*. (2020) 26:00051. doi: 10.7752/jpes.2022.12396

5. Lutter C, Tischer T, Schöffl VR. Olympic Competition climbing: the beginning of a new era; a narrative review. *Br J Sports Med*. (2020) 15:857–64. doi: 10.1136/bjsports-2020-102035

6. Saul D, Steinmetz G, Lehmann W, Schilling AF. Determinants for success in climbing: a systematic review. *J Exerc Sci Fit*. (2019) 17:91–100. doi: 10.1016/j.jesf.2019.04.002

7. Stefan RR, Camic CL, Miles GF, Kovacs AJ, Jagim AR, Hill CM. Relative contributions of handgrip and individual finger strength on climbing performance in a bouldering competition5. *Int J Sports Physiol Perform*. (2022) 17:768–73. doi: 10.1123/ijspp.2021-0422

8. Stien N, Pedersen H, Vereide VA, Sæterbakken AH, Hermans E, Kalland J, et al. Effects of two vs four weekly campus board training sessions on bouldering perfomance and climbing specific tests in advanced and elite climbers. *J Sports Sci Med*. (2021) 20:438. doi: 10.52082/jssm.2021.438

9. Torstveit MK, Sundgot-Borgen J. Participation in leanness sports but not training volume is associated with menstrual dysfunction: a national survey of elite athletes and controls. *Br J Sports Med*. (2005) 39:141–7.

10. De De Souza MJ, Toombs RJ, Scheid JL, O'Donnell E, West SL, Williams NI. High prevalence of subtle and severe menstrual disturbances in exercising women: confirmation using daily hormone measures. *Hum Reprod*. (2010) 2:491–503. doi: 10.1093/humrep/dep

11. Cole KP, Uhl RL, Rosenbaum AJ. Comprehensive review of rock climbing injuries. *Am Acad Orthop Surg*. (2020) 28(12):e501–9. doi: 10.5435/JAAOS-D-19-00575., s.l

12. Chang CY, Torriani M, Huang AJ. Rock climbing injuries: acute and chronic repetitive trauma. *Curr Probl Diagn Radiol*. (2016) 3:205–14. doi: 10.1067/j.cpradiol.2015.07.003

13. Chen DL, Meyers RN, Provance AJ, Zynda AJ, Wagner KJ 3rd, Siegel SR, et al. Early sport specialization and past injury in competitive youth rock climbers. *Wilderness Environ Med*. (2022) 33(2):179–86. doi: 10.1016/j.wem.2022.03.002

14. Lutter C, Hotfiel T, Tischer T, Lenz R, Schöffl V. Evaluation of rock climbing related injuries in older athletes. *Wilderness Environ Med*. (2019) 4:362–8. doi: 10.1016/j.wem.2019.06.008

15. Jones G, Asghar A, Llewellyn DJ. The epidemiology of rock-climbing injuries. *Br J Sports Med*. (2008) (9):773–8. doi: 10.1136/bjsm.2007.037978

16. McDonald JW, Michael Henrie A, Teramoto M, Medina E, Willick S. Descibriptive epidemiology, medical evaluation, and outcomes of rock climbing injuries. *Wilderness Environ Med*. (2017) 3:185–96. doi: 10.1016/j.wem.2017.05.001

17. Schöffl V, Morrison A, Schöffl I, Küpper T. The epidemiology of injury in mountaineering, rock and ice climbing. *Med Sport Sci*. (2012) 58:17–43. doi: 10.1159/000338575

18. Woollings KY, McKay CD, Emery CA. Risk factors for injury in sport climbing and bouldering: a systematic review of the literature. *Br J Sports Med*. (2015) 17:1094–9. doi: 10.1136/bjsports-2014-094372

19. Folk L, Alex K. Characterizing the consequences of chronic climbing-related injury in sport climbers and boulderers. *Wilderness Environ Med*. (2013) 2:153–8. doi: 10.1016/j.wem.2012.11.010

20. Cobos-Moreno P, Astasio-Picado Á, Gómez-Martín B. Epidemiological study of foot injuries in the practice of sport climbing. *Int J Environ Res Public Health*. (2022) 7:4302. doi: 10.3390/ijerph19074302

21. Müller M, Heck J, Pflüger P, Greve F, Biberthaler P, Crönlein M. Characteristics of bouldering injuries based on 430 patients presented to an urban emergency department. *Injury*. (2022) 4:1394–400. doi: 10.1016/j.injury.2022.02.003

22. Stien N, Saeterbakken AH, Hermans E, Vereide VA, Olsen E, Andersen V. Comparison of climbing-specific strength and endurance between lead and boulder climbers. *PLoS On*. (2019) 14(9):e0222529. doi: 10.1371/journal.pone.0222529

23. Fanchini M, Violette F, Impellizzeri FM, Maffiuletti NA. Differences in climbing-specific strength between boulder and lead rock climbers. *J Strength Cond Res*. (2023) 27(2):310–4. doi: 10.1519/JSC.0b013e3182577026

24. Lutter C, Tischer T, Schöffl VR. Olympic competition climbing: the beginning of a new era-a narrative review. *Br J Sports Med*. (2021) 55(15):857–64. doi: 10.1136/bjsports-2020-102035

25. Grønhaug G, Norberg M. First overview on chronic injuries in sport climbing: proposal for a change in reporting of injuries in climbing. *BMJ Open Sport Exerc Med*. (2016) 2(1):e000083. doi: 10.1136/bmjsem-2015-000083

26. Ristolainen L, Heinonen A, Waller B, Kujala UM, Kettunen JA. Gender differences in sport injury risk and types of inju-ries: a retrospective twelve-month study on cross-country skiers, swimmers, long-distance runners and soccer players. *J Sports Sci Med*. (2009) 3:443–51. PMCID: PMC3763291.

27. Joubert L, Warme A, Larson A, Grønhaug G, Michael M, Schöffl V, et al. Prevalence of amenorrhea in elite female competitive climbers. *Front Sports Act Living*. (2022) 4:895588. doi: 10.3389/fspor.2022.895588

28. International federation of sports. climbing, Available at: https://www.ifsc-climbing.org/index.php/2-uncategorised/281-member-federations

29. Rosenthal R. Parametric measures of effect size. In: Cooper H, Hedges LV, editors. *The handbook of research synthesis*. New York: Russell Sage Foundation (1994).

30. Franco MF, Madaleno FO, de Paula TMN, Ferreira TV, Pinto RZ, Resende RA. Prevalence of overuse injuries in athletes from individual and team sports: a systematic review with meta-analysis and GRADE recommendations. *Braz J Phys Ther*. (2021) 25(5):500–13. doi: 10.1016/j.bjpt.2021.04.013

31. Prieto-González P, Martínez-Castillo JL, Fernández-Galván LM, Casado A, Soporki S. Epidemiology of sports-related injuries and associated risk factors in adolescent athletes: an injury surveillance. *Int J Environ Res Public Health*. (2021) 18(9):4857. doi: 10.3390/ijerph18094857

32. Lhee S-H, Jain R, Madathur Sadasivam M, Kim S, Bae M, Yu J, et al. Sports injury and illness incidence among South Korean elite athletes in the 2018 Asian games: a single-physician prospective study of 782 athletes. *BMJ Open Sport Exerc Med*. (2021) 7:e000689. doi: 1

33. Hinds N, Angioi M, Birn-Jeffrey A, Twycross-Lewis R. A systematic review of shoulder injury prevalence, proportion, rate, type, onset, severity, mechanism and risk factors in female artistic gymnasts. *Phys Ther Sport*. (2019) 35:106–15. doi: 10.1016/j.ptsp.2018.11.012

34. Grønhaug G. Self reported chronic injuries in climbing: who gets injured when. *BMJ Open Sport Exerc Med*. (2018) 4:e000406. doi: 10.1136/bmjsem-2018-000406

35. Spörri J, Kröll J, Amesberger G, Blake OM, Müller E. Perceived key injury risk factors in world cup alpine ski racing—an explorative qualitative study with expert stakeholders. *Br J Sports Med*. (2012) 46(15):1059–64. doi: 10.1136/bjsports-2012-091048

36. Spörri J, Kröll J, Schwameder H, Scheifermüller C, Müller E. Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. *Br J Sports Med*. (2012) 46:1072–7. doi: 10.1136/bjsports-2012-091425

37. Ruedl G, Posch M, Tecklenburg K, Schranz A, Greier K, Faulhaber M, et al. Impact of ski geometry data and standing height ratio on the ACL injury risk and its use for prevention in recreational skiers. *Br J Sports Med*. (2022) 56:1104–9. doi: 10.1136/bjsports-2021-105221

38. Grønhaug G. Lean and mean? Associations of level of performance, chronic injuries and BMI in sport climbing. *BMJ Open Sport Exerc Med*. (2019) 5:e000437. doi: 10.1136/bmjsem-2018-000437, s.l

39. Joubert LM, Gonzales GB, Larson AJ. Prevalence of disordered eating among international sport lead rock climbers. *Front Sports Act Living*. (2020) 2:86. doi: 10.3389/fspor.2020.00086

40. Jones G, Schöffl V, Johnson, Mark I. Incidence, diagnosis, and management of injury in sport climbing and bouldering: a critical review. *Curr Sports Med Rep*. (2018) 17(11):396–401. doi: 10.1249/JSR.0000000000000534

41. Grønhaug G, Saeterbakken A. No pain no gain: a survey of use of healthcare and reasons not to seek healthcare by Norwegian climbers with chronic injuries. *BMJ Open Sport Exerc Med*. (2019) 5:e000513. doi: 10.1136/bmjsem-2019-000513

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Change in grip strength, hang time, and knot tying speed after 24 hours of endurance rock climbing

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Background: Non-professional climbers are increasingly attempting long routes in a single day. Many suffer injury or rely on search and rescue teams when they become too fatigued to finish. Predicting fatigue is difficult, and existing studies have only studied climbers over durations less than an hour, while many outdoor multipitch climbs require more than an hour of climbing.

Objectives: To determine how strength, endurance, and dexterity reflect fatigue after 24 h of continuous climbing.

Methods: Volunteer competitors completed measurements of grip strength, static hang time to failure, and time to tie a figure-eight follow-through knot. Measurements were taken during the registration period before the competition and again within an hour after the competition ended. Measurements were compared using the paired *t*-test. Subgroup analysis was applied to competitors by division. Linear regression was applied to determine the relationship between vertical feet climbed and the number of routes climbed during the competition on each metric.

Results: Thirty-six total climbers (average age 29.4 years old) completed pre- and post-competition measurements. After 24 h of climbing ($n = 36$), mean grip strength decreased by 14.3–15 lbs or 14.7%–15.1% ($p < 0.001$) and static hang time decreased by 54.2 s or 71.2% ($p < 0.001$). There was no significant change in time to tie a figure-eight-follow-through knot. Grip strength and hang time decreases were significant in climbers with outdoor redpoints of 5.10a and above. Hang time decreased by 5.4 s per 1,000 vertical feet climbed ($p = 0.044$).

Conclusion: Climbers can expect to experience a 14.7%–15.1% decrease in grip strength and 71.2% decrease in static hang time after 24 h of continuous climbing. These changes may make it difficult to climb consistently over a long objective, and climbers can use these measures at home to train for longer climbing routes. Future studies on shorter climbing intervals can help determine rates of decline in performance measures.

KEYWORDS

rock climbing, endurance, grip strength, hang time, speed

Introduction

The sport of rock climbing has experienced a rapid increase in participation over the past several years. The sport's increasing popularity is evidenced by increasing numbers of climbing gyms opening all over the USA and Climbing officially becoming an Olympic sport for the 2020 Tokyo games (1–3). In 2019, industry leaders released the first ever

State of Climbing report which noted a yearly increase in 440,000 climbers (4). Paralleling this growth, the US has also experienced a dramatic increase in climbing-related injuries seen in emergency departments from 1990 to 2016 (5, 6).

The American Alpine Club, which publishes an annual report of climbing accidents, notes an increase in accidents from its first publication in 15 in 1951, surpassing 100 in 1970, exceeding 200 in 1986, and staying steadily above 100 since 1982 (7, 8). Between 1951 and 2016, exceeding abilities and/or inexperience was the second most common direct cause of accidents after falls (7). Of all the indirect causes leading to accidents from 1951 to 2020, inexperience was second only to climbing without a rope (8).

There is a growing concern about climbing's overall safety for newer climbers who venture outdoors. Epidemiological literature describes that the incidence of climbing injuries is greater in outdoor climbing on real rock than that of indoor climbing in a gym (9). Furthermore, there has been a documented increase in search and rescue efforts nationwide within the National Park Service (10), and while limited, rescue efforts for climbing-related incidents have also been of notable interest in both the US and Europe (11, 12). Inexperience and fatigue have been cited as increasing contributors to these reported search and rescue efforts (13, 14).

As more climbers venture outdoors for recreational sport and traditional climbing, it is important to recognize the physical limitations athletes experience on routes that may be far longer than found in gyms, and when managing weather and other environmental factors not replicable in gym settings. Newer climbers, or those who may climb infrequently, may be at increased risk of injury due to their inexperience or lack of physical conditioning (15). Several studies have been performed in other realms of endurance sports such as marathon running to better understand factors such as age (16) and gender (17) as they relate to overall performance. While there are articles that explore physiologic characteristics (18, 19) that may be associated with increased climbing performance, there remains a paucity of literature that describes factors related to climbers who undergo continuous climbing feats (20).

Grip strength has been shown to decrease by 22.1%–23% after a 30-minute bout of indoor sport rock climbing (21), grip strength recovers within 10 min after a 2-minute bout of indoor climbing (22), and maximum hang time has been shown to decrease over eight repeated hangs with 1-minute rest intervals and plateau with 3-minute rest intervals (23). Outdoor rock climbing on long single-day routes often requires more than 30 min of climbing. Due to the nature of different routes, climbers may be required to hang with their entire body weight with rest intervals much shorter or longer than 1–3 min. Additionally, multipitch climbing with a partner requires multiple changeovers between belaying and climbing, necessitating finger dexterity in knot tying, clipping, and belaying.

Due to the limited available data on endurance climbing and how climbers' performance may be affected by multiple hours of continuous rock climbing, we sought to determine how strength, endurance, and dexterity reflect fatigue after 24 h of continuous climbing. We measured grip strength, hang time, and knot-tying time, as these are easily replicated measurements that do not require training or access to expensive or heavy equipment. Our secondary objectives were to determine how climbing ability, vertical distance climbed, and the total number of routes climbed affected those performance metrics.

Materials and methods

Setting

Measurements were taken during the 24 h of Horseshoe Hell event hosted at Horseshoe Canyon Ranch in Jasper, AR from September 23 to 24, 2022. Pre-event measurements taken on September 23rd between 7 and 9 AM; post-event measurements were taken on September 24th between 10 and 11 AM. The weather during the event was partly cloudy with temperatures ranging between 64 and 88 F, winds 0–10 mph, and humidity between 37% and 71%. There was no precipitation during the event.

The rock at Horseshoe Canyon Ranch is primarily limestone. Routes range in height from 30 to 90 ft and in difficulty from 5.2 to 5.14 (Yosemite Decimal System) in either sport, traditional, or mixed styles, which is equivalent to Lower Grade through Higher Elite in the IRCRA system (24). Each route is given a point value based on a combination of its height, difficulty, and style. Climbers are required to complete each route "clean" by free climbing and not weighting the rope to claim points for the ascent; free-soloing is expressly prohibited.

Climbers compete in pairs, swapping between belaying and climbing so that both can log points for the competition. While some climbers choose to climb different routes, most partner pairs climb the same routes and complete routes in sequence spanning an entire cliff face so that they are only traveling several feet between finishing one route and starting the next, with longer breaks in climbing to travel between cliff faces. Each team's time management in the 24 h must factor in route finding, waiting in line for other teams to complete routes, eating, drinking, toileting, traveling between routes and climbing areas, and attempting more difficult climbs during daylight hours. Pairs are self-supported and must carry their own gear, food, water, and other necessities with them as they climb throughout the ranch.

Completed routes are recorded via the honor system on a phone application or physical scorecard. Scorecards are posted on the event website and results are publicly available. We referenced the total vertical feet climbed, number of routes climbed, and entry division from scorecards.

Participants

Study participants were recruited during the registration check-in period before each competition. We collected their age, sex, gender identity, and competition category. In total, 54 competitors agreed to participate. After signing an informed consent, participants were assigned a random number and given a wristband with that number to de-identify them for testing. Their wristband number was documented on their informed consent and kept in a secured file folder by one research assistant. Spectators and support personnel were excluded. Participants voluntarily completed the study measurements at the time of enrolling in the study and again within 1 h of finishing each competition.

Each climber entered the competition in the division based on their highest outdoor redpoint: 5.9 for Recreational, 5.10d for Intermediate, 5.12a for Advanced, and 5.12b+ for Elite. These divisions are set by the competition organizers and are the same for both male and female entrants. Per the IRCRA Reporting scale, these categories would correlate with Lower Grade, Intermediate, Advanced (Female), and Advanced (Male)/Elite/ Higher Elite (24). Entry into the competition is via a lottery system or by climbing a minimum number of routes in the prior year of the same competition. While professional climbers have competed in the past, most competitors are recreational climbers.

Measurements

We measured three parameters during this study: grip strength, hang time, and knot-tying time. These were chosen because they were tests that could be reproduced by average climbers not requiring any special athletic training and with equipment that could be easily purchased and transportable by both traveling climbers and the research team to the event location.

Protocol

Participants completed these exercises in a randomized order before and another randomized order after each competition. All measurements were recorded on paper next to the wristband number of the participant to protect identifying information. Each participant was given one attempt per measurement. Maximum hand grip strength (in pounds, Handeful handheld dynamometer) was measured in for both the right and left hands of each participant in their preferred arm positioning while standing. Most participants chose to do so in a slightly bent arm position where they could see the numbers on the screen changing as they gripped down. The maximum number stays displayed on the screen once the hand lets go.

Hang time was measured by having participants hang until failure from the edge of an elevated porch balcony that is constructed out of wooden planks with a 90-degree angle at the edge, a depth of approximately six feet, and a length of approximately 50 feet. Their feet were not allowed to touch the ground while hanging, but participants could select their preferred distance between their hands and position their body however they preferred if their feet did not touch the ground. Most participants chose to hang with their proximal interphalangeal joints flexed and metacarpophalangeal joints extended (see **Figure 1**). Two matching commercially available hanging grips were initially selected for this measurement, however there was no place to hang them close to the registration area, therefore the porch edge immediately behind the registration tent was used instead.

For knot-tying time, each participant wore an adjustable 8 mm cordelette around their waist at their preferred tightness to simulate a tie-in point on a climbing harness. The cordelette was used in lieu of each participant's personal climbing harness because none had their harness available at the time of registration. Participants were timed on their speed in tying a figure-8-follow-through knot with a provided length of 9.7 mm dynamic climbing rope through this improvised harness, starting when a research assistant called "start" and started a stopwatch, and ending when the participant called "done" and the stopwatch was stopped.

Results

Participants

Thirty-six competitors completed repeat measurements. There were four competitors in the Recreational category, nine competitors in the Intermediate category, 15 competitors in the Advanced category, and eight competitors in the Elite category. Climbers ranged from 21 to 40 years of age, with an average age of 29.4 years old; 21 were male, 15 were female. See **Figure 2**. In some cases, measurement recordings were either missing or illegible and unable to be included in calculations. Any pair of

FIGURE 1
Hand positioning during hang time test, photo taken during live data collection by Elaine Yu.

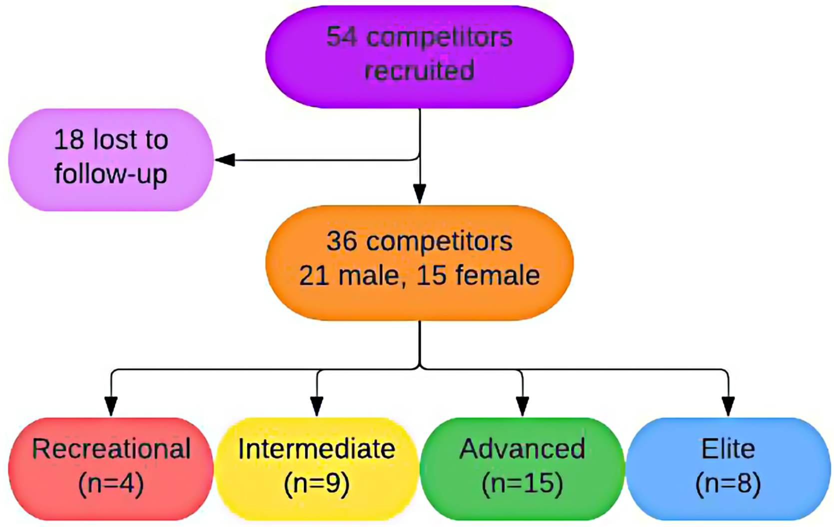

FIGURE 2
Participant characteristics. Created by Elaine Yu.

measurements that was recorded both pre- and post-competition for an individual was included in the calculations.

Statistical analysis

Percent decreases in handgrip strength from Macdonald et al. were used to determine a sample size of 8 with an alpha level of 0.5 and a power of 0.8.

We applied the paired two-tailed t-test to determine the mean difference between the pre- and post-competition data. Additionally, we performed the paired two-tailed *t*-test on subgroups based on their entry division. The α for each paired test was adjusted by Bonferroni correction with the resulting $\alpha_{adjusted}$ value used to determine significance. Cohen's *d* effect sizes were used. Percent increase or decrease in value was also calculated. We applied linear regression to predict the change in grip strength, hang time, and knot-tying time based on vertical height climbed and the number of routes climbed. $p < 0.05$ was used to determine significance.

In the 24-hour competition, the mean right hand grip strength before the competition was 99.2 lbs (SD = 25.5) and after the competition was 84.2 lbs (SD = 23.3); [$t(34) = 6$; $p < 0.001$; $d = 1.01$; $\alpha_{adjusted} = 0.001$]; or a 15.1% decrease. Mean left hand grip strength before the competition was 97 lbs (SD = 23.3) and after the competition was 82.7 lbs (SD = 22.7); [$t(31) = 8$; $p < 0.001$; $d = 1.41$; $\alpha_{adjusted} = 0.002$]; or a 14.7% decrease. Mean hang time before the competition was 76.8 s (SD = 32.6) and after the competition was 38.1 s (SD = 24.9); [$t(34) = 12.4$; $p < 0.001$; $d = 2.1$; $\alpha_{adjusted} = 0.001$]; or a 71.2% decrease. Mean knot tying time before the competition was 24.7 s (SD = 18.5) and after the competition was 20.2 s (SD = 6.8); [$t(28) = 1.3$; $p = 0.218$; $d = 0.23$; $\alpha_{adjusted} = 0.002$]; or a 18.2% decrease. Changes are displayed in **Figure 3**.

On subgroup analysis, there was a significant change in hang time in all competition categories. Grip strength of both the right and left hands showed a significant change in Intermediate,

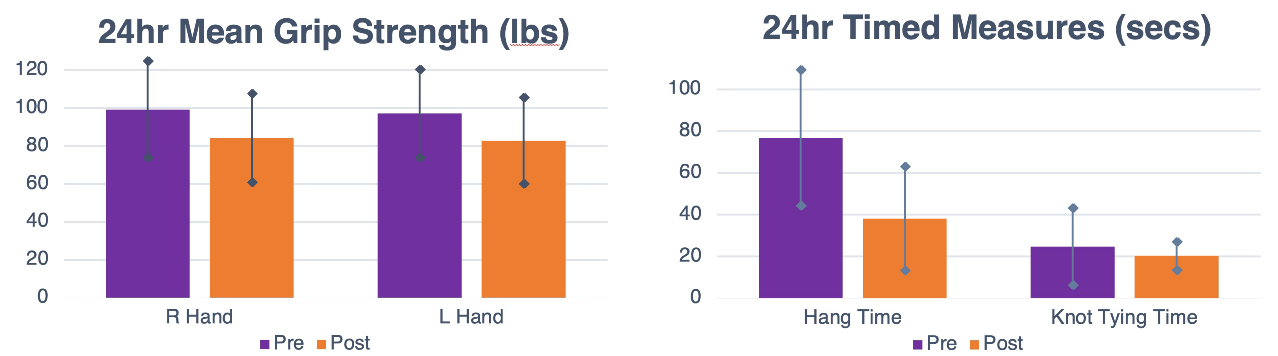

FIGURE 3
Left: Pre- and post-competition grip strength measurements in pounds of the right and left hands. Right: Pre- and post-competition hang time and knot tying time measurements in seconds.

TABLE 1 Subgroup analysis by division.

	Right hand grip strength	Left hand grip strength	Hang time	Knot tying time
Recreational (highest outdoor redpoint 5.9)				
Before	$M = 74.3$ lbs	$M = 76.5$ lbs	$M = 43.7$ s	$M = 39.4$ s
	SD = 13	SD = 9	SD = 11.8	SD = 24.8
After	$M = 72.9$ lbs	$M = 69.5$ lbs	$M = 15.3$ s	$M = 27.2$ s
	SD = 8.7	SD = 10.3	SD = 15.4	SD = 13.5
Change	$\Delta = 1.4$ lbs, −1.9%	$\Delta = 7$ lbs, −9.2%	$\Delta = 28.4$ s*, −65%	$\Delta = 12.2$ s, −31%
	$t(3) = 0.3$	$t(3) = 2.2$	$t(3) = 9.7$	$t(3) = 0.9$
	$p = 0.757$	$p = 0.116$	$p = 0.002$	$p = 0.448$
	$\alpha_{adjusted} = 0.013$	$\alpha_{adjusted} = 0.013$	$\alpha_{adjusted} = 0.013$	$\alpha_{adjusted} = 0.013$
Intermediate (highest outdoor redpoint 5.10d)				
Before	$M = 112.7$ lbs	$M = 106.8$ lbs	$M = 64.9$ s	$M = 22.5$ s
	SD = 32.4	SD = 29.5	SD = 14	SD = 11.8
After	$M = 90.1$ lbs	$M = 89.5$ lbs	$M = 22.1$ s	$M = 20.3$ s
	SD = 16.3	SD = 22.1	SD = 20.9	SD = 4.3
Change	$\Delta = 22.6$ lbs, −20.1%	$\Delta = 17.3$ lbs, −16.2%	$\Delta = 47.3$ s*, −65.9%	$\Delta = 2.2$ s, −9.8%
	$t(8) = 2.9$	$t(6) = 3.2$	$t(8) = 7$	$t(7) = 0.4$
	$p = 0.019$	$p = 0.019$	$p < 0.001$	$p = 0.708$
	$\alpha_{adjusted} = 0.006$	$\alpha_{adjusted} = 0.007$	$\alpha_{adjusted} = 0.006$	$\alpha_{adjusted} = 0.007$
Advanced (highest outdoor redpoint 5.12a)				
Before	$M = 94.2$ lbs	$M = 95.1$ lbs	$M = 89.3$ s	$M = 25.1$ s
	SD = 22.6	SD = 22.8	SD = 42	SD = 22.5
After	$M = 80.4$ lbs	$M = 81.3$ lbs	$M = 28.2$ s	$M = 20.1$ s
	SD = 30.3	SD = 26.5	SD = 32.6	SD = 5.9
Change	$\Delta = 13.8$ lbs*, −14.6%	$\Delta = 13.8$ lbs*, −14.5%	$\Delta = 61.1$ s*, −68.4%	$\Delta = 5$ s, −19.9%
	$t(13) = 5$	$t(12) = 5.8$	$t(14) = 8.2$	$t(12) = 0.6$
	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.528$
	$\alpha_{adjusted} = 0.004$	$\alpha_{adjusted} = 0.004$	$\alpha_{adjusted} = 0.003$	$\alpha_{adjusted} = 0.004$
Elite (highest outdoor redpoint 5.12b+)				
Before	$M = 106$ lbs	$M = 99.5$ lbs	$M = 84$ s	$M = 17.4$ s
	SD = 16.1	SD = 16.5	SD = 13.8	SD = 2.4
After	$M = 90.3$ lbs	$M = 84.1$ lbs	$M = 15.5$ s	$M = 15.7$ s
	SD = 18.6	SD = 20.9	SD = 12.9	SD = 1.8
Change	$\Delta = 15.7$ lbs, −14.8%	$\Delta = 15.4$ lbs*, −15.5%	$\Delta = 68.5$ s*, −81.5%	$\Delta = 1.7$ s, −9.8%
	$t(7) = 3.5$	$t(6) = 8.1$	$t(6) = 9.5$	$t(5) = 1.8$
	$p = 0.011$	$p < 0.001$	$p < 0.001$	$p = 0.127$
	$\alpha_{adjusted} = 0.007$	$\alpha_{adjusted} = 0.007$	$\alpha_{adjusted} = 0.007$	$\alpha_{adjusted} = 0.008$

*Indicates $p < \alpha_{adjusted}$.

Advanced, and Elite climbers, but not Recreational climbers. Change in knot tying time was not significant in any category. Subgroup analysis by division are presented in Table 1.

Right hand grip strength decreased by 0.9 lbs per 1,000 ft climbed and 3.1 lbs per 100 routes climbed. Left hand grip strength decreased by 1.5 lbs per 1,000 ft climbed and 5 lbs per 100 routes climbed. Hang time decreased by 5.4 s per 1,000 ft climbed and 21 s per 100 routes climbed. Knot tying time increased by 1.7 s per 1,000 ft climbed and 6.5 s per 100 routes climbed. Fitted regression models are summarized in Table 2.

Discussion

Generalizability

The competitors in the 24 h of Horseshoe Hell competition are generally recreational climbers that climb in their free time, without significant income from brand sponsorships, and who do not climb as their primary profession. Therefore, we believe that the data from the sampled participants can be applied broadly to recreational climbers worldwide.

Additionally, as the competition take place outdoors, on real rock faces, and requires partner teams to clip bolts, place gear, clean gear, and swap belays, we feel that this most accurately parallels multipitch outdoor climbing. Given that this competition was timed at 24 h, requiring teams to manage their hydration, food consumption, rest, waiting in line for routes, and toileting along with achieving their climbing goals, the results from this study are most relevant to climbers planning to spend half to a full day on a climbing objective.

An example of a popular climbing route where this could be applicable is the route Epinephrine, a 13-pitch, 1,600 ft, 5.9 that is often timed car-to-car ranging from 5 h 30 min to 20 h 30 min with an average time of 12 h 46 min for the 45 parties that ticked the climb in 2022 on Mountain Project, a community

TABLE 2 Fitted regression models.

	Right hand grip strength	Left hand grip strength	Hang time	Knot tying time
Vertical height	$\hat{Y} = 11.34 + 0.0008834*(ft)$	$\hat{Y} = 8.1453 + 0.001469*(ft)$	$\hat{Y} = 32.3137 + 0.005373*(ft)$	$\hat{Y} = 11.3479 - 0.001687*(ft)$
	$R^2 = 0.0069$	$R^2 = 0.03$	$R^2 = 0.12$	$R^2 = 0.026$
	$F(1,34) = 0.24$	$F(1,33) = 1.03$	$F(1,33) = 4.4$	$F(1,32) = 0.85$
	$p = 0.629$	$p = 0.318$	$p = 0.044$	$p = 0.363$
	$\beta = 0.0009$	$\beta = 0.0015$	$\beta = 0.0054$	$\beta = -0.0017$
Route number	$\hat{Y} = 11.8749 + 0.03083*(\#)$	$\hat{Y} = 9.1435 + 0.05029*(\#)$	$\hat{Y} = 33.1412 + 0.211*(\#)$	$\hat{Y} = 10.9732 - 0.06511*(\#)$
	$R^2 = 0.0052$	$R^2 = 0.022$	$R^2 = 0.11$	$R^2 = 0.024$
	$F(1,34) = 0.18$	$F(1,33) = 0.73$	$F(1,33) = 4.12$	$F(1,32) = 0.77$
	$p = 0.677$	$p = 0.399$	$p = 0.05$	$p = 0.386$
	$\beta = 0.031$	$\beta = 0.05$	$\beta = 0.21$	$\beta = -0.065$

*Indicates multiplication.
#Indicates number of routes.

climbing forum (25). In 2022, 12 parties bailed off the route due to adverse conditions while 11 reported an "epic", which is defined as "when a climb turns into an ordeal, often taking much longer than anticipated by being affected by adverse conditions or unexpected difficulties" (26). While none reported injury or requiring rescue, climbers who become fatigued are more prone to experiencing a climbing accident.

Aspiring climbers training for this route could measure their baseline grip strength and hang time, go climb for several hours, and then re-measure their grip strength and hang time once fatigued and compare the change they experience with the change from the competitors in this study to predict when they would reach the level of fatigue equivalent to 24 h of climbing, and therefore predict whether they would be likely to epic or require rescue.

Results interpretation

This study found that competitors' grip strength decreased due to fatigue from repeated use of forearm, hand, and finger musculature after 24 h of climbing. When divided into subgroups based on division, the decrease in hang time remained significant for all groups. Grip strength was significantly decreased in all but the Recreational subgroup. This is likely because recreational climbers have been shown to have similar handgrip strength to physically active non-climbers (27). It is worth noting that while the mean grip strengths of the Intermediate climbers were greater than those of the Advanced group, the Advanced group had longer hang times, disproving the common misconception that "stronger" climbers have better grip strength, as even non-climbers have been found to have similar grip strength as elite climbers (28).

The results from this study add to the pool of knowledge on handgrip strength change in rock climbers, which has been shown to decrease 22% in 5.12a climbers climbing until a fall (29) and 22.1%–23% in 5.9 climbers climbing for 30 min (21). We found that a 1.9%–9.2% decrease in 5.9 climbers, a 16.2%–20.1% decrease in 5.10d climbers, 14.5%–14.6% decrease in 5.12a climbers, and a 14.8%–15.5% decrease in 5.12b+ climbers over a 24-hour period.

Our study also looked at how the number of vertical feet climbed and the number of routes climbed could predict changes in grip strength, hang time, and knot-tying. Although these predictors did not reach significance when addressing grip strength or knot-tying times, we were able to predict with significance how vertical feet could affect hang time. The number of routes climbed did not predict any change in measurements, which indicates that the time spent climbing contributes more to fatigue than the number of iterations of changeovers from belay to climb and climb to belay.

Watts et al. has previously demonstrated that max time for repeated hangs plateaued with 1–3 min rest intervals, with a mean hang time of 36.3–40.7 s over 8 tries within <30 mins. In our study, mean hang time was 38.1 s after 24 h climbing, which is similar to the values they found. However, participants in our study had higher mean hang times before the competition (76.8 s) which may reflect the endurance competitors had built up in preparation for the event lasting multiple hours.

Hang time is a useful proxy for measuring climber endurance (30), especially when considering longer objectives for climbers, such as multi-pitch routes or big-wall climbing. A climber's self-selected speed of climbing is thought to be a balance between time doing isometric work and the avoidance of early muscle fatigue (31). Hangboard exercises have been proven to improve grip endurance after 4–8 weeks of training (32) and are a popular training technique to delay the onset of the dreaded forearm pump that ails climbers who become fatigued.

Our prediction model may be useful for climbers preparing for large outdoor objectives. By using their current maximum hang time as a data point for their present level of climbing fitness, climbers may utilize the predictors in this study to estimate their change in hang time after their desired objective and target their training to decrease this difference. Climbers may also aim for a certain hang time objective during their training period to maximize chances of a successful ascent and thus avoid unplanned overnight bivouacs or emergency calls for rescue. Climbers may also use the prediction model to compare different objectives and expected changes in their performance as a marker of fatigue.

Limitations

There are several limitations that we encountered during our study. While we measured right and left hand grip strengths, we did not indicate which laterality was the climber's dominant hand, which would have been an interesting additional point of investigation. Climbers also gave varying degrees of effort during their pre-test hang times. While most competitors gave their maximal efforts during the pre- and post-test hang times, a handful of them indicated that they did not want to tire themselves out prior to the start of the competition for fear of overexertion, or "pumping themselves out," and thus let go before what would otherwise have been their maximal hang time. Additionally, we did not measure climbers' height or weight to calculate a strength to body mass ratio, which has been shown to determine performance in indoor World Cub sport climbers (33).

This was an observational study, so we did not specify which routes each climber chose in the course of the competition. Climbers competing in the Elite category could select to climb the same number and difficulty of routes as someone competing in the Recreational category, and therefore may demonstrate a smaller change in their grip strength, hanging endurance, and knot tying speed by the end of the competition.

We were unable to standardize the exact times for when each measurement was taken after the competition. Thus, some competitors were measured directly after their finish, while others were measured up to an hour after the official finish. The order in which we took the three measurements also varied between climbers. Lastly, we were also unable to control for any possible effects of drugs used before or after the event.

This study was undertaken over the course of 24 h of consecutive competition. Of the 54 original participants, 18 did not present for repeat measurement immediately after the competition and were lost to follow-up. Additionally, some measurements were not recorded or not legible for interpretation. Therefore, the data presented in this study is limited by our small sample size.

Future avenues of study

Repeating this study on shorter intervals of continuous climbing can provide insight into the level of fatigue expected after shorter climbing objectives. Replicating this study using a standard climbing harness and hangboard with a fixed grip width would better standardize the results and can also help recreational climbers repeat these measurements at home to assess their own fatigue after training sessions or unexpected days out.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by University of California San Diego Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

EY—primary researcher, logistics coordinator, statistical analysis, majority of manuscript writing. JL, JM, KT—data collection, assisted in manuscript writing. CC—principal investigator, IRB approval, manuscript editing. All authors contributed to the article and approved the submitted version.

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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References

1. Climbing Business Journal. Gyms and trends 2021 (2022). Available at: https://www.climbingbusinessjournal.com/gyms-and-trends-2021/ (Accessed March 30, 2023).

2. Lutter C, El-Sheikh Y, Schöffl I, Schoffl V. Sport climbing: medical considerations for this new Olympic discipline. *Br J Sports Med*. (2017) 51:2–3. doi: 10.1136/bjsports-2016-096871

3. Murtha R, Özyurtçu T. Untangling the differences between live and filmed sport, or why are sport movies bad. *Aethlon*. (2020) 37(2):79–88.

4. Powers P. State of climbing (report). Retrieved from American Alpine Club database (2019).

5. Buzzacott P, Schöffl I, Chimiak J, Schöffl V. Rock climbing injuries treated in US emergency departments, 2008-2016. *Wilderness Environ Med*. (2019) 30(2):121–8. doi: 10.1016/j.wem.2018.11.009

6. Nelson NG, McKenzie LB. Rock climbing injuries treated in emergency departments in the U.S., 1990-2007. *Am J Prev Med*. (2009) 37(3):195–200. doi: 10.1016/j.amepre.2009.04.025

7. MacDonald D. *Accidents in north American climbing 2018*. Vol. 11, Number 3, Issue 71. Golden: American Alpine Club (2018).

8. Takeda P. *Accidents in north American climbing 2022*. Vol. 12, Number 3, Issue 75. Golden: American Alpine Club (2022).

9. McDonald JW, Henrie AM, Teramoto M, Medina E, Willick SE. Descriptive epidemiology, medical evaluation, and outcomes of rock climbing injuries. *Wilderness Environ Med*. (2017) 28(3):185–96. doi: 10.1016/j.wem.2017.05.001

10. Heggie TW, Amundson ME. Dead men walking: search and rescue in US national parks. *Wilderness Environ Med*. (2009) 20(3):244–9. doi: 10.1580/08-WEME-OR-299R.1

11. Lack DA, Sheets AL, Entin JM, Christenson DC. Rock climbing rescues: causes, injuries, and trends in boulder county, Colorado. *Wilderness Environ Med*. (2012) 23 (3):223–30. doi: 10.1016/j.wem.2012.04.002

12. Rugg C, Tiefenthaler L, Rauch S, Gatterer H, Paal P, Ströhle M. Rock climbing emergencies in the Austrian Alps: injury patterns, risk analysis and preventive measures. *Int J Environ Res Public Health*. (2020) 17(20):7596. doi: 10.3390/ijerph17207596

13. Ciesa M, Grigolato S, Cavalli R. Retrospective study on search and rescue operations in two Prealps areas of Italy. *Wilderness Environ Med*. (2015) 26 (2):150–8. doi: 10.1016/j.wem.2014.10.008

14. Sadeghi R, Konwinski JC, Cydulka RK. Adirondack park incidents: a retrospective review of search and rescue reports from 2008 to 2009. *Wilderness Environ Med*. (2015) 26(2):159–63. doi: 10.1016/j.wem.2014.08.004

15. Nikolaidis PT, Alvero-Cruz JR, Villiger E, Rosemann T, Knechtle B. The age-related performance decline in marathon running: the paradigm of the Berlin marathon. *Int J Environ Res Public Health*. (2019) 16(11):2022. doi: 10.3390/ijerph16112022

16. Schöffl V, Lutter C. The "newbie" syndrome. *Wilderness Environ Med*. (2017) 28 (4):377–80. doi: 10.1016/j.wem.2017.07.008

17. Zavorsky GS, Tomko KA, Smoliga JM. Declines in marathon performance: sex differences in elite and recreational athletes. *PLoS One*. (2017) 12(2):e0172121. doi: 10.1371/journal.pone.0172121

18. Saul D, Steinmetz G, Lehmann W, Schilling AF. Determinants for success in climbing: a systematic review. *J Exerc Sci Fit*. (2019) 17(3):91–100. doi: 10.1016/j.jesf.2019.04.002

19. MacKenzie R, Monaghan L, Masson RA, Werner AK, Caprez TS, Johnston L, et al. Physical and physiological determinants of rock climbing. *Int J Sports Physiol Perform*. (2020) 15(2):168–79. doi: 10.1123/ijspp.2018-0901

20. Stien N, Saeterbakken AH, Andersen V. Tests and procedures for measuring endurance, strength, and power in climbing-a mini-review. *Front Sports Act Living*. (2022) 4:847447. doi: 10.3389/fspor.2022.847447

21. Macdonald GA, Manning JW, Bodell NG, Young JC, Schilling BK, Lee SP, et al. Acute handgrip fatigue and forearm girth in recreational sport rock climbers. *Int J Exerc Sci*. (2022) 15(4):834–45.

22. Matsuoka O, Nani S, Papadimitrou K, Astrapellos K, Beneka A, Malliou P. Time course changes in hand grip strength performance and hand position sense in climbing. *J Hum Sport Exerc*. (2020) 15(1):23–33.

23. Watts PB, Jensen RL, Agena SM, Majchrzak JA, Schellinger RA, Wubbels CS. Changes in EMG and finger force with repeated hangs from the hands in rock climbers. *Int J Exerc Sci*. (2008) 1(2):62–70.

24. Draper N, Giles D, Schoffl V, Fuss FK, Watts P, Wolf P, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: international rock climbing research association position statement. *Sports Technol*. (2015) 8(3-4):88–94. doi: 10.1080/19346182.2015.1107081

25. Statistics for Epinephrine. Mountain project. Available at: https://www.mountainproject.com/route/stats/105732422/epinephrine.

26. Foxfield A. Rock climbing terms: our guide to climber jargon and slang. Advnture. (2022). Available at: https://www.advnture.com/features/rock-climbing-terms.

27. Grant S, Hynes V, Whittaker A, Aitchison T. Anthropometric, strength endurance and flexibility characteristics of elite and recreational climbers. *J Sports Sci*. (1996) 14(4):301–9. doi: 10.1080/02640419608727715

28. Grant S, Hasler T, Davies C, Aitchison TC, Wilson J, Whittaker A. A comparison of the anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers and non-climbers. *J Sports Sci*. (2001) 19(7):499–505. doi: 10.1080/026404101750238953

29. Watts P, Newbury V, Sulentic J. Acute changes in handgrip strength, endurance, and blood lactate with sustained sport rock climbing. *J Sports Med Phys Fitness*. (1996) 36(4):255–60.

30. Devise M, Lechaptois C, Berton E, Vigoroux L. Effects of different hangboard training intensities on finger grip strength, stamina, and endurance. *Front Sports Act Living*. (2022) 4:862782. doi: 10.3389/fspor.2022.862782

31. Rosponi A, Schena F, Leonardi A, Tosi P. Influence of ascent speed on rock climbing economy. *Sport Sci Health*. (2012) 7:71–80. doi: 10.1007/s11332-012-0115-8

32. Lopez-Rivera E, Gonzalez-Badill JJ. Comparison of the effects of three hangboard strength and endurance training programs on grip endurance in sport climbers. *J Hum Kinet*. (2019) 66:183–93. doi: 10.2478/hukin-2018-0057

33. Watts PB, Martin DT, Durtschi S. Anthropometric profiles of elite male and female competitive sport rock climbers. *J Sports Sci*. (1993) 11(2):113–7. doi: 10.1080/02640419308729974

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Evaluation of finger cartilage composition in recreational climbers with 7 Tesla T2 mapping magnetic resonance imaging

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Purpose: Sport climbing may lead to tissue adaptation including finger cartilage before apparent surface damage is detectable. The main aim was to assess finger cartilage composition with T2 mapping in young, active climbers and to compare the results to a non-climbers' collective. A secondary aim was to compare whether differences in cartilage T2 times are observed between older vs. younger volunteers.
Methods and materials: 7 Tesla MRI of the fingers Dig.2–4 was performed using a multi-echo spin echo sequence. Manual segmentation of 3 ROIs at the metacarpal heads, 1 ROI at the base phalanx and 1 ROI at the proximal interphalangeal joint was performed. Included were 13 volunteers without history of trauma who are regularly performing climbing activities as a recreational sport (>20 h/month). These were age-matched with 10 control subjects not performing climbing activities.
Results: Mean age was 32.4 years for the climbing group and 25.8 years for the controls. Mean T2 values for the 5 different ROIs were 42.2 ± 7.8 msec for climbers and 41.4 ± 6.8 msec for non-climbers. No significant differences were observed for T2 values between both groups. However, higher age had a significant impact on T2 values for all assessed ROIs (higher age 44.2 ± 9.5, younger age 32.9 ± 5.7, $p = 0.001$).
Discussion: This study evaluated the cartilage composition of young, engaged climbers with a T2 mapping MRI technique with the purpose to depict early onset joint changes. No negative impact on cartilage composition due to the sport activity was found, whereas age-related effects on the cartilage seemed to be more prominent.

KEYWORDS
climbing, finger, cartilage, mapping, magenetic resonance imaging

Introduction

Climbing, as a new Olympic discipline, exposes the human body to various patterns of musculoskeletal adaptation and may be associated with a specific risk for joint, muscle or cartilage injuries (1, 2). The large community of professional and recreational athletes is the reason why knowledge about this has an increasingly great medical importance (3–7).

Injuries notably concern the upper extremity and finger joints due to high loads during repetitive tension and compression motion (8). This is associated with a high incidence of acute injuries, such as finger pulley rupture, which represents the most common climbing injury (9). Concerning joint tissue adaptation as a response to repetitive stress and loading, cartilage alterations and osteoarthritis (OA) development in the finger joints have been examined in several studies but an association between climbing activity and early OA development could not be shown (10–13). Young top athletes may develop tissue adaptations such as an increase in cartilage thickness and cortical thickness (13, 14) at an early stage of their career. Studies by Pastor et al. focussed on long-term climbing athletes performing at a high level and investigated a possible connection between cartilage and cortical thickness, osteophyte development and pain symptoms in follow-up studies (12, 13). Studies investigating a potential impact on finger cartilage for recreational climbing activities at an early stage are pending. However, knowledge about the earliest cartilage changes caused by climbing would be relevant, particularly in the early phase of an athlete's career. Sport behavioural adaptions with improved or gentler climbing techniques or training methods in terms of degeneration prevention might be possible.

High field magnetic resonance imaging (MRI), particularly with field strengths beyond 3 Tesla, has potential for high resolution structural imaging of the cartilage quality (15). This has been investigated in several studies, especially for bigger joints of the human skeleton, such as the hip, knee and ankle (16–18). Various MRI techniques such as delayed gadolinium-enhanced MRI (dGEMRIC) (19), diffusion weighted imaging and T2 mapping, a composite measure of water content, collagen content and organization (17), are available for this purpose. 7 Tesla MRI has the highest magnetic field strength approved for routine clinical scanning. The high magnetic field strength can be used for improvement of spatial resolution, image contrast and/or signal to noise ratios (SNR) (20). This might be beneficial for imaging of thin cartilage joint layers of smaller joints (15).

The aim of our study was to investigate finger cartilage quality as characterized by T2 mapping using 7 Tesla MRI in young climbers and to compare the results to age-matched non-climbers. An additional research question was to analyse whether age had an influence on the T2 time of cartilage.

Materials and methods

Study population

The study included 23 healthy volunteers (22.6–47.8 y, mean age 30.5 y, m:f = 13:10), between June and October 2017. Thirteen participants were climbers (22.6–47.8 y, mean age 32.4 y, m:f = 7:6) and ten were non climbers (24.4–35.4 y, mean age 25.8 y, m:f = 6:4). The mean climbing level was 20 (min 16 max 25; on the IRCRA climbing scale ranging from 1 to 32), the mean climbing career duration was 7.7 years (min 5.9 max 18.9 years), the average regular climbing time was 20.9 h/month. This represented an advanced recreational climber collective. Sporting or occupational stress on the fingers was considered an exclusion criterion for the control group. Participants were free to select the hand to be measured. None of the individuals had a contraindication for a 7 T high field MRI. All subjects gave written consent to participate and undergo the MRI examination, as well as to the use of their anonymized data. The study was approved by the institutional review board (260_15 Bc) and all patients provided informed consent. The study followed the declaration of Helsinki.

Imaging

All imaging was performed on a 7 Tesla MRI scanner (MAGNETOM Terra, Siemens Healthineers, Erlangen, Germany). The subjects were examined in the superman position. The hand was fixed to reduce motion artifacts. A custom-made dedicated 1-channel transmit, 16-channel receive wrist coil (7 Tesla wrist coil, RAPID Biomedical, Würzburg, Germany) with an elliptical cross-section (78 mm × 98 mm) and a length of 70 mm was used. For each subject/specimen, T2-weighted multi-echo, spin-echo sequences (MESE) were acquired in the sagittal plane. T1-, T2-, and Proton density-weighted sequences in the axial direction, as well as three-dimensional double-echo steady state (DESS) sequences were obtained to visualize the finger anatomy and morphological joint changes. The latter served for subjective anatomical correlation and had no influence on the quantitative image analysis/region-of-interest (ROI) measurements. Details on the applied scanning parameters can be taken from **Table 1**.

Image analysis/quantitative T2 mapping

All data sets were evaluated by two researchers in consensus regarding anatomical abnormalities/pathologies (M.B., 3 years; T.B.; 17 years of experience in musculoskeletal MRI). A ROI-analysis was performed with dedicated Software on a DICOM viewer (Leonardo syngo Multimo-dality Workplace VE36A; MapIt Software, both Siemens Healthineers, Erlangen, Germany). All ROIs were placed by the same researcher (M.B.) in consensus with (T.B.). A freehand drawing tool was used to create ROIs manually on the index, middle and ring finger of each individual in the central sagittal finger slice, which suited for optimal depiction of the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint cartilage. The thicker cartilage layers of the MCP joint allowed an individual ROI placement at the proximal and distal joint side with three different cartilage segments defined for the MC head and with one cartilage segment defined for the ground phalanx base. The thinner PIP joint cartilage layers allowed a common ROI placement including the ground phalanx head and middle phalanx base cartilage. The ROIs were defined as following: proximal MCP joint dorsal (ROI 1), proximal MCP joint central (ROI 2), proximal MCP joint palmar (ROI 3), distal entire MCP joint cartilage layer (ROI 4)

TABLE 1 Details on the applied scanning parameters for 5 MRI sequences.

Parameter	T2 MESE	T1 TSE	T2 TSE	PD TSE	DESS
TR (msec)	3,030.0	700	68	14	17.97
TE (msec)	14.7–88.2	17	5,000	6,540	6.38
TA (min, sec)	8.31	4.46	6.32	6.32	8.55
Field of view	608 × 608	500 × 500	500 × 500	500 × 500	640 × 540
Flip angle	180°	90°	177°	177°	21°
Voxel size (mm)	0.2 × 0.2 × 2.5	0.2 × 0.2 × 1.5	0.2 × 0.2 × 1.5	0.2 × 0.2 × 1.5	0.3 × 0.3 × 0.3

and PIP joint including the entire proximal and distal cartilage layer (ROI 5). The MapIt software enabled fully automated parametric inline T2 mapping of the imaged cartilage. The results of each ROI were the mean values of the T2 relaxation times in milliseconds (msec), the standard deviation, the size of the ROI in square centimetres (sq.cm), as well as the number of pixels. A pixel-wise, monoexponential, non-negative least squares (NNLS) suitability analysis was used for image fusion of the resulting maps with the corresponding anatomic image (**Figure 1**).

Statistical analyses

Data collection was performed with anonymization in Microsoft Excel. The statistical software program R (version 3.5.3., R Foundation for statistical Computing, Vienna, Austria) was used for calculation. Mixed modelling was performed to determine differences of T2 relaxation times in between the different ROI groups depending on age and climbing activity. Also, differences for gender and different joints (PIP joints vs. DIP joints) were tested. The median age was determined as a cut point for defining an additional group analysis depending on the individuals' age (≤26.5 y; >26.5 y) dividing the study collective and older and younger individuals. Unless stated otherwise, data were expressed as mean ± standard deviation (range). *P*-values <0.05 were considered statistically significant.

Results

MRI showed normal finger joint anatomy for all individuals without presence of any pathological or degenerative joint alteration and without presence of any osteophytes. T2-mapping was technically successful in all individuals and a total of 345 ROIs could be created with color-coded maps for subsequent ROI analysis. Sixteen subjects had imaging of the right hand and seven subjects of the left. The mean size of the ROIs was 0.04 cm^2 and ranged from 0.01 cm^2 to 0.13 cm^2. Mean T2 values for all ROIs were 42.2 ± 7.78 msec for climbers and 41.4 ± 6.78 msec for non-climbers. The respective average T2 value was 44.2 ± 9.48 msec for older and 32.9 ± 5.71 msec for younger individuals. Further information on mean values of the T2 times of the individual ROIs, as well as their standard deviations (SD) are shown in **Table 2** and **Figure 2**. Statistical analysis revealed no significant differences for T2 values between climbers and non-climbers. Within the MCP joints of all fingers, significant differences ($p = 0.001$) were found for the different ROIs 1,2,3 and 4. The averaged T2 time of all T2 times representing the MCP joint (ROI: 1–4) had no significant difference compared to ROI 5, representing the PIP joint. No significant difference was found between different genders. However, higher age had a significant impact on T2 values for all assessed ROIs ($p = 0.001$).

Discussion

Our study used 7 Tesla MRI T2 mapping techniques to detect potential early cartilage changes in the fingers in a collective of recreational young climbers. In comparison with an age-matched group of non-climbers, no differences in cartilage quality was found. Independent of the climbing sport, we found significant differences in cartilage composition in regard to age. We were able to define five distinct cartilage regions of the MCP and PIP joints of each finger, indicating feasibility of this T2 mapping technique for evaluating finger joint cartilage composition with MRI.

Several studies have investigated joint tissue adaptions in finger joints of climbers. Pastor et al. reported that the thickness of the cartilage layer in the PIP and DIP joints will decrease whereas the occurrence of osteophytes will increase during the career of elite sport climbers (12, 13). However, a clear connection between changes in the thickness of the cartilage, the development of osteophytes and degenerative symptoms could not be shown in their 10-year follow-up study (12, 13). In this context, it was discussed that osteophyte development in young climbers could be a mechanical adaptation to finger-stressing, which does not necessarily have to be accompanied by cartilage degeneration (12, 13). Schöffl et al. reported that one quarter of the German youth national team climbers showed a mild form of osteoarthritis Grade 2, however this study based on radiographic and clinical evaluation only (14). With integration of MRI assessment, a more comprehensive assessment on the cartilage quality may be possible in comparison to clinical, ultrasonographic or radiographic evaluation alone. Compositional MRI is suited to detect possible early pre-morphologic cartilage changes with T2 realxometry being the most widely applied technique as a surrogate parameter of collagen content and organization and water content of cartilage (15). Compositional imaging with finger T2 mapping was applied clinically in a study by Renner et al. (21), who investigated cartilage of MCP joints of patients with underlying rheumatic disease. In their study, inflammatory activity correlated to changes of the cartilage T2 times.

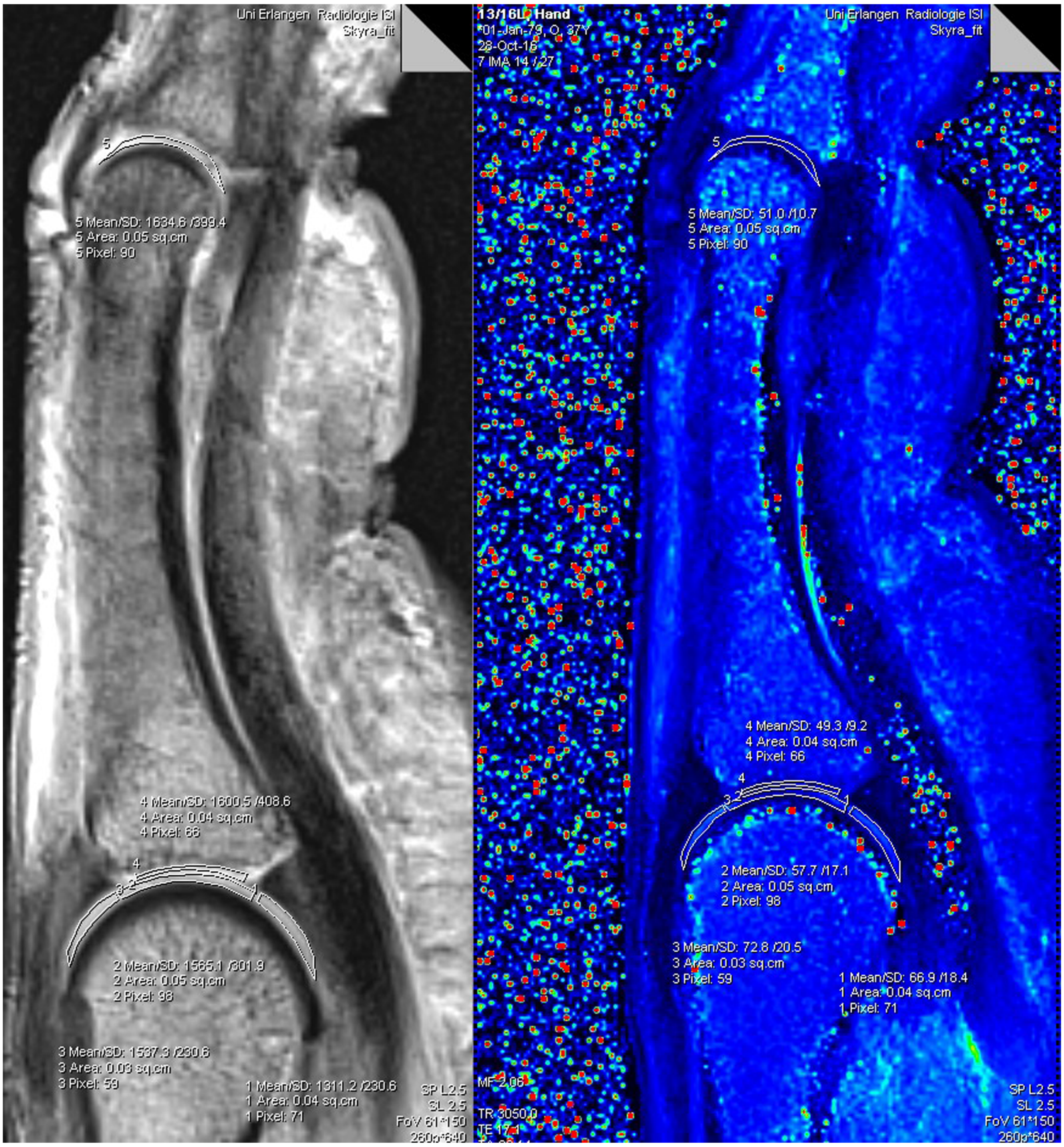

FIGURE 1
Software analysis for T2-mapping of a finger: the freehand drawn ROIs 1–5 in the morphological (grey left image) was transferred to the colour coded T2 map (right image). ROIs in the T2 map provide values for T2 time (Mean), standard deviation (SD), size of the individual ROIs (Area), as well as the number of pixels (Pixel).

Our methodology differs to the aforementioned study, as a compositional imaging technique was used with the highest clinically approved magnetic field strength of 7 Tesla which allowed for maximized spatial resolution and an increased signal to noise ratio in comparison to 3.0 Tesla. Therefore, we could perform T2 mapping analysis also for the smaller PIP joint.

The mechanisms leading to cartilage degradation due to repetitive strain and/or aging are assumed to contribute to a decrease in proteoglycans and to changes of the collagen network. This subsequently yields to an increase of cartilage permeability and water content as the earliest demonstrable changes in cartilage damage (22), typically localized and quantified by the T2 relaxation time. In our study, a gender-specific difference in T2 times could not be shown. We found differences in T2 times for the different finger and ROI groups, which did not show a statistically significance, in relation to climbing sport and age using mixed modelling. In this respect, differing T2 values for the different ROI groups of the MCP may be interpreted as physiologic normal observation. It is possible

TABLE 2 Mean T2 values (ms) ± standard deviations of the entire study collective (n = 23), climbers (n = 13), non-climbers (n = 10), individuals ≤ 26.5 y (n = 13) and individuals > 26.5 y (n = 12) measured for three fingers and 5 different regions of interest (ROI) in-7 T MRI.

All participitants	ROI 1	ROI 2	ROI 3	ROI 4	ROI 5
Dig. 2	35.04 ± 12.75	49.84 ± 17.56	35.89 ± 7.04	54.74 ± 16.47	40.33 ± 13.77
Dig. 3	31.68 ± 10.78	44.85 ± 12.78	37.57 ± 7.93	46.47 ± 10.87	38.98 ± 11.33
Dig. 4	28.19 ± 8.86	47.63 ± 15.54	31.82 ± 9.72	53.8 ± 13.39	36.14 ± 10.57
Climbers					
Dig. 2	34.85 ± 9.51	55.56 ± 31.61	37.01 ± 8.24	59.15 ± 14.48	43.06 ± 14.49
Dig. 3	33.13 ± 5.01	44.92 ± 8.47	38.01 ± 4.45	47.74 ± 10.93	42.39 ± 16.6
Dig. 4	29.43 ± 5.58	54.64 ± 21.81	33.42 ± 6.47	52.22 ± 14.25	37.34 ± 11.99
Non-Climbers					
Dig. 2	46.48 ± 44.44	51.03 ± 17.85	34.42 ± 4.99	59.8 ± 28.69	36.77 ± 7.01
Dig. 3	29.15 ± 6.12	44.76 ± 8.47	37 ± 8.63	44.83 ± 7.77	34.54 ± 6.31
Dig. 4	26.58 ± 6.19	54.64 ± 21.81	29.75 ± 6.58	55.85 ± 13.08	34.59 ± 6.66
≤26.5 y					
Dig. 2	41.35 ± 41.38	48.52 ± 17.53	34.21 ± 5.36	55.68 ± 27.35	34.92 ± 7.66
Dig. 3	29.08 ± 5.74	42.93 ± 8.23	37.61 ± 8.73	44.18 ± 6.56	32.28 ± 5.27
Dig. 4	24.9 ± 3.62	48.83 ± 22.17	28.26 ± 5.55	50.82 ± 14.52	33.43 ± 6.32
>26.5 y					
Dig. 2	38.34 ± 8.56	59.12 ± 33.09	37.72 ± 8.3	63.53 ± 19.83	46.23 ± 13.43
Dig. 3	34.52 ± 4.1	46.95 ± 8.08	37.53 ± 2.75	48.98 ± 11.48	46.28 ± 16.08
Dig. 4	31.78 ± 5.91	49.84 ± 7.99	33.82 ± 5.56	56.83 ± 12.29	39.11 ± 12.42

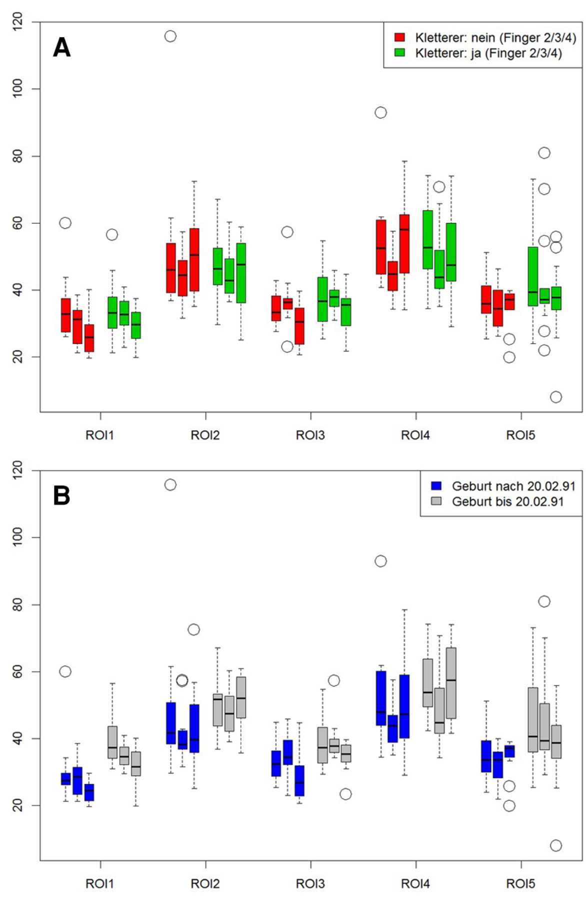

FIGURE 2
Influence of climbing and age on cartilage. ROIs 1 to 4 represent the metacarpal-phalangeal joints, ROI 5 reflects the proximal interphalangeal joint. Left bar = index, middle bar = middle finger, right bar = ring finger. First graph (A) shows the comparison between climbers (red bars) vs. non climbers (green bars). Second graph (B) compares subjects older (gray bars) vs. those younger (blue bars) 26.5 years of age.

that with future technical improvements (e.g., dedicated 7.0 Tesla hand/finger receiving MRI coil), further knowledge about that may be possible in subsequent studies using a more precise segmentation of the distinct cartilage layer segments also for the PIP joint and DIP joint (analogous to MCP).

7 Tesla MRI is not commonly applied clinically, although regulatory approval for routine clinical use has been granted. The advantages of a decreased acquisition time and higher spatial resolution at high magnetic field strength is advantageous for visualization of small anatomical structures such as the wrist (23) or finger joints (24).

Manual segmentation of the cartilage is dependent from the subjective judgement of each observer, which means that measurement accuracy can vary both between different observers and with repeated assessment by the same observer. In addition, manual T2 mapping takes a lot of time. Simplification could be achieved by developing automated assessment or evaluation tools with artificial intelligence algorithms, not only for 7 Tesla but also for the more widespread 3.0 Tesla installations, which would be easily accessible for follow-up studies on larger collectives. However, to date manual segmentation is still considered the gold standard technique (17).

Regarding the prevention of cartilage degeneration in climbers, comprehensive MRI analyses such as in our study could help to better understand the different stress mechanisms to finger cartilage segments. The influence of grip techniques such as slope grip or crimp grip (25, 26) on the cartilage at different cartilage locations could be investigated with compositional MRI techniques as in our study. Likewise, differences between diverse climbing disciplines (sport climbing, multi-pitch, bouldering, speed climbing) or different forms of training (static training, dynamic training) would be accessible in future studies. It is not yet understood whether climbing related bony adaptations, such as osteophytes or cortical thickening, are associated with cartilaginous damage in older athletes, or whether they are merely mechanical reactions as discussed before (13). Further knowledge on that will be increasingly more important with the gaining popularity of climbing.

Our study has several limitations. It is a small cross-sectional study and therefore does not allow any conclusions to be drawn about the changes found in the T2 times with regard to the actual occurrence of OA. We did not correlate MRIs with ultrasound/radiography and no analysis of the cartilage thickness was performed. An analysis for the DIP joint was not possible due to technical limitations, particularly owing to the coil design. The MRIs had to be performed without the use of dedicated hand/finger receiving coils, and as such are not yet commercially available. Further experience with larger collectives and with corresponding clinical classification into different degrees of osteoarthritis is necessary, in particular to better assess the sensitivity of the method to changes in cartilage in climbers. Such studies also could evaluate a possible reversibility of T2 time changes through adaption of climbing techniques and/or training methods, especially with consideration of clinical symptoms.

At this stage, the current data support the concept that the assessment of compositional T2 relaxation times reflects non-specific changes in cartilage in terms of early sport and age dependent alteration. Our study showed that T2 mapping is a feasible method for the direct evaluation of cartilage composition in young climbers. In our limited study collective, we did not register early onset cartilage changes dependent to climbing sport activity, whereas age-related effects seemed to be more prominent. T2 mapping seems appropriate as methodology to depict early hydration changes and collagen fibre damage in finger joint cartilage of larger subsequent studies.

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 humans were approved by Ethikkommission Universität Erlangen: institutional review board (260_15 Bc). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

TB, MB, AN, CL, RJ, RH, MU, and FR designed the study, monitored the data collection, analysed, and interpreted the data and drafted the paper. FR, MB, RH, and TB interpreted the MRIs. Statistical analysis was performed by WA. The final version was approved for publication by all authors All authors contributed to the article and approved the submitted version.

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Conflict of interest

FR is a shareholder, Director of Research and CMO of Boston Imaging Core Lab (BICL), LLC. He is consultant to Grünenthal GmbH.

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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References

1. Lutter C, El-Sheikh Y, Schoffl I, Schoffl V. Sport climbing: medical considerations for this new Olympic discipline. *Br J Sports Med.* (2017) 51(1):2–3. doi: 10.1136/bjsports-2016-096871

2. Lutter C, Tischer T, Schoffl VR. Olympic Competition climbing: the beginning of a new era-a narrative review. *Br J Sports Med.* (2021) 55(15):857–64. doi: 10.1136/bjsports-2020-102035

3. Cole KP, Uhl RL, Rosenbaum AJ. Comprehensive review of rock climbing injuries. *J Am Acad Orthop Surg.* (2020) 28(12):e501–9. doi: 10.5435/JAAOS-D-19-00575

4. Rooks MD. Rock climbing injuries. *Sports Med.* (1997) 23(4):261–70. doi: 10.2165/00007256-199723040-00005

5. Schoffl V, Simon M, Lutter C. Finger and shoulder injuries in rock climbing. *Orthopade.* (2019) 48(12):1005–12. doi: 10.1007/s00132-019-03825-3

6. Schöffl V, Winkelmann HP. Injury-risk on indoor climbing walls. *Ö J Sportmed*. (1999) 3:53.

7. Woollings KY, McKay CD, Emery CA. Risk factors for injury in sport climbing and bouldering: a systematic review of the literature. *Br J Sports Med*. (2015) 49 (17):1094–9. doi: 10.1136/bjsports-2014-094372

8. Rauch S, Wallner B, Strohle M, Dal Cappello T, Brodmann Maeder M. Climbing accidents-prospective data analysis from the international alpine trauma registry and systematic review of the literature. *Int J Environ Res Public Health*. (2019) 17(1). doi: 10.3390/ijerph17010203

9. Miro PH, van Sonnenberg E, Sabb DM, Schoffl V. Finger flexor pulley injuries in rock climbers. *Wilderness Environ Med*. (2021) 32(2):247–58. doi: 10.1016/j.wem.2021.01.011

10. Allenspach P, Saupe N, Rufibach K, Schweizer A. Radiological changes and signs of osteoarthritis in the fingers of male performance sport climbers. *J Sports Med Phys Fitness*. (2011) 51(3):497–505.

11. Frohlich S, Schweizer A, Reissner L, Pastor T, Sporri J, Pastor T. Long term evolution of soft tissue response in the fingers of high-level sport climbers: a cross-sectional 10 year follow-up study. *Phys Ther Sport*. (2021) 52:173–9. doi: 10.1016/j.ptsp.2021.09.006

12. Pastor T, Frohlich S, Sporri J, Schreiber T, Schweizer A. Cartilage abnormalities and osteophytes in the fingers of elite sport climbers: an ultrasonography-based cross-sectional study. *Eur J Sport Sci*. (2020) 20(2):269–76. doi: 10.1080/17461391.2019.1631389

13. Pastor T, Schweizer A, Reissner L, Pastor T, Sporri J, Frohlich S. Long-term evolution of cartilage abnormalities and osteophytes in the fingers of elite sport climbers: a cross-sectional 10-year follow-up study. *Eur J Sport Sci*. (2022) 22 (9):1452–8. doi: 10.1080/17461391.2021.1943716

14. Schöffl VR, Schoffl I. Finger pain in rock climbers: reaching the right differential diagnosis and therapy. *J Sports Med Phys Fitness*. (2007) 47 (1):70–8.

15. Heiss R, Janka R, Uder M, Nagel AM, Trattnig S, Roemer FW. Update cartilage imaging of the small joints: focus on high-field MRI. *Radiologe*. (2019) 59(8):732–41. doi: 10.1007/s00117-019-0521-x

16. Crema MD, Roemer FW, Marra MD, Burstein D, Gold GE, Eckstein F, et al. Articular cartilage in the knee: current MR imaging techniques and applications in clinical practice and research. *Radiographics*. (2011) 31(1):37–61. doi: 10.1148/rg.311105084

17. Zibetti MVW, Menon RG, de Moura HL, Zhang X, Kijowski R, Regatte RR. Updates on compositional MRI mapping of the cartilage: emerging techniques and applications. *J Magn Reson Imaging*. (2023) 58(1):44–60. doi: 10.1002/jmri.28689

18. Springer E, Bohndorf K, Juras V, Szomolanyi P, Zbyn S, Schreiner MM, et al. Comparison of routine knee magnetic resonance imaging at 3 T and 7 T. *Invest Radiol*. (2017) 52(1):42–54. doi: 10.1097/RLI.0000000000000303

19. Zilkens C, Tiderius CJ, Krauspe R, Bittersohl B. Current knowledge and importance of dGEMRIC techniques in diagnosis of hip joint diseases. *Skeletal Radiol*. (2015) 44(8):1073–83. doi: 10.1007/s00256-015-2135-3

20. Ladd ME, Bachert P, Meyerspeer M, Moser E, Nagel AM, Norris DG, et al. Pros and cons of ultra-high-field MRI/MRS for human application. *Prog Nucl Magn Reson Spectrosc*. (2018) 109:1–50. doi: 10.1016/j.pnmrs.2018.06.001

21. Renner N, Kleyer A, Kronke G, Simon D, Sollner S, Rech J, et al. T2 mapping as a new method for quantitative assessment of cartilage damage in rheumatoid arthritis. *J Rheumatol*. (2020) 47(6):820–5. doi: 10.3899/jrheum.180728

22. Lazovic-Stojkovic J, Mosher TJ, Smith HE, Yang QX, Dardzinski BJ, Smith MB. Interphalangeal joint cartilage: high-spatial-resolution in vivo MR T2 mapping–a feasibility study. *Radiology*. (2004) 233(1):292–6. doi: 10.1148/radiol.2331031791

23. Heiss R, Weber MA, Balbach E, Schmitt R, Rehnitz C, Laqmani A, et al. Clinical application of ultrahigh-field-strength wrist MRI: a multireader 3-T and 7-T comparison study. *Radiology*. (2023) 307(2):e220753. doi: 10.1148/radiol.220753

24. Heiss R, Librimir A, Lutter C, Janka R, Kuerten S, Roemer FW, et al. MRI Of finger pulleys at 7T-direct characterization of pulley ruptures in an ex vivo model. *Diagnostics (Basel)*. (2021) 11(7). doi: 10.3390/diagnostics11071206

25. Schweizer A. Biomechanical properties of the crimp grip position in rock climbers. *J Biomech*. (2001) 34(2):217–23. doi: 10.1016/S0021-9290(00)00184-6

26. Schweizer A, Hudek R. Kinetics of crimp and slope grip in rock climbing. *J Appl Biomech*. (2011) 27(2):116–21. doi: 10.1123/jab.27.2.116

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Comparing low volume of blood flow restricted to high-intensity resistance training of the finger flexors to maintain climbing-specific strength and endurance: a crossover study

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Introduction: It is acknowledged that training during recovery periods after injury involves reducing both volume and intensity, often resulting in losses of sport-specific fitness. Therefore, this study aimed to compare the effects of high-intensity training (HIT) and low-intensity training with blood flow restriction (LIT + BFR) of the finger flexors in order to preserve climbing-specific strength and endurance.

Methods: In a crossover design, thirteen intermediate climbers completed two 5-week periods of isometric finger flexors training on a hangboard. The trainings consisted of ten LIT + BFR (30% of max) or HIT sessions (60% of max without BFR) and were undertaken in a randomized order. The training session consisted of 6 unilateral sets of 1 min intermittent hanging at a 7:3 work relief ratio for both hands. Maximal voluntary contraction (MVC), force impulse from the 4 min all out test (W), critical force (CF) and force impulse above the critical force (W′) of the finger flexors were assessed before, after the first, and after the second training period, using a climbing-specific dynamometer. Forearm muscle oxidative capacity was estimated from an occlusion test using near-infrared spectroscopy at the same time points.

Results: Both training methods led to maintaining strength and endurance indicators, however, no interaction ($P > 0.05$) was found between the training methods for any strength or endurance variable. A significant increase ($P = 0.002$) was found for W, primarily driven by the HIT group (pretest—25078 ± 7584 N.s, post-test—27327 ± 8051 N.s, $P = 0.012$, Cohen's $d = 0.29$). There were no significant ($P > 0.05$) pre- post-test changes for MVC (HIT: Cohen's $d = 0.13$; LIT + BFR: Cohen's $d = -0.10$), CF (HIT: Cohen's $d = 0.36$; LIT + BFR = 0.05), W` (HIT: Cohen's $d = -0.03$, LIT + BFR = 0.12), and forearm muscle oxidative capacity (HIT: Cohen's $d = -0.23$; LIT + BFR: Cohen's $d = -0.07$).

Conclusions: Low volume of BFR and HIT led to similar results, maintaining climbing-specific strength and endurance in lower grade and intermediate climbers. It appears that using BFR training may be an alternative approach after finger injury as low mechanical impact occurs during training.

KEYWORDS
injury, hypertrophy, hypoxia, ischemia, intermittent exercise, isometric contraction, strength, oxidative capacity

Introduction

Sport climbers heavily rely on finger flexor contractions, making finger flexor strength and endurance crucial predictors of climbing performance (1, 2). Previous research has extensively investigated the physiological adaptations induced by high-intensity training (HIT) on finger strength and endurance (3, 4). For example, specific maximal strength and hypertrophy training designed for climbers have demonstrated significant increases in finger flexor strength and endurance after 5–10 weeks of training (5–8). However, HIT of the finger flexors may increase the risk of injuries in the fingers, hands, elbows, or shoulders, with chronic injuries being the most common among sport climbers (9, 10). Moreover, when recovering from injuries such as pulley ruptures or strains it is recommended to gradually increase training loads (11). Consequently, recovery periods require climbers to train with decreased intensity, often resulting in losses of sport-specific fitness.

An alternative approach to HIT for improving or maintaining finger strength and muscle hypertrophy is training at low intensities (typically 20%–40% of maximum strength) with blood flow restriction (LIT + BFR), achieved by applying external pressure to the limb proximal to the working muscle (12). LIT + BFR exercise creates a localized hypoxic environment and promotes recruitment of both types I and II muscle fibres, leading to enhanced muscle strength and power (13–15). Furthermore, changes in key markers of protein synthesis, such as mTOR and HIF-1, support the observed adaptations in the muscle following LIT + BFR training (16, 17). Accordingly, LIT + BFR triggers an upregulation of protein synthesis, facilitating muscle growth and strength gains despite the use of lower training loads (decreased mechanical stress). This suggests that the metabolic stress induced by LIT + BFR exercise can stimulate muscle protein synthesis to a comparable extent as high-intensity exercise (18, 19). To date there are no studies comparing HIT and LIT + BFR in climbing-specific hangboard resistance training. However, based on the existing literature, it is reasonable to hypothesize that LIT + BFR and HIT may yield comparable effects in finger flexors training in climbers.

Previous research has shown that increasing strength can be achieved with low volume of HIT per week (20, 21). However, it remains unknown whether the same training volume of LIT + BFR would yield similar effects. Most studies investigating blood flow restriction (BFR) interventions have primarily focused on designs maximizing their effectiveness for increasing muscle strength and hypertrophy (22, 23). However, during the recovery period following an injury, the primary objective of training is to maintain strength and endurance levels using minimal load and training volume (20). Low-intensity training (LIT) with BFR training has been proposed and utilized as a method of recovery after various types of injuries in lower limbs such as knee osteoarthritis (24) or arthroplasty (25), however, to authors best knowledge, there is not any literature available on this topic on the upper extremities related to the climbing.

Therefore, the objective of this study was to investigate the effects of low volume of LIT + BFR training and HIT on maintaining climbing-specific strength and endurance. We hypothesised that HIT and LIT + BFR will be equally effective in preserving sport specific strength and endurance in intermediate climbers.

Methods

Participants

Thirteen lower grade to intermediate climbers [6 male, 7 female participants: males—age, 24.3 ± 2.0 yrs; climbing ability level 13 ± 4 IRCRA (International Rock Climbing Research Association) grade; females—age, 32.6 ± 12.5 yrs; climbing ability 9 ± 2 IRCRA grade] volunteered to take part in the study. Participants self-reported their climbing ability using French/Sport grade which was transformed to the IRCRA difficulty scale ranging from 1 to 32 (26). At the beginning, all participants completed written informed consent forms and medical health questionnaires. Exclusion criteria included venous thrombosis, cardiovascular diseases (including high blood pressure and diabetes), unexplained chest pain, heart pathologies, and fainting during physical activities. Additionally, participants with carpal tunnel syndrome, acute upper limb injuries, tendosynovitis, or tendon injuries in the upper limb, pregnancy, or in the injury recovery phase were also excluded.

Participants were instructed to abstain from engaging in any strenuous exercise, consuming caffeine, and consuming alcohol within 24 h before each experimental testing session. Furthermore, participants were not allowed to maintain normal training routine or engage in any finger flexor strength and endurance training. This was achieved partially by the ongoing COVID lockdown when sport facilities were closed. Additionally, participants were asked to continue their regular dietary and supplement habits. The study was approved by Ethics Committee of Charles University, Faculty of Physical Education and Sport. The participants provided their written informed consent to participate in this study.

Experimental protocol

The 13 weeks long experimental protocol is depicted at **Figure 1**. All participants completed two 5 weeks periods of finger flexors training in a cross-over randomized order with a 1-week long washout period. The two training interventions consisted of either isometric HIT or LIT + BFR on a hangboard. Testing climbing specific strength and endurance was applied before and after each period of training (**Figure 1**).

To eliminate interference between individual tests, the participants underwent two separate testing sessions during the testing week. In the first session, the muscle oxidative capacity and the maximal voluntary contraction (MVC) were assessed.

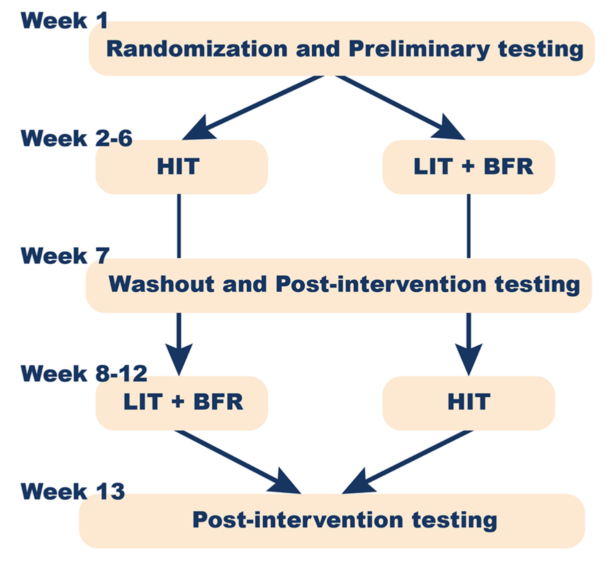

FIGURE 1
Experimental design of the study.

The second testing session involved performing a 4-min all-out test after the measurement of blood pressure to determine the level of occlusion.

Upon their first visit, participants were randomly assigned into two groups based on the training intervention. They were also familiarized with the laboratory setup. Additionally, they completed a questionnaire and signed the medical consent form. In the questionnaire, participants reported their climbing ability as proposed by Draper et al. (26).

Warm-up

All subjects completed a standardized self-directed warm-up prior to the assessment and training protocol. The warm-up consisted of three minutes of pulse-raising activity, such as jogging or cycling, followed by three minutes of climbing, which is considered a sport-specific activity. In addition, the warm-up included a series of 5:5 s work-to-rest ratio hangs on the testing edge in a half-crimp position at ∼50% of the perceived maximum force (27).

Training interventions

Both training interventions consisted of 10 training sessions (2 sessions per week during each 5-week period). The LIT + BFR and HIT participants previously scheduled a time of the day for the individual sessions of hangboard strength exercises. The intensity for each training type was based on the MVC tested prior to each intervention. The training was performed on the same wooden rung as for testing MVC and all-out test (see below) in standing position with arms ∼180° flexed in shoulder, and slightly flexed in elbows. Participants applied the target force on the rung by hanging (bending the knees). The online feedback of applied force was visible on the screen of the testing/training device (1D-SAC, Spacelab, Sofia, Bulgaria).

Blood flow restriction training

To implement BFR, we utilized a cuff provided by Occlude ApS (Aarhaus, Denmark). Prior to each training session, the cuff was inflated to 60% of the complete arterial occlusion pressure (21, 28) on training arm, which caused decrease in the blood flow in the downstream vascular system by 47%–48% (29). In each session both arms performed 6 sets over two blocks (one block consisted of three consecutive sets) unilaterally for each arm, and each set comprising 6 repetitions performed at 30% of MVC, with a work-to-rest ratio of 7 to 3 s. Following the completion of set 3 (60 s rest in between) for one arm, the cuff was deflated and participants immediately continued with the other arm for next three sets. In total, 36 isometric contractions for each arm were completed (Figure 2). The cuff pressure was monitored and controlled during the rest periods between sets.

FIGURE 2
Position of participant during the Low-intensity training with the blood flow restriction.

High-Intensity training

Participants performed HIT sessions at 60% of their MVC. The same volume of training as for LIT + BFR was applied. Each training session consisted of 12 working sets (i.e., 6 sets of each arm divided into two blocks with 5 min rest in between), with each set comprising 6 repetitions and a work-to-rest ratio of 7 to 3 s. Following the completion of the third set, participants were given a 5 min recovery period while the other arm was exercising.

Testing climbing specific strength and endurance

Maximal strength

The maximal strength of the finger flexors was determined using a custom-made dynamometer (1D-SAC, Spacelab, Sofia, Bulgaria). The participant was instructed to maintain a 5 s long half-crimp position while "hanging" on the wooden rung. The rung depth was 23 mm with a 10 mm radius to maximize the activation of the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) (30). Two attempts were performed separated by a two-minute rest in between. Participants were instructed to progressively transfer as much of their weight as possible onto the wooden rung with their dominant arm. The highest peak value from the two trials was considered as the MVC of finger flexors, and this value was used to determine relative workloads for the following training intervention.

All-out test

To assess the critical force (CF), force impulse from all contractions (W), and impulse above the critical force (W'), the 4-min all-out test was performed (31). This test involved 24 isometric maximal voluntary contractions on the same rung as for maximal strength (1D-SAC, Spacelab, Sofia, Bulgaria) in a half crimp position with a 7:3 s work to rest ratio.

During the "rest" phase, participants were instructed to maintain the anatomical position with upper-limb over the head level and were not allowed to shake their forearms or hands, as shaking is known to aid recovery (32). However, participants could dry their fingers using the chalk. Loud verbal encouragements were given to all participants to reach their maximum force during every contraction. Force and time data were continuously recorded throughout the test. For the visual representation see Figure 3.

For each contraction in all tests, the length (in seconds), peak and mean force (in kilograms), and the impulse were determined. The CF was defined as the mean force from the last three contractions of the test.

Muscle oxidative capacity

To assess the muscle oxidative capacity, near-infrared spectroscopy (NIRS) (Portamon, Artinis Medical Systems BV, The Netherlands) was employed to monitor changes in tissue oxygenation levels of the FDP. A chartered physiotherapist located the FDP using the technique recommended by Schweizer and Hudek (30), where the thumb and first finger were squeezed together, and the middle of the muscle belly was palpated (30). The NIRS device sampling frequency was set to 10 Hz and data were processed using the Oxysoft software (Artinis Medical System, BV, The Netherlands). Path length factor was set to 4. Muscle oxidative capacity was estimated by calculating half-time to recovery of the tissue oxygen saturation (O_2HTR) after arterial occlusion (33).

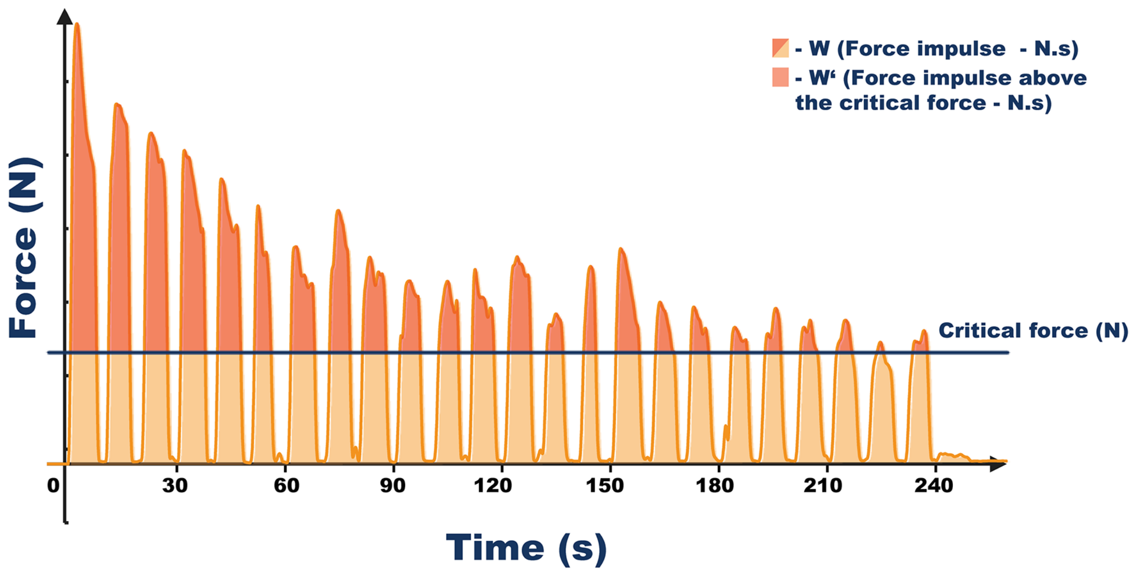

FIGURE 3
Vizualization of data acquired by the all-out test for the finger flexors. Critical force was calculated as the average force from the last three contractions. The duration of the all-out test was 240 s with 7:3 work to rest ratio. Force impulse from all contractions was calculated as the area under the force-time curve and represents total isometric muscle work during the test (W). Impulse above the critical force represents energy store component (W').

Participants were instructed to rest in a supine position with their arm elevated above heart level for 20 min after fitting the artery tourniquet. Following the initial measurement of the baseline, the tourniquet was inflated to a supramaximal pressure of 250 mmHg for 5 min. After that, the cuff was rapidly released, and recovery muscle tissue oxygen saturation (StO_2) values were recorded for 3 min. Half-time of StO_2 recovery was calculated, which represents a valid estimate of oxidative capacity (33).

Statistical analysis

Statistical analyses were performed using IBM SPSS for Windows (IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp). Descriptive statistics (mean ± standard deviation) were used to characterize strength and endurance indicators during pretest and post-test. The analysis of variance (ANOVA) 2 × 2 with repeated measures was conducted to examine the main effects of time (pretest vs. post-test) and training method (LIT + BFR vs. HIT), as well as their interaction effect. The significance level was set at $P < 0.05$. Post hoc analysis using Bonferroni correction was performed to compare specific pairs of interventions in terms of their effects on the pretest and post-test measures. Effect sizes of 0.3, 0.5, and 0.8 were interpreted as small, medium, and large effects, respectively (34). Utilizing the Shapiro-Wilk test, all data were determined to be normal and met the criteria of Mauchly's test of sphericity.

Results

At baseline, no differences for were observed between the training methods for any of the variables ($P > 0.05$).

There was a significant main effect of time for impulse (delta W = + 1568 Ns; $P = 0.002$). However, there was no significant interaction of time and training method demonstrating no substantial differences between LIT + BFR and HIT ($P = 0.057$–0.855).

Pairwise comparisons showed significant increases of force impulse only for HIT method (**Table 1**, **Figure 4**). Otherwise, non-significant improvements with small or no effect size were found for all strength and endurance indicators and no significant decreases of climbing specific strength or endurance indicators were demonstrated (**Table 1**, **Figure 4**).

Discussion

The main finding of the current study was that small volume of LIT + BFR was equally effective as HIT to maintain finger flexor strength and endurance in lower grade and intermediate climbers.

To evaluate maximum finger flexor strength, we employed an ecological setting with the arm positioned overhead without any fixation. This method has been demonstrated to be a valid and reliable measure of climbing-specific strength, with a standard error of measurement (SEM) of 35 N (35). Neither the HIT, nor LIT + BFR interventions resulted in significant changes in finger flexor strength. The observed pretest-post-test changes fell within the previously mentioned SEM range. It has been observed that strength decreases occur rapidly with a training interruption, becoming more pronounced after 8 days of inactivity (36) It is hypothesized that neural factors such as motor unit recruitment and synchronization, firing frequency, and intramuscular coordination are responsible for strength losses during the early stages of inactivity, while morphological factors contribute to greater strength decreases thereafter (37). Our study demonstrates that low volume of intermittent isometric HIT (60% MVC, with a total exercise time of 36 × 10:3 s work: relief cycles per session, two sessions per week) and an equivalent volume of low-intensity with BFR (30% MVC) were effective in maintaining the initial strength level for 5 weeks. All participants were able to sustain both training protocols without premature localized exhaustion. Therefore, it may be speculated that 2 sessions per week, with a total of 12 min of isometric non-exhaustive exercise per arm at low intensity and with BFR, counteracted the deteriorating changes that neural factors may have on maximal strength due to inactivity.

During high-intensity resistance training, a single set of 6–12 repetitions with loads ranging from approximately 70%–85% 1 repetition maximum 2–3 times per week reaching volitional or momentary failure for 8–12 weeks can produce suboptimal, yet significant increases in squat and bench press strength in resistance-trained men (20). Our non-exhaustive protocol with smaller muscle groups, slightly lower intensity, and similar volume did not result in significant improvements. It appears that exhaustive protocols are necessary to induce structural changes leading to strength increases (38, 39). However, a similar volume of non-exhaustive exercise may have benefits in maintaining the current level of strength.

TABLE 1 Mean (± standard deviation) score of pretest and post-test measurements for high intensity training (HIT) and low intensity training with blood flow restrictions (LIT + BFR).

	HIT				LIT + BFR			
	Pretest	Post-test	*P*	Cohen's *d*	Pretest	Post-test	*P*	Cohen's *d*
MVC (N)	356 ± 134	373 ± 113	0.241	0.13	376 ± 138	362 ± 125	0.158	−0.10
Cf (N)	103 ± 26	113 ± 30	0.237	0.36	114.3 ± 31	116 ± 30	0.844	0.05
W (N.s)	25,078 ± 7,583	27,327 ± 8,051	0.012	0.29	26,661 ± 8,415	27,551 ± 6,593	0.392	0.12
W' (N.s)	10,246 ± 6,011	10,092 ± 5,979	0.845	−0.03	9,494 ± 5,278	10,152 ± 5,599	0.353	0.12
O_2HTR (s)	14.3 ± 5.1	13.1 ± 5.1	0.569	−0.23	13.6 ± 4.9	13.2 ± 4.8	0.830	−0.07

W, impulse from the 4 min all-out test; W', impulse above the critical force; CF, critical force; O_2HTR, oxygen saturation ½ time to recovery after arterial occlusion.

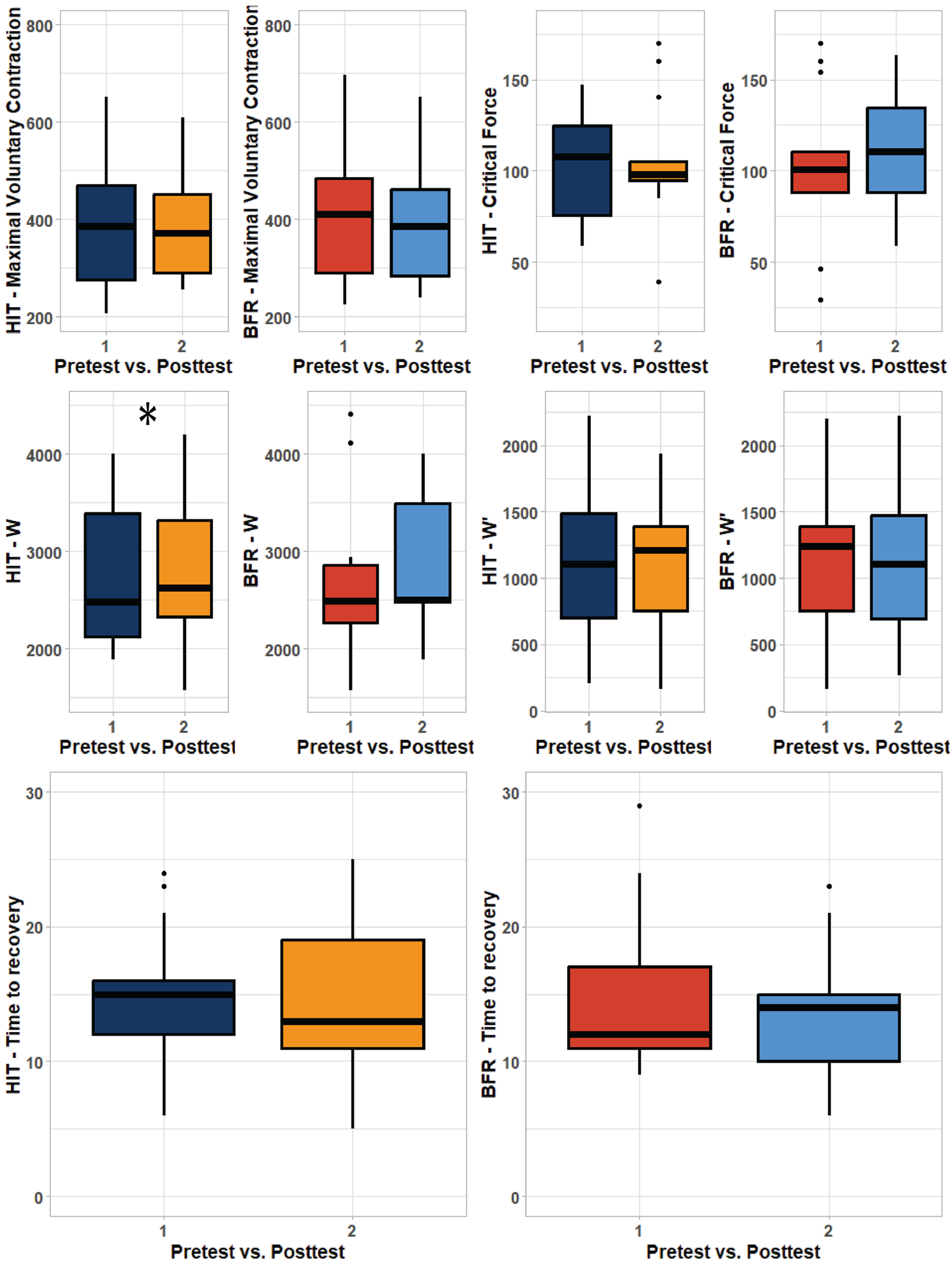

FIGURE 4
Boxplot visualization of pretest post-test results. Left panel represent high intensity training (HIT) while right panels represent low intensity training with blood flow restriction (LIT + BFR) The area of box shows quartile and whiskers represent 1.5 interquartile range between the first and third quartile. The line in the middle corresponds to the mean value. W—impulse, W'—impulse above the critical force, O_2HTR—oxygen ½ time to recovery after occlusion. * represents significant improvements from pretest ($P < 0.05$).

LIT + BFR training does not only have impact on maximal strength improvements but may also, due to peripheric and central adaptations, have direct or indirect impact on endurance performance (40, 41). In our study, we estimated endurance of the finger flexors using several indicators: W, W', CF from 4 min all out test and O_2HTR from arterial occlusion test. W is an indicator of total working capacity and represents an overall measure of finger strength and endurance. W' is the capacity to release energy above the CF and is often related to strength-endurance capacity while the level of CF represents the amount of energy predominantly released by aerobic metabolism (42). O_2HTR is a standardized NIRS derived functional index estimating muscle aerobic capacity. Faster recovery of FDP has been associated with increased climbing ability (43). Similar to maximal strength, no decreases in any endurance indicators were observed. On the contrary, after HIT, W was statistically higher, suggesting that low volume of HIT may lead to overall improvement in finger flexor working capacity in intermediate climbers as W represents both strength and endurance components. However, the effect size for improvement changes was low, and no differences between the two methods were found. The maintenance of all endurance indicators during 5-weeks LIT + BFR training is very promising as submaximal resistance to fatigue appears to be deteriorated to a greater extent from training interruption in comparison with maximal force and maximal power (37).

Endurance adaptations following LIT + BFR training have been associated with improvements in macro- and microvascular functions, muscle redox and ionic buffering, and mitochondrial respiratory capacity (40, 41). In our study, the aerobic capacity of the finger flexor muscles was estimated from the NIRS signal. It is important to note that the sensitivity of StO_2 recovery as a training indicator in climbers is still unknown, and further experimental studies are needed to validate its use. Subsequent studies should also aim to investigate the pathways explaining forearm oxidative capacity and consider using NIRS technology to independently assess skeletal muscle oxygen diffusion capacity and mitochondrial respiratory capacity (44).

There are other strength and limitations to be stated. A strength of the study is that all participants refrained from engaging in any climbing-specific or upper-body strength activities during the 13-week experimental period, ensuring that any observed changes could be attributed to our experimental conditions. The intervention may be regarded as a simulation of a rehabilitation period. Participants were fit enough to train under controlled environment but could not train/climb in an uncontrolled environment due to lock-down restrictions. The crossover design allowed for a direct comparison between the two training modalities within the same group of participants, minimizing inter-individual variability (45). However, due to time requirements, a relatively short one-week washout period between the training interventions was applied. Of note, a control group was not included which might be useful of quantifying no strength training or the short washout period. Nevertheless, this does not seem to influence our results as no changes in any indicator were observed after the HIT or LIT + BFR intervention. The small group size in this study may limit the generalizability of the findings and the ability to detect small differences between the training modalities. Moreover, using BFR with more advanced climbers may have provided different results. MVC was assessed only once before each training intervention to set the training load. In other words, the climbers trained at the same relative intensity throughout the whole period. This may also explain the lack of changes during the different periods. If MVC was tested every week, there may had been a progression in the training which ultimately may have led to an increase in (some of) the variables. On the other hand, during recovery periods from an injury, regular testing of MVC would increase stress on injured tissues and may slow the recovery process.

Our findings support the hypothesis that both approaches, with and without BFR, were equally effective in preserving the studied parameters during the minimal training period. However, it is important to note that physiology of these adaptations may differ during exercise at 30% of MVC compared to higher intensity exercise (23, 46, 47). Therefore, BFR training at a lower intensity (30% of MVC) appears to be a viable substitute for HIT during recovery periods and may offer advantages, particularly for climbers recovering from injuries, although it is more discomforting and less enjoyable compared to HIT (48).

In conclusion, this study demonstrates that low volume of non-exhaustive BFR training at a lower intensity can be as effective as HIT in preserving sport-specific strength and endurance. These findings suggest that LIT + BFR training may be a viable alternative for climbers recovering from injuries.

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 humans were approved by Ethics Committee of Charles University, Faculty of Physical Education and Sport. The studies were conducted in accordance with the local legislation and institutional requirements. The 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

TJ: Writing – original draft, Conceptualization, Investigation, Data curation. AS: Writing – review & editing, Methodology. VA: Methodology, Writing – review & editing. JB: Conceptualization, Methodology, Supervision, Writing – review & editing.

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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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Supplementary material

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References

1. Maciejczyk M, Michailov ML, Wiecek M, Szymura J, Rokowski R, Szygula Z, et al. Climbing-Specific exercise tests: energy system contributions and relationships with sport performance. *Front Physiol.* (2022) 12:787902. doi: 10.3389/fphys.2021.787902

2. Philippe M, Wegst D, Müller T, Raschner C, Burtscher M. Climbing-specific finger flexor performance and forearm muscle oxygenation in elite male and female sport climbers. *Eur J Appl Physiol.* (2012) 112(8):2839–47. doi: 10.1007/s00421-011-2260-1

3. Langer K, Simon C, Wiemeyer J. Strength training in climbing: a systematic review. *J Strength Cond Res.* (2023) 37(3):751–67. doi: 10.1519/JSC.0000000000004286

4. Thompson EB, Farrow L, Hunt JE, Lewis MP, Ferguson RA. Brachial artery characteristics and micro-vascular filtration capacity in rock climbers. *Eur J Sport Sci.* (2015) 15(4):296–304. doi: 10.1080/17461391.2014.940560

5. Hermans E, Saeterbakken AH, Vereide V, Nord ISO, Stien N, Andersen V. The effects of 10 weeks hangboard training on climbing specific maximal strength, explosive strength, and finger endurance. *Front Sports Act Living.* (2022) 4:888158. doi: 10.3389/fspor.2022.888158

6. Levernier G, Laffaye G. Four weeks of finger grip training increases the rate of force development and the maximal force in elite and top world-ranking climbers. *J Strength Cond Res.* (2019) 33(9):2471–80. doi: 10.1519/JSC.0000000000002230

7. López-Rivera E, González-Badillo JJ. Comparison of the effects of three hangboard strength and endurance training programs on grip endurance in sport climbers. *J Hum Kinet.* (2019) 66:183–95. doi: 10.2478/hukin-2018-0057

8. Medernach JP, Kleinöder H, Lötzerich HH. Fingerboard in competitive bouldering: training effects on grip strength and endurance. *J Strength Cond Res.* (2015) 29(8):2286–95. doi: 10.1519/JSC.0000000000000873

9. Barrile AM, Feng S, Nesiama J, Huang C. Injury rates, patterns, mechanisms, and risk factors among competitive youth climbers in the United States. *Wilderness Environ Med.* (2022) 33(1):25–32. doi: 10.1016/j.wem.2021.09.005

10. Grønhaug G. Self-reported chronic injuries in climbing: who gets injured when ? *Open Sport Exerc Med.* (2018) 4(1):1–6. doi: 10.1136/bmjsem-2018-000406

11. Lum ZC, Park L. Rock climbing injuries and time to return to sport in the recreational climber. *J Orthop.* (2019) 16(4):361–3. doi: 10.1016/j.jor.2019.04.001

12. Patterson SD, Hughes L, Warmington S, Burr J, Scott BR, Owens J, et al. Blood flow restriction exercise: considerations of methodology, application, and safety. *Front Physiol.* (2019) 10:533. doi: 10.3389/fphys.2019.00533

13. BjØrnsen T, Wernbom M, Kirketeig A, Paulsen G, SamnØy L, BÆkken L, et al. Type 1 muscle fiber hypertrophy after blood flow-restricted training in powerlifters. *Med Sci Sports Exerc.* (2019) 51(2):288–98. doi: 10.1249/MSS.0000000000001775

14. Reece TM, Godwin JS, Strube MJ, Ciccone AB, Stout KW, Pearson JR, et al. Myofiber hypertrophy adaptations following 6 weeks of low-load resistance training with blood flow restriction in untrained males and females. *J Appl Physiol.* (2023) 134(5):1240–55. doi: 10.1152/japplphysiol.00704.2022

15. Wang J, Mogensen AG, Thybo F, Brandbyge M, Brorson J, van Hall G, et al. Low-load blood flow-restricted resistance exercise produces fiber type-independent hypertrophy and improves muscle functional capacity in older individuals. *J Appl Physiol.* (2023) 134(4):1047–62. doi: 10.1152/japplphysiol.00789.2022

16. Fujita S, Abe T, Drummond MJ, Cadenas JG, Dreyer HC, Sato Y, et al. Blood flow restriction during low-intensity resistance exercise increases S6K1 phosphorylation and muscle protein synthesis. *J Appl Physiol.* (2007) 103(3):903–10. doi: 10.1152/japplphysiol.00195.2007

17. Panzhinskiy E, Culver B, Ren J, Bagchi D, Nair S. Chapter 22 - Role of mammalian target of rapamycin (mTOR) in muscle growth. In: Bagchi D, Nair S, Sen CK, editors. *Nutrition and enhanced sports performance.* San Diego: Academic Press (2013). p. 217–27. doi: 10.1016/B978-0-12-396454-0.00022-9

18. Barbieri E, Sestili P. Reactive oxygen Species in skeletal muscle signaling. *J Signal Transduct.* (2012) 2012:1–17. doi: 10.1155/2012/982794

19. Steinbacher P, Eckl P. Impact of oxidative stress on exercising skeletal muscle. *Biomolecules.* (2015) 5(2):356–77. doi: 10.3390/biom5020356

20. Androulakis P, James K, James PF. The Minimum effective training dose required to increase 1RM strength in resistance - trained men: a systematic review and meta - analysis. *Sport Med.* (2020) 50(4):751–65. doi: 10.1007/s40279-019-01236-0

21. Das A, Paton B. Is there a minimum effective dose for vascular occlusion during blood flow restriction training? *Front Physiol.* (2022) 13:838115. doi: 10.3389/fphys.2022.838115

22. Abe T, Fujita S, Nakajima T, Sakamaki M, Ozaki H, Oga-sawara R, et al. Effects of low-intensity cycle training with restricted leg blood flow on thigh muscle volume and VO2max in young men. *J Sport Sci Med.* (2010) 9(April):452–8.

23. Abe T, Kearns CF, Sato Y. Muscle size and strength are increased following walk training with restricted venous blood flow from the leg muscle, Kaatsu-walk training. *J Appl Physiol.* (2006) 100(5):1460–6. doi: 10.1152/japplphysiol.01267.2005

24. Ferraz RB, Gualano B, Rodrigues R, Kurimori CO, Fuller R, Lima FR, et al. Benefits of resistance training with blood flow restriction in knee osteoarthritis. *Med Sci Sport Exerc.* (2018) 50(5):897–905. doi: 10.1249/MSS.0000000000001530

25. Franz A, Ji S, Bittersohl B, Zilkens C, Behringer M. Impact of a six-week prehabilitation with blood-flow restriction training on pre- and postoperative skeletal muscle mass and strength in patients receiving primary total knee arthroplasty. *Front Physiol.* (2022) 13:881484. doi: 10.3389/fphys.2022.881484

26. Draper N, Giles D, Schöffl V, Fuss FK, Watts PB, Wolf P, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: international rock climbing research association position statement. *Sports Technol.* (2016) 8(3-4):88–94. doi: 10.1080/19346182.2015.1107081

27. Baláš J, Kodejška J, Krupková D, Hannsmann J, Fryer S. Reliability of near-infrared spectroscopy for measuring intermittent handgrip contractions in sport climbers. *J Strength Cond Res.* (2018) 32(2):494–501. doi: 10.1519/JSC.0000000000002341

28. Sieljacks P, Matzon A, Wernbom M, Ringgaard S, Vissing K, Overgaard K. Muscle damage and repeated bout effect following blood flow restricted exercise. *Eur J Appl Physiol.* (2016) 116(3):513–25. doi: 10.1007/s00421-015-3304-8

29. Singer TJ, Stavres J, Elmer SJ, Kilgas MA, Pollock BS, Kearney SG, et al. Knee extension with blood flow restriction : impact of cuff pressure on hemodynamics. *Eur J Appl Physiol.* (2020) 120(1):79–90. doi: 10.1007/s00421-019-04250-2

30. Schweizer A, Hudek R. Kinetics of crimp and slope grip in rock climbing. *J Appl Biomech.* (2011) 27(2):116–21. doi: 10.1123/jab.27.2.116

31. Giles D, Hartley C, Maslen H, Hadley J, Taylor N, Torr O, et al. An all-out test to determine finger flexor critical force in rock climbers. *Int J Sports Physiol Perform.* (2021) 16(7):942–9. doi: 10.1123/ijspp.2020-0637

32. Baláš J, Michailov M, Giles D, Kodejška J, Panáčková M, Fryer S, et al. Active recovery of the finger flexors enhances intermittent handgrip performance in rock climbers performance in rock climbers. *Eur J Sport Sci*. (2016) 16(7):764–72. doi: 10.1080/17461391.2015.1119198

33. Fryer S, Stoner L, Giles KSD, Sveen J, Garrido I. Forearm muscle oxidative capacity index predicts sport rock - climbing performance. *Eur J Appl Physiol*. (2016) 116(8):1479–84. doi: 10.1007/s00421-016-3403-1

34. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for *t*-tests and ANOVAs. *Front Psychol*. (2013) 4:863. doi: 10.3389/fpsyg.2013.00863

35. Michailov ML, Baláš J, Tanev SK, Stoyanov H, Kodejška J, Brown L. Reliability and validity of finger strength and endurance measurements in rock climbing reliability and validity of finger strength and endurance measurements in rock. *Res Q Exerc Sport*. (2018) 89(2):246–54. doi: 10.1080/02701367.2018.1441484

36. Wortman RJ, Brown SM, Savage-elliott I, Finley ZJ, Mulcahey MK. Blood flow restriction training for athletes: a systematic review. *Am J Sports Med*. (2021) 49 (7):1938–44. doi: 10.1177/0363546520964454

37. Bosquet L, Berryman N, Dupuy O, Mekary S, Arvisais D, Bherer L, et al. Effect of training cessation on muscular performance: a meta-analysis. *Scand J Med Sci Sports*. (2013) 23(3):e140–9. doi: 10.1111/sms.12047

38. Hermans E, Andersen V, Saeterbakken AH. The effects of high resistance-few repetitions and low resistance-high repetitions resistance training on climbing performance. *Eur J Sport Sci*. (2017) 17(4):378–85. doi: 10.1080/17461391.2016.1248499

39. Schoenfeld BJ, Wilson JM, Lowery RP, Krieger JW. Muscular adaptations in low-versus high-load resistance training: a meta-analysis. *Eur J Sport Sci*. (2016) 16 (1):1–10. doi: 10.1080/17461391.2014.989922

40. Horiuchi M, Stoner L, Poles J. The effect of four weeks blood flow restricted resistance training on macro - and micro - vascular function in healthy, young men. *Eur J Appl Physiol*. (2023) 123:2179–89. doi: 10.1007/s00421-023-05230-3

41. Pignanelli C, Petrick HL, Keyvani F, Heigenhauser GJF, Quadrilatero J, Holloway GP, et al. Low-load resistance training to task failure with and without blood flow restriction: muscular functional and structural adaptations. *Am J Physiol Regul Integr Comp Physiol*. (2020) 318(2):R284–95. doi: 10.1152/ajpregu.00243.2019

42. Giles D, Chidley JB, Taylor N, Torr O, Hadley J, Randall T, et al. The determination of finger-flexor critical force in rock climbers. *Int J Sports Physiol Perform*. (2019) 14(7):972–9. doi: 10.1123/ijspp.2018-0809

43. Fryer S, Stone KJ, Sveen J, Dickson T, Giles D, Baláš J, et al. Differences in forearm strength, endurance, and hemodynamic kinetics between male boulderers and lead rock climbers. *Eur J Sport Sci*. (2017) 17(9):1177–83. doi: 10.1080/17461391.2017.1353135

44. Pilotto AM, Adami A, Mazzolari R, Brocca L, Crea E, Zuccarelli L, et al. Near-infrared spectroscopy estimation of combined skeletal muscle oxidative capacity and O2 diffusion capacity in humans. *J Physiol*. (2022) 18:4153–68. doi: 10.1113/JP283267

45. Nolan SJ, Hambleton I, Dwan K. The use and reporting of the cross-over study design in clinical trials and systematic reviews: a systematic assessment. *Plos One*. (2016) 69:1–14. doi: 10.1371/journal.pone.0159014

46. Cook SB, Scott BR, Hayes KL, Murphy BG. Neuromuscular adaptations to low-load blood flow restricted resistance training. *J Sports Sci Med*. (2018) 17 (1):66–73.

47. Ratamess NA, Brent A, Evetoch TK, Housh TJ. Progression models in resistance training for healthy adults. *Med Sci Sport Exerc*. (2009) 41(3):687–708. doi: 10.1249/MSS.0b013e3181915670

48. Andersen V, Hermans E, Vereide V, Stien N, Paulsen G, Baláš J, et al. Comparison of finger flexor resistance training, with and without blood flow restriction, on perceptional and physiological responses in advanced climbers. *Sci Rep*. (2023) 13(1):3287. doi: 10.1038/s41598-023-30499-x

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Neuromechanics of finger hangs with arm lock-offs: analyzing joint moments and muscle activations to improve practice guidelines for climbing

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Introduction: Climbing imposes substantial demands on the upper limbs and understanding the mechanical loads experienced by the joints during climbing movements is crucial for injury prevention and optimizing training protocols. This study aimed to quantify and compare upper limb joint loads and muscle activations during isometric finger hanging exercises with different arm lock-off positions.
Methods: Seventeen recreational climbers performed six finger dead hangs with arm lock-offs at 90° and 135° of elbow flexion, as well as arms fully extended. Upper limb joint moments were calculated using personalized models in OpenSim, based on three-dimensional motion capture data and forces measured on an instrumented hang board. Muscle activations of upper limb muscles were recorded with surface electromyography electrodes.
Results: Results revealed that the shoulder exhibited higher flexion moments during arm lock-offs at 90° compared to full extension ($p = 0.006$). The adduction moment was higher at 135° and 90° compared to full extension ($p < 0.001$), as well as the rotation moments ($p < 0.001$). The elbows exhibited increasing flexion moments with the increase in the arm lock-off angle ($p < 0.001$). Muscle activations varied across conditions for biceps brachii ($p < 0.001$), trapezius ($p < 0.001$), and latissimus dorsi, except for the finger flexors ($p = 0.15$).
Discussion: Our findings indicate that isometric finger dead hangs with arms fully extended are effective for training forearm force capacities while minimizing stress on the elbow and shoulder joints. These findings have important implications for injury prevention and optimizing training strategies in climbing.

KEYWORDS
climbing, neuromechanics, arm lock-offs, injury prevention, training optimization

1. Introduction

The importance of sustained isometric strength in the fingers and forearm muscles for climbing success has been well-established (1). Climbers face the challenge of harnessing this specific strength capacity to navigate a large variety of climbing styles, characterized by different hold shapes, orientations, and wall steepness. Consequently, the upper limbs have consistently been identified as the most vulnerable to injuries across all levels of performance, age, and gender (2–5), with injuries due to overuse being particularly prevalent (6, 7). Notably, a significant proportion (42% to 71%) of climbing injuries occur in the wrists, elbows, and shoulders, resulting from overuse or acute atraumatic incidents (2).

The mechanical loading experienced by the body can lead to physiological adaptations and therefore impact performance and function of the musculoskeletal system (1, 8). These loading patterns, characterized by interacting physical forces—magnitude, duration, frequency, rate of force development, type, and direction of application—yield various effects on the tissues, ranging from favorable functional adaptations (e.g., increased strength, coordinated movement) to potential chronic overload injuries (9). Previous studies investigating mechanical loading in climbing have predominantly focused on the fingers, either *in vivo* or *in situ*. These studies examined finger force capacities under different hold depths and grip techniques and highlighted that maximal forces increase with the hold depth, with crimping requiring higher finger flexion force (10–12). Biomechanical models have been applied to estimate the forces acting on finger tendons and pulleys during specific climbing grip techniques and indicated that crimping elicits higher forces on the finger pulleys compared to more open grip techniques (13), while also demanding greater forces on the ring and middle fingers (14). To the best of the authors' knowledge, no studies evaluated the mechanical loads during climbing or climbing-related activities at other anatomical structures, e.g., elbow and shoulder joints. Considering that these joints are prone to injuries (2), quantifying elbow and shoulder loads might help to enhance our understanding of certain injury mechanisms and prevent overuse injuries in the future.

One aspect associated with climbing performance is the lock-off ability (15). This term refers to the gesture involved in pulling movements during ascent. While climbers apply force with one hand to the initiating hold (H), they release the other hand to reach the next target hold (T). During this brief period, known as lock-off, H engages in static and isometric exertion. Once the target hold is reached, H and T often remain in a partially locked-off state, enabling climbers to regain balance and execute the necessary footwork for the subsequent move (16). Lock-offs are performed across a range of upper-body joint angles, depending on the steepness of the climbing surface and the initial and final positions between subsequent holds (16). In some instances, climbers can utilize lower limb support to perform the movement, while in others, they cannot. Consequently, the intensity of a lock-off also depends on the type of movement being executed during the ascent. Under such conditions, climbers may experience varying degrees of joint loading.

Gaining a better understanding of the neuromechanical behavior during climbing movements could enhance the quality of training protocols by ensuring effectiveness and mitigating injury risks. Therefore, the aim of the present study was to quantify and compare upper limb joint loads and muscle activations between three isometric finger hanging exercises with specific lock-off positions, i.e., (1) elbows flexed at 90°, (2) elbows flexed at 135°, and (3) elbows fully extended at 180°. We hypothesized that shoulder and elbow joint loads will increase with increasing elbow flexion, whereas forearm muscle activations will remain the same.

2. Methods

2.1. Sample

A total of 17 recreational climbers (age: 26.3 ± 3.7; height: 1.70 ± 0.1 m; weight: 62.0 ± 9.2 kg) were recruited to participate in the study. The sample consisted of advanced/elite climbers, with a mean ability rating of 22.1 ± 1.8 according to the IRCRA reporting scale (17). To be eligible for participation, climbers had to have prior experience using a hang board, which is a commonly used instrument for finger strength training. Additionally, participants were required to have no history of upper-limb musculoskeletal injuries that could hinder their involvement in the study. The research protocol received approval from the Ethics Committee of the University of Vienna (00690), and all participants were provided with detailed information about the study's objectives. Before participating, they voluntarily signed an informed consent form indicating their willingness to take part in the research.

2.2. Experimental protocol

The experimental protocol involved conducting six trials of isometric finger hangings on a custom-designed and instrumented hang board consisted of 2 separate handles, and utilizing a 22 mm-depth edge (**Figure 1**). The hangings were performed with fingers positioned in an open crimp grip, under three different conditions: elbows flexed at 90° (**Figure 2C**), 135° (**Figure 2B**), and in full 180° extension (**Figure 2A**), and the order was self-selected by the participant. The distance between the handles was adjusted to enable participants to perform the task with the desired elbow flexion positions, confirmed with the help of a goniometer, while maintaining the forearm vertical. Each position was held for a duration of 12 s. A one-minute rest period was provided between trials, while a five-minute rest period was given between conditions. With this design, the low-intensity exercises could be carried out by the participants without interference from previous training or climbing sessions. Prior to commencing data collection, participants were instructed to engage in a 10-min warm-up routine. They were allowed to choose between a self-selected routine or a suggested routine, which included joint-mobility exercises, rowing, push-ups, and assisted finger dead hangs.

2.3. Measurements

To capture the body kinematics of our participants, a total of 33 retroreflective surface markers were attached to each

FIGURE 1
Instrumented hang board used in the study. The force sensors were placed in separate hand holds, with height and width being adjusted according to participant's individual anthropometry and the desired arm lock-off angles required in the tasks.

participant (**Figure 3**), and their trajectories were recorded using a 12-camera motion capture system (Vicon Motion Systems, Oxford, UK) at a sampling frequency of 200 Hz. The marker model used was a modified version of the Plug-in-Gait marker set (18), with additional markers placed on the phalanx distalis, as well as the index and pinky fingers. Following data collection, the markers were labeled, gap-filled, and low-pass filtered using Nexus 2.14.0 software (Vicon Motion Systems, Oxford, UK).

Electromyographic signals (EMG) from the finger digitorium superficialis (finger flexor), biceps brachii—long head (biceps brachii), trapezius, and latissimus dorsi were recorded from both left and right limbs using a wireless system (Cometa®, Milan, Italy) at a sampling rate of 2,000 Hz, synchronized with the motion capture system. The placement of surface electrodes followed the SENIAM guidelines (19) for all muscles, except for the finger flexor, which was placed according to Vigouroux et al. (20). The recorded EMG data was filtered using an 4th-order band-pass filter with cutoff frequencies of 6 Hz and 600 Hz, and demeaned (21).

Forces applied during the finger hangings in the vertical and medial-lateral directions were measured using force sensors mounted on the hang board (**Figure 1**). These 2D sensors are based on 4 HBM strain gauges for each direction, as Wheatstone bridge circuit, mounted on a National Instruments cDAQ-9174. For further details, see Maffiodo et al. (22). The force sensor was synchronized with the motion capture system and collected data at a sampling frequency of 1,000 Hz.

2.4. Data processing

2.4.1. Estimation of joint loads

OpenSim (23) was used to quantify wrist, elbow and shoulder angles and moments for each trial. The Rajagopal model (24) was slightly modified to ensure an adequate range of motion in the upper limb joints for the tasks performed. In this model, the

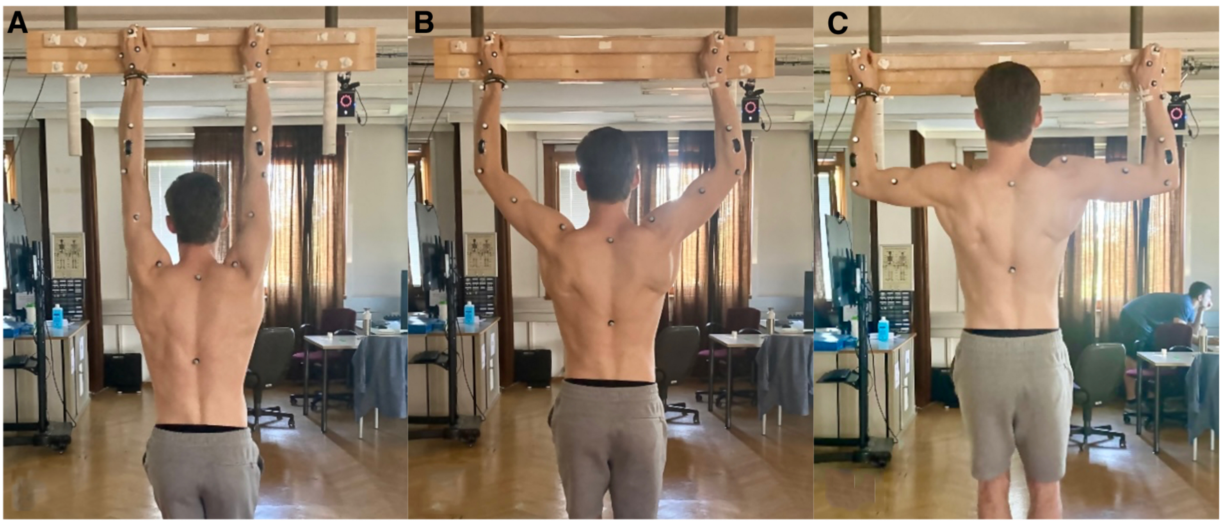

FIGURE 2
Dead hang exercises performed in the present study. (A) represents the hanging performed at full elbow extension (180°). (B) indicates the arm lock-off at 135° of elbow flexion, and in (C) it is represented the position of the participants during the lock-off at 90° of elbow flexion.

FIGURE 3
Participant with surface markers and EMG sensors. The leg markers are not included in the Plug-in-Gait model used in this study for the kinematic measurements, but it was applied for visualization purposes only.

shoulder joint was represented as a ball and socket joint with three degrees-of-freedom (DoF), while the elbow and wrist joints included two DoF, enabling flexion/extension and pronation/supination at the elbow, and radial/ulnar deviations at the wrist.

To personalize the model, the generic model was scaled based on the surface marker locations from a static trial to match each participant's anthropometry. This is performed by comparing the experimental marker data from the motion capture to the virtual markers from the Rajagopal model used. Subsequently, the personalized model and the corresponding marker trajectories from the arm lock-offs were used to calculate joint angles using inverse kinematics. The vertical and lateral forces measured with the force sensors were applied to the hand segment of the model at the location of the finger markers. Inverse dynamics analysis was employed to compute joint moments for all degrees of freedom. The joint moments were then smoothed using a LOESS function, and the parameters were defined after residual analysis and inspection of the derivatives. The peak values from the middle 10 ms of each trial were extracted. Additionally, peak joint moments were normalized by participant's body weight for further analysis. Therefore, the upper limb loads were normalized by individual's body weight (Nm/kg) and are represented by their estimated peak joint moments, defined as follows: flexion (+) and extension (−) in the sagittal plane; internal rotation/pronation (+) and external rotation/supination (−) in the transverse plane; adduction/radial deviation (+) and abduction/ulnar deviation (−) in the frontal plane.

2.4.2. Estimation of muscle activity

Muscle activity in the upper body was assessed using the root mean square (RMS) of the recorded EMG signals from the finger flexor, biceps brachii, trapezius, and latissimus dorsi muscles. The RMS was computed with a window size of 250 ms and overlaps of 125 ms. Data was amplitude-normalized by the peak activation observed in the trials performed at 180° elbow condition. For analysis purposes, the peak RMS-relative to 180° values from the middle windows of each trial were expressed as a percentage and will be presented accordingly (%RMS180°).

2.5. Statistical analysis

Prior to the analyses, data normality was assessed using the Shapiro-Wilk test. For normally distributed data, comparisons were performed using ANOVA for repeated measures with Bonferroni correction for multiple comparison, and the results were reported accordingly. In the case of non-normally distributed data, Friedman's Two-way Analysis of Variance by Ranks Summary was applied. Side differences were tested using the Wilcoxon signed rank test. In all tests, statistical significance was considered when $p < 0.05$. Data analysis was carried out using custom-built scripts in MATLAB 2022a (MathWorks Inc., Natick, MA, USA) and IBM SPSS Statistics 29.0.0.0 (Armonk, NY: IBM Corp).

3. Results

Friedman's showed that the muscle activation obtained for all of the upper body muscles across the arm lock-off conditions was significantly different for all muscles ($\chi^2(2) = 52.62$, $p < 0.001$ for the biceps brachii; $\chi^2(2) = 52.51$, $p < 0.001$ for the trapezius; $\chi^2(2) = 62.90$, $p < 0.001$ for the latissimus dorsi) except for the finger flexors ($\chi^2(2) = 1.55$, $p = 0.45$). We found significantly higher %RMS180° at 135° and 90° when compared to full elbow extension, and no differences were found between 135° and 90°, as can be seen in in **Figure 4**.

The mean %RMS180° (± standard deviation) recorded for the finger flexor was 102.2 ± 33.2%, 103.4 ± 14.2%, and 102.8 ± 18.42% at full extension, 135°, and 9°, respectively, and did not change across conditions. Biceps brachii %RMS180° was significantly lower when participants performed at full extension (97.2% ± 12.0%), compared to the arm lock-off at 135° (447.26 ± 386.21%, $p < 0.001$) and 90° (524.5% ± 468.5, $p < 0.001$). No differences were found when comparing biceps brachii at 90° and 135° ($p = 0.90$). Trapezius and latissimus dorsi %RMS180° were lower at full extension (103.02 ± 13.00%, and 99.67 ± 10.52%, respectively) when compared to 135° (158.42 ± 90.02%, 212.03 ± 104.65%, respectively, with $p = 0.001$), and 90° (277.67 ± 207.09%, and 314.74 ± 236.00%, $p < 0.001$). Both muscles also showed significant differences when compared between 135° and 90° ($p = 0.002$ and $p = 0.001$, respectively).

The ANOVA showed that the joint moments differed between arm lock-offs at different conditions (**Table 1**). The shoulder presented significant differences in the moments in all planes [F (1,33) = 23.54, $p < 0.001$]. The adduction moment was higher [F (1,33) = 93.80, $p < 0.001$] for the conditions at 135° and 90° when compared to arms fully extended ($p < 0.001$ for both comparisons). The internal-external rotation moments at the shoulder were significantly different across all conditions [F (1,33) = 471.41, $p < 0.001$], being higher in the lock-offs performed at 90° and at 135° compared to arms at full extension ($p < 0.001$ in all comparisons).

For the elbow in the sagittal plane, ANOVA also revealed that the external joint moments were different across all exercise conditions [F (1,33) = 88.77, $p < 0.001$]. The highest moments

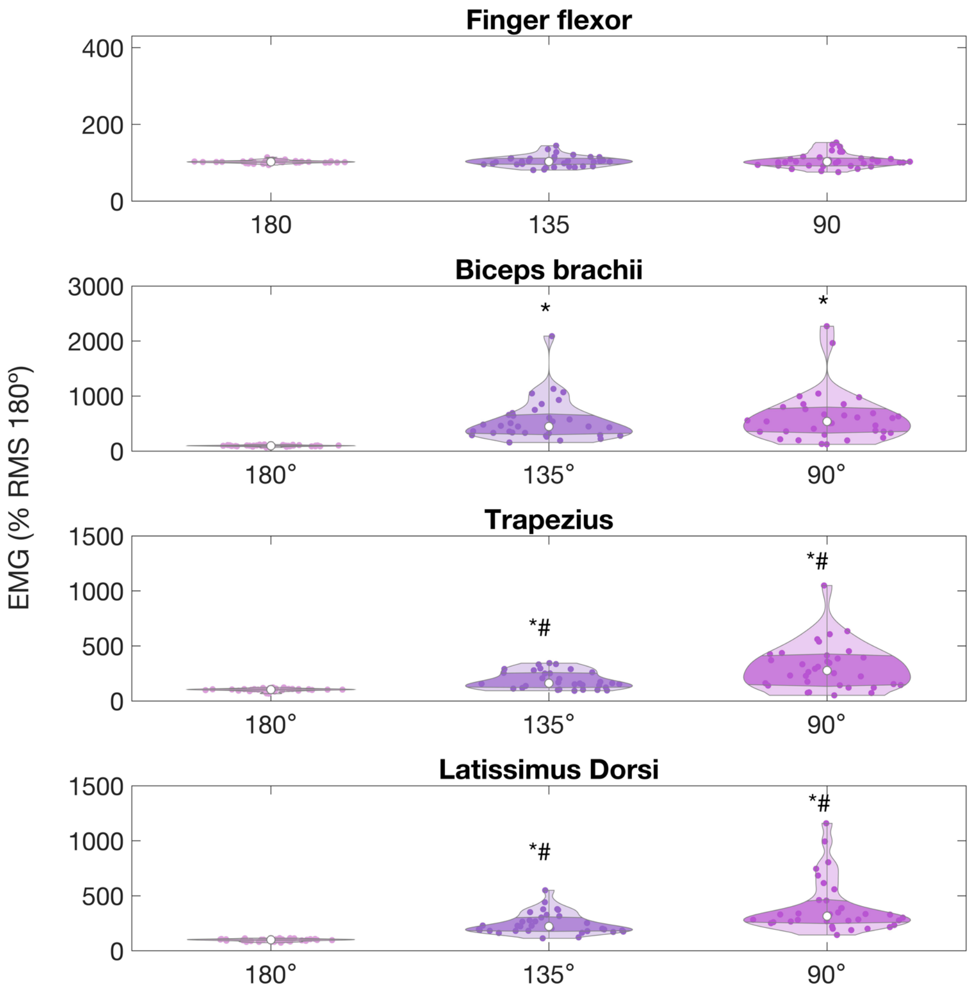

FIGURE 4
Average EMG RMS, represented as % relative to the peak value observed at 180°, for upper limb muscles of climbers during arm lock-offs performed at full elbow extension (180°), 135° and 90° of elbow flexion, in a 22-mm depth ledge. Values are expressed as percentage of the peak normalized by the full elbow extension condition. (*) indicates significant difference with the 180° condition. (#) indicates significant difference with 135° condition.

TABLE 1 Estimated external upper body joint moments of climbers during dead hang exercises performed with arm lock-offs at different degrees of elbow flexion.

Joint Moments (Nm/kg)							
Arm lock-off condition	Shoulder sagittal	Shoulder frontal	Shoulder transversal	Elbow sagittal	Elbow transversal	Wrist sagittal	Wrist frontal
90°	0.56 ± 0.18*,#	0.53 ± 0.22*	0.41 ± 0.10*,#	0.39 ± 0.16*,#	0.001 ± 0.03*	0.30 ± 0.04	−0.02 ± 0.06*
135°	0.49 ± 0.16	0.45 ± 0.16*	0.23 ± 0.07*	0.24 ± 0.14*	0.02 ± 0.02#	0.31 ± 0.05*	−0.002 ± 0.062*
Full elbow extension	0.41 ± 0.15	0.19 ± 0.09	0.07 ± 0.03	0.13 ± 0.07	0.01 ± 0.01	0.30 ± 0.04	0.07 ± 0.05
p-value*	**0.006**	**<0.001**	**<0.001**	**<0.001**	**0.02**	**1.00**	**<0.001**
p-value#	**0.005**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.42**	**0.13**
p-value∅	**0.006**	**0.08**	**<0.001**	**<0.001**	**0.81**	**0.02**	**<0.001**

p-value* of the comparison between 90°–180°; *p*-value# of the comparison between 90°–13°; *p*-value∅ of the comparison between 180°–135°.
*Significantly different from full elbow extension.
#Significantly different from 135°.
∅Significantly different from 90°. Movements in the sagittal plane: flexion/extension (+/–); Movements in the transversal plane: internal—pronation/external—supination rotations (+/–); Movements in the frontal plane: adduction—ulnar deviation/ abduction—radial deviation (+/–).

were found when participants performed arm lock-offs at 90°, followed by lock-offs at 135°, when compared with arms fully extended. Although the magnitudes were considerably small, pronation moments were significantly lower in 90° lock-offs when compared to 180° and also lower for 135° when compared to 90° [F (1,33) = 8.55, $p = 0.006$].

The ANOVA showed that the wrist did not present significant differences in the sagittal plane [F (1,33) = 0.85, $p = 0.36$] but did for the movements in the frontal [F (1,33) = 35.46, $p < 0.001$]. When participants performed the exercises with elbows fully extended, the moments significantly changed from a small radial deviation to ulnar deviation moment as the degree of arm lock-offs decreased from 90° and 135° to arms fully extended.

Wilcoxon results on the side imbalances for some joints showed significant differences across arm lock-off conditions, and seemed to increase concomitantly with increasing elbow flexion angles, as can be seen in **Figures 5–7**. The shoulder moments in the sagittal plane presented left-right significant differences at arms fully extended (absolute differences ± standard deviation: −0.08 ± 0.09 Nm/kg, Z = −2.91, $p = 0.003$), at 135° (−0.10 ± 0.15 Nm/kg; Z = −2.15, $p = 0.03$), but not at 90° (0.11 ± 0.25 Nm/kg; Z = −1.77, $p = 0.07$). The shoulder in the transversal plane also had left-right significant differences in all conditions (−0.02 ± 0.02 Nm/kg, Z = −2.8, $p = 0.005$ for full extension; −0.05 ± 0.08 Nm/kg, Z = −2.05, $p = 0.04$ for 135°; and −0.08 ± 0.09 Nm/kg Z = 2.95, $p = 0.003$ for 90°). The wrist moments presented left-right differences in the sagittal plane only in arm full extension condition (−0.03 ± 0.05 Nm/kg, Z = −2.39, $p = 0.02$). No differences were found for the elbow.

4. Discussion

The aim of the present study was to quantify muscle activities and joint loads during dead hangs performed with different arm lock-off positions. Our findings are in agreement with our hypothesis: the external joint moments in the shoulder and elbow increase with increasing elbow flexion in the arm lock-offs but muscle activations of the finger flexor muscles remained the same. These results highlight that different lock-off positions during dead hangs have the same training effect for finger flexor muscles but lead to different shoulder and elbow joint loads.

Increasing elbow flexion in the arm lock-offs resulted in higher elbow and shoulder moments. Although no previous studies have explored this specific isometric action, our findings are complementary to what has been reported for pull-ups. Variants of pull-ups involving different hand grip positions and orientations have been shown to significantly affect upper limb joint loads (25). It is known that the mechanical demands placed on the muscles and joints depend on the joint kinematics, and specific poses may increase pain and potentially the risk of pathology. For instance, rotator cuff related shoulder pain (RCRSP; historically called subacromial impingement syndrome), is a frequently reported shoulder condition in overhead athletes (26) as climbers (27). This condition has been formerly associated to glenohumeral instability as a primary cause (28), which would be facilitated by the smaller subacromial space at 120° of elevation, 90° of abduction and 45° of external rotation of the shoulder (29). However, recent literature has challenged the role of the impingement in the acromion in causing pathologies associated to pain in shoulder structures (30). Not only the recent tools are better capable of differentiating rotator cuff disorders (31), but it has been reported that exercise therapies presented the same benefits as acromioplasty, further putting impingement as the main symptom mechanism (32). The current consensus is that pain linked to poor mechanical load management in the performance of overhead activities are the most determining causal factors in RCRSP and its progression (33). Considering that dead hangs with arm lock-offs are commonly incorporated into training regimens to develop strength capacities, and most injuries in climbers occur due to overuse (7), it is crucial to prescribe them cautiously. Additionally, although study examined isometric exercises performed for a relatively short duration, it is known that exercising at intensities that induce fatigue and repetitive loading can alter muscle activations and joint kinematics and therefore the load distribution across upper extremity joints (34). The increased joint loads found for the shoulder in arm lock-offs can potentially represent a source RCRSP at long term.

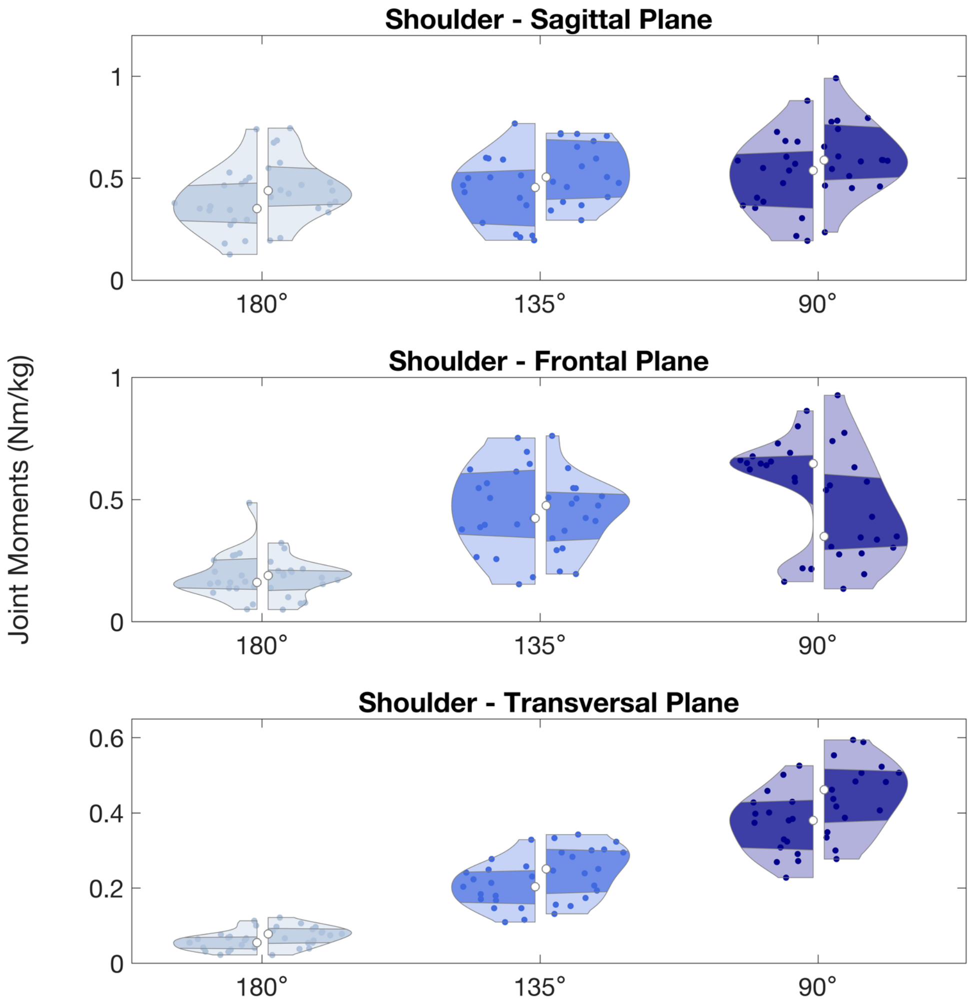

FIGURE 5
Shoulder peak joint moments (Nm/kg) observed during arm lock-offs performed by climbers at full elbow extension (180°), 135° and 90° of elbow flexion. Left and right sides of the violin plots represent the left and right upper limbs. (*) indicates significant difference between left and right sides.

We observed increased participation of the biceps brachii, trapezius, and latissimus dorsi with higher degrees of elbow flexion during arm lock-offs. These findings are consistent with studies on similar actions such as pull-ups and chin-ups, which have demonstrated that different angular positions in these movements elicit distinct recruitment strategies in the surrounding muscles (25). Furthermore, the greater involvement of the latissimus dorsi at 135° and 90° arm lock-offs compared to the biceps brachii and trapezius aligns with previous literature highlighting the latissimus dorsi as the most active muscle during these types of actions (25, 35, 36). Also, our results showed a high variability in the %RMS180° of the latissimus dorsi across participants. EMG is naturally affected by biological and instrumental sources of variability. Additionally, the shoulder is a joint with high degrees of freedom, therefore favoring variable length-tension outcomes, especially considering the large-volume of this muscle. However, the phenomena referenced as "climber's back" might also have a contribution to the variability of latissimus dorsi activations in the lock-off positions with increased elbow flexion. "Climber's back" is characterized by an imbalance between strong inwardly and weak outwardly muscles responsible to rotate the shoulder griddle, in combination with shortened pectoralis muscles (37). Although the present study did not monitor antagonist muscles, it is possible that participants might have had different levels of co-contraction and antagonist activity around the shoulder to maintain the lock-offs at high angles of elbow flexion, leading to the observed variability in the latissimus dorsi.

We found that left-right asymmetries in shoulder flexion and internal rotation moments tended to increase with increasing elbow lock-off angles. Functional asymmetries are inherent in symmetrical tasks performance (38, 39) but are also associated with increased risks for injuries (40). The objective of symmetry analysis in our study was not to emphasize the impact of side differences in performance, as this has been recently investigated in indoor climbing (41), but to comprehend the implications of potential asymmetries in shoulder and elbow moments during arm lock-offs. The findings of our study highlight that greater elbow flexion during isometric hangings may exacerbate the

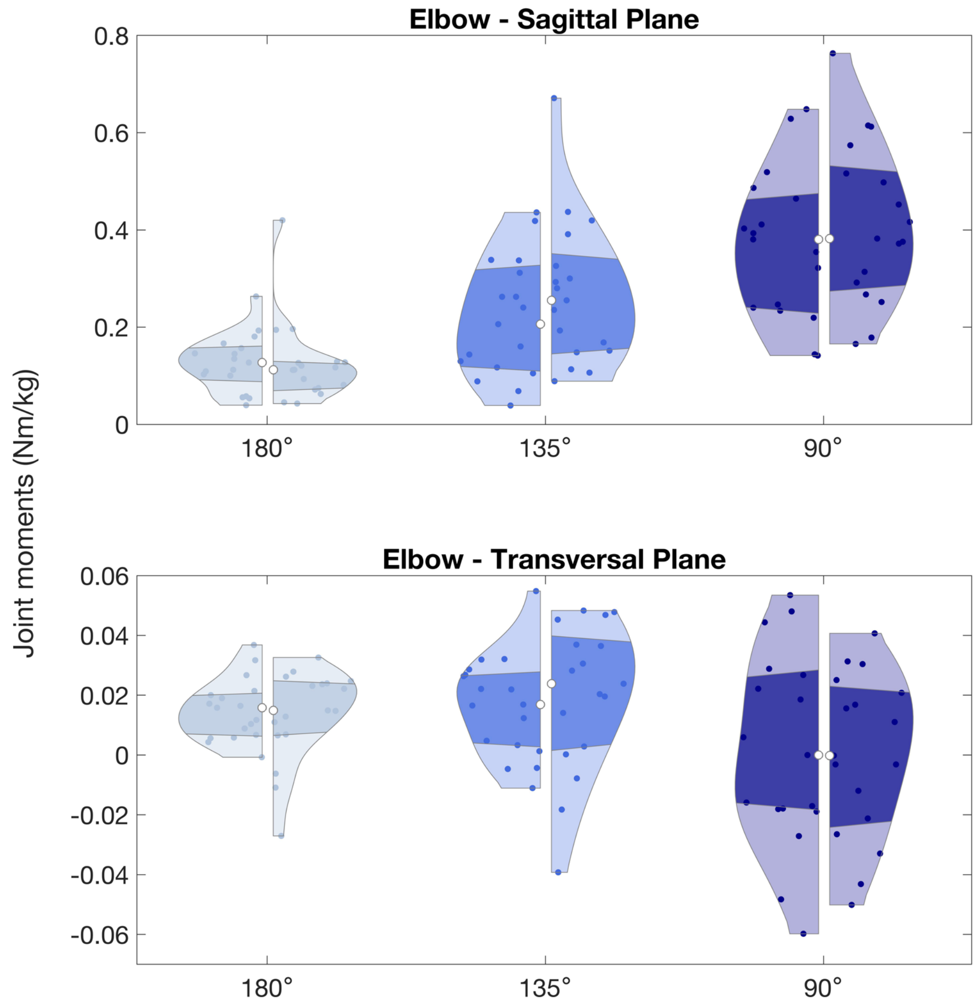

FIGURE 6
Elbow peak joint moments (Nm/kg) observed during arm lock-offs performed by climbers at full elbow extension (180°), 135° and 90° of elbow flexion. Left and right sides of the violin plots represent the left and right upper limbs.

effects of sudden increased peak loads on the upper limb joints, thereby increasing the risk of injuries.

A worthy reflection to this discussion, which is critical to sports medicine and science, concerns the relationship between training load, injury, fitness, and performance. One might question: how can we help climbers enhance performance, knowing that repeated peak workloads result in pain and injuries and, at the same time, are necessary to elicit the adaptations that would make them stronger? The "Training-injury Prevention Paradox model", by Tim Gabbett (42), debates over the fact that high training loads are necessary to enhance fitness and sport performance, but costs soft tissue injury risk. Moreover, lower workloads exposure is also related to susceptibility to injuries, thus training loads provide protective effect against it. The view about this dogma highlights the importance of monitoring load, so athletes are appropriately prescribed graded training loads to improve fitness and protect against pain and injury. In this sense, the primary purpose of dead hangs is typically to assess or improve finger flexor strength capacities (43–45), as hanging ability is a predictor of climbing performance (15, 46). Arm lock-offs are frequently incorporated into climbing-related tests (15), training protocols, and sport-specific movements (16, 47, 48). The present study provides novel and valuable insights into the functional aspects of isometric dead hangs with arm lock-offs, revealing the amount of load that climbers can expect to experience. The activation of the finger flexors remained unaffected by the increase in elbow flexion resulting from different lock-off angles, differently from the upper limb and trunk muscles, which increased participation. These findings would, then, support the recommendation to prescribe dead hang focusing on finger strength training with full elbows extension, thus minimizing unnecessary joint loading at elbows and shoulders. Still, it is reasonable that one might want to enhance strength capacities for back, shoulder, arm, and trunk muscles using climbing-oriented hand holds in overhead exercises. The optimization of this process needs to consider elements that would better translate to gains in sport performance and protect against pain and injury, thus pull-ups can be a better option to develop upper body strength and coordination in climbers (49).

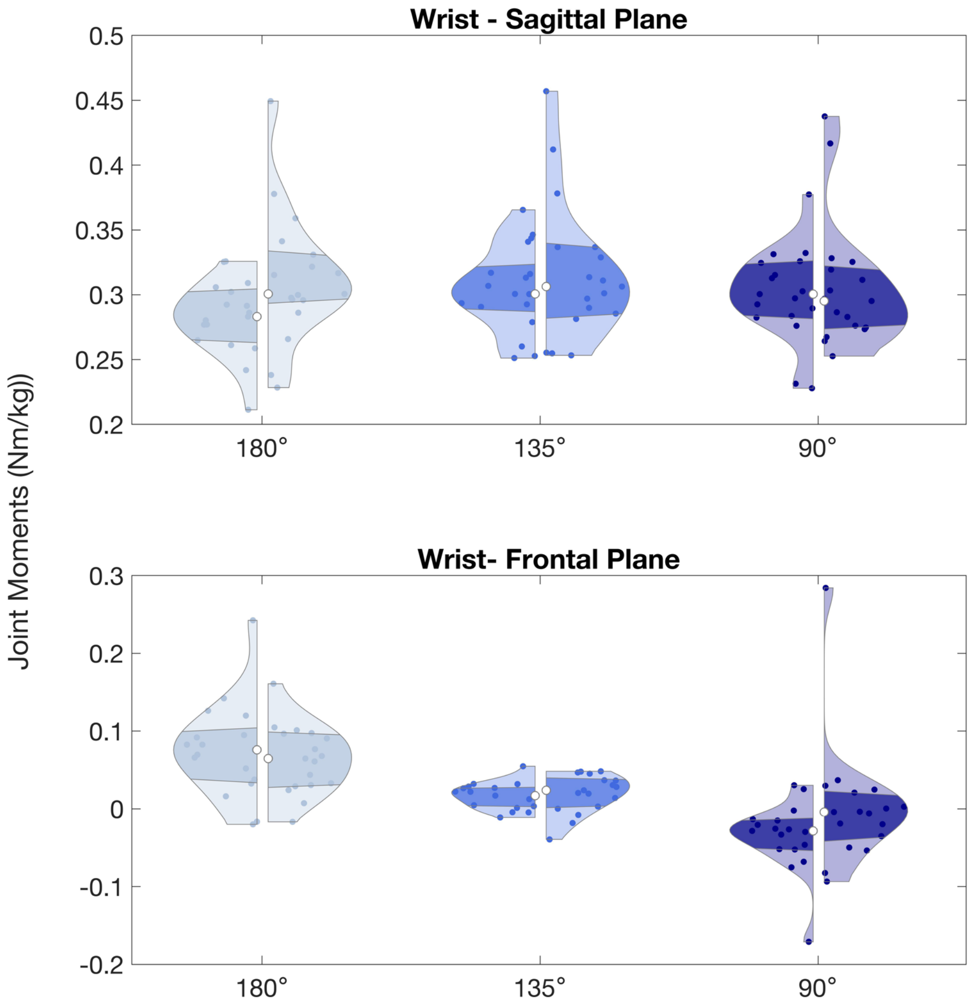

FIGURE 7
Wrist peak joint moments (Nm/kg) observed during arm lock-offs performed by climbers at full elbow extension (180°), 135° and 90° of elbow flexion. Left and right sides of the violin plots represent the left and right upper limbs. (*) indicates significant difference between left and right sides.

Nevertheless, biomechanical modeling enables a comprehensive analysis of movements and loads applied to the musculoskeletal system (50). To the best of our knowledge, this study represents the first neuromechanical analysis of a specific exercises commonly used for strength training and assessments in climbing. The findings of this study have implications for training optimization in the sport. Coaches, trainers, and climbers can use this information as a guideline to develop smarter training protocols that target specific muscle groups and joint angles to enhance climbing performance while managing the factors related to upper limb joint pain and injuries.

5. Limitations and future directions

Our study includes the following limitations. First, we only evaluated muscle activity of a small set of muscles. We analyzed the primary muscles at the forearm, arm, and trunk that are used during the dead hangs with different arm lock-offs, which was sufficient to address our research questions. Additional investigations of antagonist muscles could provide insights into the stabilization strategies employed in the tasks. Second, our participants performed the dead hangs on one predefined hold size. Evaluating how joint moments and muscle activations change with varying hold sizes would enhance our understanding of the relationship between load distribution across the upper body joints and the increased involvement of finger flexor activity. Third, we only analyzed static, isometric dead hangs. Campus boarding, a common exercise in climbing, involves dynamic movement in combination with arm lock-offs, which might significantly increase joint loads. Hence, future studies should collect data from dynamic tasks to get a comprehensive overview of joint loads experienced during different climbing-specific movements. Fourth, we estimated finger strength training load solely based on the available EMG data, and no reliability measurement was performed. However, considering that we analyzed isometric exercises and the different lock-off positions did not alter the length of the forearm and finger muscles, we believe our estimations are reasonable and valid. Additionally, worth it mentioning that the vertical forces did not change across conditions, while lateral forces were slightly higher (in the order of 4 to 6 kg) in the lock-off positions. In the future, we plan to use musculoskeletal simulations to estimate in-vivo muscle forces during different climbing-related movements.

6. Conclusion

In summary, this study examined the neuromechanical characteristics of dead hangs with arm lock-offs at varying elbow flexion angles. The findings of this study offer valuable insights that can be applied to smarten training guidelines, once it demonstrates that performing isometric finger dead hangs with arms fully extended is an effective method for developing forearm force capacities. This exercise allows for targeted training of the forearm muscles while minimizing the strain on the elbow and shoulder joints. Overall, this study contributes to the understanding of the neuromechanical aspects of climbing-specific exercises, providing novel and applied information for climbers, trainers, and researchers in the field.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Ethics Committee of the University of Vienna (process number 00690). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual for the publication of any potentially identifiable images or data included in this article.

Author contributions

JE: contributed to conception, design of the study, data collection and analysis, and wrote the first draft of the manuscript. HK: contributed to conception, data analysis, and design of the study, as well as manuscript revision. DD, WK, and CW: contributed to conception, design of the study, data collection and analysis. AB, DM, RS, and AC: contributed to conception and instrumentalization used for the study.

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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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References

1. Saul D, Steinmetz G, Lehmann W, Schilling AF. Determinants for success in climbing: a systematic review. *J Exerc Sci Fit*. (2019) 17(3):91–100. doi: 10.1016/j.jesf.2019.04.002

2. Cole KP, Uhl RL, Rosenbaum AJ. Comprehensive review of rock climbing injuries. *J Am Acad Orthop Sur*. (2020) 28(12):e501–9. doi: 10.5435/JAAOS-D-19-00575

3. Grønhaug G. Self-reported chronic injuries in climbing: who gets injured when? *BMJ Open Sport Exerc Med*. (2018) 4(1):e000406. doi: 10.1136/bmjsem-2018-000406

4. Leung J. A guide to indoor rock climbing injuries. *Curr Sports Med Rep*. (2023) 22 (2):55–60. doi: 10.1249/JSR.0000000000001036

5. Rooks MD. Rock climbing injuries. *Sports Med*. (1997) 23(4):261–70. doi: 10.2165/00007256-199723040-00005

6. Backe S, Ericson L, Janson S, Timpka T. Rock climbing injury rates and associated risk factors in a general climbing population. *Scand J Med Sci Sports*. (2009) 19 (6):850–6. doi: 10.1111/j.1600-0838.2008.00851.x

7. Lutter C, Hotfiel T, Tischer T, Lenz R, Schöffl V. Evaluation of rock climbing related injuries in older athletes. *Wilderness Environ Med*. (2019) 30(4):362–8. doi: 10.1016/j.wem.2019.06.008

8. Morenas Martín J, Del Campo VL, Leyton Román M, Gómez-Valadés Horrillo JM, Gómez Navarrete JS. Description of the finger mechanical load of climbers of different levels during different hand grips in sport climbing. *J Sports Sci*. (2013) 31 (15):1713–21. doi: 10.1080/02640414.2013.797592

9. Lu T-W, Chang C-F. Biomechanics of human movement and its clinical applications. *Kaohsiung J Med Sci*. (2012) 28(2):S13–25. doi: 10.1016/j.kjms.2011.08.004

10. Amca AM, Vigouroux L, Aritan S, Berton E. Effect of hold depth and grip technique on maximal finger forces in rock climbing. *J Sports Sci*. (2012) 30 (7):669–77. doi: 10.1080/02640414.2012.658845

11. Schweizer A. Biomechanical properties of the crimp grip position in rock climbers. *J Biomech*. (2001) 34(2):217–23. doi: 10.1016/S0021-9290(00)00184-6

12. Schweizer A, Hudek R. Kinetics of crimp and slope grip in rock climbing. *J Appl Biomech*. (2011) 27(2):116–21. doi: 10.1123/jab.27.2.116

13. Vigouroux L, Quaine F, Labarre-Vila A, Moutet F. Estimation of finger muscle tendon tensions and pulley forces during specific sport-climbing grip techniques. *J Biomech*. (2006) 39(14):2583–92. doi: https://doi.org/10.1016/j.jbiomech.2005.08.027

14. Vigouroux L, Quaine F, Paclet F, Colloud F, Moutet F. Middle and ring fingers are more exposed to pulley rupture than index and little during sport-climbing: a

biomechanical explanation. *Clin Biomech*. (2008) 23(5):562–70. doi: 10.1016/j.clinbiomech.2007.12.009

15. Baláš J, Pecha O, Martin AJ, Cochrane D. Hand–arm strength and endurance as predictors of climbing performance. *Eur J Sport Sci*. (2012) 12(1):16–25. doi: 10.1080/17461391.2010.546431

16. López-Rivera E. (2012). Lock-off training in Sport Climbing (III) Do you really lock-off? *Eva López, PhD. Evidence based Athletic Training for Climbing*. Available at: http://en-eva-lopez.blogspot.com/2012/09/lock-off-training-iii-do-you-really.html

17. Draper N, Giles D, Schöffl V, Konstantin Fuss F, Watts P, Wolf P, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: international rock climbing research association position statement. *Sports Technol*. (2015) 8(3–4):88–94. doi: 10.1080/19346182.2015.1107081

18. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res*. (1990) 8(3):383–92. doi: 10.1002/jor.1100080310

19. SENIAM. (2009). *Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles*. Available at: http://www.seniam.org/

20. Vigouroux L, Goislard de Monsabert B, Berton E. Estimation of hand and wrist muscle capacities in rock climbers. *Eur J Appl Physiol*. (2015) 115(5):947–57. doi: 10.1007/s00421-014-3076-6

21. Farina D, Negro F, Jiang N. Identification of common synaptic inputs to motor neurons from the rectified electromyogram: EMG rectification. *J Physiol*. (2013) 591 (10):2403–18. doi: 10.1113/jphysiol.2012.246082

22. Maffiodo D, Sesana R, Gabetti S, Colombo A. Innovative force sensor for indoor climbing holds—real-time measurements and data processing, design and validation. *Proc Inst Mech Eng Part P J Sports Eng Technol*. (2020) 234(4):298–311. doi: 10.1177/1754337120927122

23. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, et al. Opensim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng*. (2007) 54(11):1940–50. doi: 10.1109/TBME.2007.901024

24. Rajagopal A, Dembia CL, DeMers MS, Delp DD, Hicks JL, Delp SL. Full-body musculoskeletal model for muscle-driven simulation of human gait. *IEEE Trans Biomed Eng*. (2016) 63(10):2068–79. doi: 10.1109/TBME.2016.2586891

25. Urbanczyk CA, Prinold JAI, Reilly P, Bull AMJ. Avoiding high-risk rotator cuff loading: muscle force during three pull-up techniques. *Scand J Med Sci Sports*. (2020) 30(11):2205–14. doi: 10.1111/sms.13780

26. Hochholzer T, Schoeffl V, Zapf J. *One move too many –: How to understand the injuries and overuse syndroms of rock climbing*. Munich: Lochner (2003).

27. Schöffl V, Schneider H, Küpper T. Coracoid impingement syndrome due to intensive rock climbing training. *Wilderness Environ Med*. (2011) 22(2):126–9. doi: 10.1016/j.wem.2010.12.005

28. Bak K, Faunø P. Clinical findings in competitive swimmers with shoulder pain. *Am J Sports Med*. (1997) 25(2):254–60. doi: 10.1177/036354659702500221

29. Graichen H, Bonel H, Stammberger T, Haubner M, Rohrer H, Englmeier KH, et al. Three-dimensional analysis of the width of the subacromial space in healthy subjects and patients with impingement syndrome. *Am J Roentgenol*. (1999) 172 (4):1081–6. doi: 10.2214/ajr.172.4.10587151

30. Paavola M, Malmivaara A, Taimela S, Kanto K, Inkinen J, Kalske J, et al. Subacromial decompression versus diagnostic arthroscopy for shoulder impingement: randomised, placebo surgery controlled clinical trial. *Br Med J*. (2018) 362:k2860. doi: 10.1136/bmj.k2860

31. Papadonikolakis A, McKenna M, Warme W, Martin BI, Matsen FA. Published evidence relevant to the diagnosis of impingement syndrome of the shoulder. *J Bone Joint Surg*. (2011) 93(19):1827–32. doi: 10.2106/JBJS.J.01748

32. Lewis J. Rotator cuff related shoulder pain: assessment, management and uncertainties. *Man Ther*. (2016) 23:57–68. doi: 10.1016/j.math.2016.03.009

33. Requejo-Salinas N, Lewis J, Michener LA, La Touche R, Fernández-Matías R, Tercero-Lucas J, et al. International physical therapists consensus on clinical descriptors for diagnosing rotator cuff related shoulder pain: a Delphi study. *Braz J Phys Ther*. (2022) 26(2):100395. doi: 10.1016/j.bjpt.2022.100395

34. Mulla DM, McDonald AC, Keir PJ. Joint moment trade-offs across the upper extremity and trunk during repetitive work. *Appl Ergon*. (2020) 88:103142. doi: 10.1016/j.apergo.2020.103142

35. Dinunzio C, Porter N, Van Scoy J, Cordice D, McCulloch RS. Alterations in kinematics and muscle activation patterns with the addition of a kipping action during a pull-up activity. *Sports Biomech*. (2019) 18(6):622–35. doi: 10.1080/14763141.2018.1452971

36. Doma K, Deakin GB, Ness KF. Kinematic and electromyographic comparisons between chin-ups and lat-pull down exercises. *Sports Biomech*. (2013) 12(3):302–13. doi: 10.1080/14763141.2012.760204

37. Förster R, Penka G, Bösl T, Schöffl V. Climber's back—form and mobility of the thoracolumbar spine leading to postural adaptations in male high ability rock climbers. *Int J Sports Med*. (2009) 30(01):53–9. doi: 10.1055/s-2008-1038762

38. Ross S, Guskiewicz K, Prentice W, Schneider R, Yu B. Comparison of biomechanical factors between the kicking and stance limbs. *J Sport Rehabil*. (2004) 13(2):135–50. doi: 10.1123/jsr.13.2.135

39. Sato K, Heise GD. Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. *J Strength Cond Res*. (2012) 26(2):342–9. doi: 10.1519/JSC.0b013e318220e0a3

40. Reiser RF, Rocheford EC, DeVoe DE, Hickey MS. Effect of previous unilateral injuries on ground reaction force asymmetries during static lifting: 1694. *Med Sci Sports Exerc*. (2006) 38(Supplement):S264–5. doi: 10.1249/00005768-200605001-02028

41. Donath L, Roesner K, Schöffl V, Gabriel HHW. Work-relief ratios and imbalances of load application in sport climbing: another link to overuse-induced injuries?: Upper-extremity imbalance of load application. *Scand J Med Sci Sports*. (2013) 23(4):406–14. doi: 10.1111/j.1600-0838.2011.01399.x

42. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med*. (2016) 50(5):273–80. doi: 10.1136/bjsports-2015-095788

43. Ferrer-Uris B, Arias D, Torrado P, Marina M, Busquets A. Exploring forearm muscle coordination and training applications of various grip positions during maximal isometric finger dead-hangs in rock climbers. *PeerJ*. (2023) 11:e15464. doi: 10.7717/peerj.15464

44. López-Rivera E, González-Badillo JJ. Comparison of the effects of three hangboard strength and endurance training programs on grip endurance in sport climbers. *J Hum Kinet*. (2019) 66(1):183–95. doi: 10.2478/hukin-2018-0057

45. Medernach JPJ, Kleinöder H, Lötzerich HHH. Fingerboard in competitive bouldering: training effects on grip strength and endurance. *J Strength Cond Res*. (2015) 29(8):2286–95. doi: 10.1519/JSC.0000000000000873

46. Bergua P, Montero-Marin J, Gomez-Bruton A, Casajús JA. Hanging ability in climbing: an approach by finger hangs on adjusted depth edges in advanced and elite sport climbers. *Int J Perform Anal Sport*. (2018) 18(3):437–50. doi: 10.1080/24748668.2018.1486115

47. Desnivel. (2001). Entrenamiento en Tabla multipresa. Los métodos de la inquisición (I). *Desnivel*. Available at: https://www.desnivel.com/escalada-roca/entrenamiento/los-metodos-de-la-inquisicion-1/

48. Saeterbakken AH, Loken E, Scott S, Hermans E, Vereide VA, Andersen V. Effects of ten weeks dynamic or isometric core training on climbing performance among highly trained climbers. *PLoS One*. (2018) 13(10):e0203766. doi: 10.1371/journal.pone.0203766

49. Vigouroux L, Devise M, Cartier T, Aubert C, Berton E. Performing pull-ups with small climbing holds influences grip and biomechanical arm action. *J Sports Sci*. (2019) 37(8):886–94. doi: 10.1080/02640414.2018.1532546

50. Seth A, Sherman M, Reinbolt JA, Delp SL. Opensim: a musculoskeletal modeling and simulation framework for in silico investigations and exchange. *Procedia IUTAM*. (2011) 2:212–32. doi: 10.1016/j.piutam.2011.04.021

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Finger flexion to extension ratio in healthy climbers: a proposal for evaluation and rebalance

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Introduction: Finger strength is a key factor in climbing performance and is highly dependent on the capacity of the finger flexor muscles. The majority of finger-specific training therefore focuses on improving such capabilities by performing finger flexion contraction during hanging exercises on small holds. However, greater strength in the finger flexors causes an imbalance with the extensor muscle capacities. Such an unfavourable imbalance may be detrimental to finger strength and could possibly lead to an increase in the risk of finger injury. The aim of this study was to develop an easily implementable method to assess the flexor-to-extensor imbalance and evaluate the effects of different training on it.
Methods: Seventy-eight experienced climbers were tested to assess their maximum finger flexion strength (MFS), maximum finger extension strength (MES) and MFS/MES ratio. Fifty-two of them were randomly assigned to one of three training regimens: intermittent static flexion at 80% MFS (TFlex; $n = 11$), intermittent static extension at 80% MES (TExt; $n = 10$), intermittent repetition of alternating flexion and extension (TPaired; $n = 11$) or no specific training (CTRL; $n = 20$). They trained twice a week for four weeks on a hangboard. Before and after training, force data were recorded on a force-sensing hangboard and MFS, MES and the MFS/MES ratio were compared using ANCOVA.
Results: The mean value of the MFS/MES ratio was 6.27 (confidence interval: 5.94–6.61) and the extreme ratio was defined above 8.75. Concerning the training intervention, no difference was observed in the CTRL group between pre- and post-tests. MFS improved significantly in the TFlex (+8.4 ± 4.4%) and TPaired (+11.9 ± 10.5%) groups, whereas MES increased significantly in the TExt group (+41.4 ± 31.3%). The MFS/MES ratio remained statistically stable among all groups (+0.9 ± 17.5% in TFlex, −1.9 ± 16.1% in TPaired), although the TExt group showed a decreasing trend ($p = 0.1$; −27.8 ± 17.6%).
Discussion: These results showed that only the extensor-based training had an effect on finger extension strength and the potential to rebalance the MFS/MES ratio.

KEYWORDS
muscle force ratio, muscular imbalance, finger, sport climbing, training

1. Introduction

Rock climbing has become immensely popular over the past 20 years with nearly 45 million climbers worldwide in 2019 according to the International Federation of Sport Climbing (IFSC). During climbing, practitioners apply force on their feet and pull with their arms to move upwards (1–3). In these movements, the athletes exert high-force intensities with the fingers on holds of different shapes and sizes (4). Climbers thus need very high finger strength to be able to hold onto the thinnest possible holds. Previous studies have shown that the maximum finger strength was 18%–27% greater in climbers compared with non-climbers (5–7). Finger strength is also highly related to the climbing grade level (8, 9), i.e., expert climbers have greater strength than skilled climbers, who in turn have greater strength than novices.

The effort exerted on the fingertips induces high mechanical loadings on the musculoskeletal system of the upper limbs, including wrist, forearm, elbow, shoulder and shoulder girdle regions. When grasping a hold, the muscular forces generated produce net joint moments in the hand joints that allow the specific hand/finger position to be maintained and produce the external force applied to the hold. Under the influence of these loadings, the climbers' hands develop many adaptations which may be bony (10), ligamentous and/or muscular (11). Since finger flexors are the main agonist muscle for climbing grips (12, 13), it is logical that the climbers develop flexor muscle capacities over time and throughout years of practice. Vigouroux et al. (14) used a biomechanical model and an overall hand testing procedure to determine that the finger flexor force capabilities are 37% higher in climbers compared with non-climbers. When focusing on the antagonist muscle groups, the estimation of muscle forces during climbing grip showed that finger extensor muscles are also highly engaged (15). Moreover, EMG parameters indicated that extensors fatigued at the same intensity as flexors (7). In spite of this, the extensors' force capacities of climbers estimated in the study of Vigouroux et al. (13) did not show the same strengthening as flexors and were comparable with those of non-climbers, and even tended to be lower. These findings showcased a higher flexor-to-extensor finger force ratio (the ratio of the agonist to antagonist muscle force capacities) in climbers (6.1 on average) compared with non-climbers (3.7 on average), with a difference of 67% between the two populations. These observations raise concerns regarding the optimum balance between flexor and extensor (agonist and antagonist) strengths necessary for both maximizing finger performance and practising climbing safely.

The agonist-to-antagonist balance of strength has been widely investigated to quantify the co-contraction in different joints such as knee, ankle, shoulder or wrist in various populations (16, 17). It is thought that the role of an imbalance of the joint musculature, i.e., values that deviating from previous references, may be a possible cause of pathologies by reducing the stability of the joint. Thus, the imbalanced flexor-to-extensor ratio in climbers' finger muscles raises doubts about their ability to balance the entire chain of segments from the forearm to the fingertips by maintaining stability and effectively controlling the joints to enhance finger strength. Peters (18) and Phillips et al. (19) suggest that the potential risk factor for finger injury could be attributed to the imbalance resulting from underdeveloped finger extensor muscles. However, since no measurements or values were obtained in these studies, this link remains unsubstantiated in the current state-of-the-art. Nonetheless, exploring this potential source of injury is crucial, given the prevalence of upper extremity injuries, particularly those to the fingers, during climbing (20). For example, joint instability and overuse injuries, especially in the wrist, are the potential injuries that could be caused in part by an unfavourable flexor-to-extensor ratio, as is the case with the shoulder (21).

Since finger grip strength is related to climbing performance (8), climbers and trainers tend to focus on finger-specific training to constantly improve their finger flexion strength, mostly by hanging on a fingerboard or campus board (22). However, this training strategy (i.e., using the finger- and campus board) does not necessarily reduce the imbalance of the flexor-to-extensor ratio. Some authors (18, 19) have proposed to regulate this imbalance by including finger extension exercises in a training routine. This idea is of interest since, for full hand grip, Shimose et al. (23) have shown that the training of wrist extension significantly improved both the wrist extension strength by about 91% and the hand grip strength by about 3% in an untrained healthy population. Similarly, elbow extension training was found to increase both the elbow extension (+8.5%) and flexion (+5.8%) strength in untrained women (24). Therefore, antagonist-based training seems to be potentially beneficial both for strength enhancement and for reducing the finger flexor-to-extensor imbalance with a greater increase in extension/antagonist strength than in flexion/agonist strength.

To summarize, even if no proof of links between flexor-to-extensor balance, injuries and finger strength has been found, many climbers and coaches already train extensor muscles in the perspective of improving finger strength or preventing injuries. Nevertheless, such practice faces several unknowns. The first is that the only available method (14) to evaluate the flexor-to-extensor ratio is too complex to be used daily and the climbers thus have no means to appreciate the level of imbalance. The second is that no training methods to improve this imbalance have been quantified and evaluated. The climbers and trainers are therefore unaware of the effectiveness of extensor training. The overall objective of this study was thus to investigate the issue of antagonist muscle adaptation in climbers from the point of view of muscular capabilities, and was twofold. The first was to propose an easily implementable test to assess the flexor-to-extensor imbalance of climbers' fingers and to establish a reference database. To this aim, the finger flexion and the finger extension strengths were measured to compute the ratio in a sample of climbers. The results obtained were used to estimate the normal distribution of values among climbers and classify them to help diagnose climbers. Correlation with the climbing grade level was tested to examine a link between imbalance and grade level. We hypothesized that (i) the extensor capacities would not correlate with the climbing grade level, unlike the trend for flexor capacities and thus that (ii) the flexor-to-extensor imbalance would increase with the climbing grade level. The second objective was to provide an effective training protocol to modify this ratio by quantifying the effect of different types of extensor training. We hypothesized that flexor-based training would increase flexor strength, whereas extensor-based training would enhance both flexor and extensor strength, allowing a rebalance of the flexor-to-extensor ratio.

2. Methods

2.1. Participants

Seventy–eight climbers were assessed (22 women and 56 men, 25.7 ± 6.7 years old, 64.9 ± 8.6 kg, 173.0 ± 9.0 cm) for the finger strength profile (including flexor strength, extensor strength and flexor-to-extensor ratio). Participants' climbing levels ranged from intermediate to elite on the International Rock Climbing Research Association (IRCRA) scale (25), with an average of 20.3 ± 4.3 in their self-reported best red-point grade in the past six months. They had all practised climbing (indoors and/or outdoors) at least twice a week for the past two years, and had had no upper limb injuries in the previous six months. In addition, although carrying out regular practice, no climber had followed a specific training protocol lasting several weeks in the six months prior to this study. All participants volunteered and signed an informed consent form. The study was conducted with the formal approval of the CERSTAPS Ethics Committee.

2.2. Procedures

The 78 climbers were tested in a pre- and post-format described below. Of the initial sample, 52 climbers (15 women and 37 men, 25.7 ± 6.9 years old, 65.4 ± 8.5 kg, 172.9 ± 9.7 cm; 19.0 ± 4.3 in their best red-point grade) participated in the experiment by following a specific training protocol. The climbers were randomly assigned into four different training protocols. Based on previous research done on finger-specific training in climbing (26, 27), the training program lasted 4 weeks (weeks 1–4) with 2 sessions per week and started the week after the pre-test session (week 0). A post-test session, identical to the pre-test, was performed the week after the end of the training sessions (week 5) (22). All climbers were instructed to continue their climbing activities normally and regularly outside of the study throughout week 0 to week 5.

2.3. Pre- and post-test sessions

The pre- and post-tests consisted in measuring the finger flexion and extension strengths using a hangboard (SmartBoard, Peypin d'Aigues, France) instrumented with force sensors (strain gauges) measuring the vertical force applied on the holds (0.8 N accuracy, 50 Hz acquisition, 0–4,000 N range of measurement). The associated app provided real-time feedback on the force exerted, allowing precise modulation of the force intensity during training. Before each test session, participants first underwent a 20-min standardized warm-up and familiarization with the instrumented hangboard, consisting of muscular awakening (scapular retractions, shoulder and wrist circles, finger grips, etc.) traverses and specific exercises (pull down, push up with fingers) on the hangboard with increasing intensity. Then, they performed the tests, which consisted of assessing maximum finger flexor strength (MFS) and maximum finger extensor strength (MES). Four trials were performed in each condition (two warm-up trials and two maximum trials). Participants were asked not to train or climb the day before the experiment and to be ready to perform as much as possible. The same experimenter was present during all test sessions (before and after training), checked the correct execution of the tasks for each test and verbally motivated the participants to ensure maximum performance.

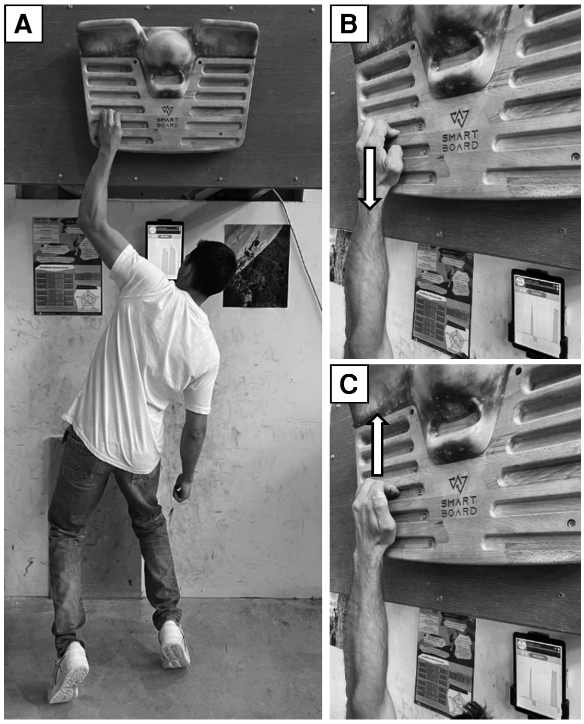

FIGURE 1
Illustrations of the position of the climbers on the SmartBoard (A), with a zoomed-in view of the fingers for flexion (B) and extension (C) during the test and the training sessions (with both hands during training). Arrows indicate the direction of the applied force.

2.3.1. Flexor strength test

Participants were asked to exert a maximum force downwards with the palmar aspect of the fingers of both hands on a 12 mm hold for 6 s with the right hand and then with the left hand. When pulling, the participants kept their feet on the ground and tried to hang with a maximum amount of weight (**Figures 1A,B**). One participant was able to hang with his entire body weight with one hand. To allow him to exert a greater force, we loaded him with a 20 kg mass attached to his harness so that he could not hang completely. Each participant self-selected the grip type (either half-crimp or slope grip), although thumb use was not allowed, and each climber was required to use the same grip throughout all test sessions. Self-selection of grip type was done to ensure maximum finger flexion performance for each participant, allowing a condition to be tested in which the finger flexors were activated as much as possible. For each trial, the MFS was evaluated as the mean of the total force exerted by both hands and recorded by the instrumented hangboard during the 4-s window centred on the force peak. The absolute value was displayed directly on the app in newtons (N) and was considered as the MFS. MFS was also normalized by body weight. Two trials, separated by a 3-min rest period, were evaluated and the best was selected for the analysis.

2.3.2. Extensor strength test

On an inverted 12 mm hold with light padding to avoid pain, participants had to exert a maximum force upwards using the dorsal aspect of the distal phalanges of their fingers, with the intention of extending them, while being prevented from doing so by the top of the hold (**Figure 1C**). The fingernails were positioned almost horizontally and parallel to the hold surface. The distal interphalangeal joints did not touch the hold at any point. Participants were asked to adopt a finger position close to a half-crimp grip, whereby the distal interphalangeal joints were slightly flexed, while the proximal interphalangeal joints were highly flexed (>40°), thereby preventing the intrinsic muscles from extending at the distal finger joints. The thumb was not in contact with the hold. Both hands were tested successively for 6 s. As with MFS, MES was evaluated from the same absolute mean value of the total force exerted by both hands that was displayed by the app in *N*. MES was also normalized by body weight. Two trials with a 3-min rest in between were evaluated and the best was selected for the analysis.

Following the recording of MFS and MES, the flexion-to-extension ratio (MFS/MES ratio) was computed by dividing the MFS by the MES. A ratio superior to 1 means that MFS is higher than MES.

2.4. Training sessions

The participants were first randomly divided and followed three different types of training (TFlex, TExt, TPaired described below) and a control group (CTRL). Taking into account dropouts, other participants were recruited so that the climbing level, gender and age matched between the groups. TFlex focused on training finger flexion strength only, TExt focused on finger extension strength only, while TPaired aimed to train both flexion and extension strengths simultaneously. The same grip types (in flexion and extension) were used for all training sessions as for the test sessions. The CTRL group ($n = 20$) did not follow any specific training and only continued their normal climbing activity. The three training sessions were best matched in terms of the duration of effort, the perception of the load during the pre-test. In this sense, 10 s of effort in flexion appeared as an equivalent perception of effort of 5 s for extensors. We therefore added a set of repetitions for TExt compared with TFlex in order to achieve, at best, a similar duration. For TPaired, the duration of effort was longer than for the others, as we took into account the time needed to switch from flexion to extension.

2.4.1. Flexor training protocol (TFlex)

Participants ($n = 11$) in the TFlex group followed a flexor training protocol consisting of reproducing the "F80" training presented by Devise et al. (22). To sum up, this training consisted of exerting finger flexion isometric contractions at an intensity of 80% MFS with both hands on the 12mm-hold of the hangboard. They completed a series of 12 repetitions with a 10-s effort phase followed by a 6-s rest phase. If the participants were unable to achieve 70% MFS during the hanging phase, the series was stopped. The force level was controlled throughout the protocol by the visual feedback and carefully adjusted by off-loading with the feet on the ground or conversely using an additional load attached to a harness. Three sets were performed, with 8 min of recovery time between each set.

2.4.2. Extensor training protocol (TExt)

The participants ($n = 10$) in the TExt group followed an extensor training protocol equivalent (number of sets, repetitions and intensity) to the TFlex training: it consisted of exerting finger extension isometric contractions with both hands, alternating a 5-s push phase (in the same position as for the extensor strength test) and a 6-s rest phase, for a maximum of 10 repetitions or, if the participants were unable to apply 70% MES, the series was stopped. Four sets were performed, separated by a 2-min recovery period.

2.4.3. Paired flexor and extensor training (TPaired)

A final group ($n = 11$, TPaired group) followed a flexor-extensor training protocol based on agonist-antagonist paired (APS) training, a method involving the alternation of agonist and antagonist exercises (28). Thus, the current training consisted of exerting finger flexion at 80% MFS intensity with both hands, followed immediately by finger extension at maximum intensity. During the extension phase, the finger position was identical to that of the extensor strength test. Participants completed a series of 12 repetitions of an 8-s flexion phase, followed by a 5-s extension phase on the inverted 12 mm-hold, then followed by a 6-s rest phase. When any climber was unable to achieve 70% MFS during the hanging phase, the series was stopped. Three sets were performed, with an 8-min recovery period between each set.

2.5. Statistics

Data are reported as mean ± SD. Descriptive statistics were used to verify whether the basic assumption of normality was correct for all the variables studied. As we were testing a mixed gender group, we first tested for the presence of any differences between men and women using ANCOVA (with climbing level as a co-variate) or non-parametric ANCOVA when variables did not follow a normal distribution. Then, to categorize the participants, the results of the MFS/MES ratio were divided into eight classes allowing them to be listed from "very low" to "extreme" ratio. The number of classes was determined using Sturges' rule, appropriate for $n < 200$ (29). Considering a normal distribution, the value of Z-score for a probability of <0.05 was computed and the confidence interval of the MFS/MES ratio was computed. Pearson's correlations were used to observe the relationship between the climbing level and the different parameters (MFS, MES, and the MFS/MES ratio). The effects of training on MFS, MES and the MFS/MES ratio were assessed by comparing the training groups (CTRL, TFlex and TExt and TPaired) over time (pre- and post-tests) using a 2-factor repeated-measures ANCOVA (Time × Group, with climbing level as a co-variate), with Tukey *post-hoc* analysis and power (1-β) when ANCOVAs were significant. In addition, effect sizes (partial eta squared, η^2) were computed and were defined as small for η^2>0.01, medium for η^2>0.09 and large for η^2>0.14 (30).

TABLE 1 Results (mean ± SD) of maximum finger flexor (MFS) and extensor (MES) strengths in absolute values and normalized to body weight (BW) and flexor-to-extensor ratio (MFS/MES ratio) for all participants, in men and women during the pre-tests and correlation of variables with climbing grade level.

		Absolute strength (*N*)	BW normalized strength	*r*
MFS	Total	791 ± 178	1.25 ± 0.24	0.68*
	Men	854 ± 159	1.28 ± 0.23	0.67*
	Women	632 ± 117[a]	1.16 ± 0.25	0.65*
MES	Total	130 ± 30	0.21 ± 0.04	0.04
	Men	136 ± 29	0.20 ± 0.04	0.03
	Women	113 ± 24[a]	0.21 ± 0.05	0.23
MFS/MES Ratio	Total	6.27 ± 1.5		0.52*
	Men	6.44 ± 1.43		0.43*
	Women	5.86 ± 1.63		0.65*

[a]Significant difference with men ($p < 0.001$).
*Significant correlation with climbing grade level ($p < 0.001$).

3. Results

3.1. Finger strength profile

The finger strength profile variables for all participants are presented in Table 1. Analysis of the data performed after dividing the groups based on gender indicated that MFS and MES were higher in men than in women when expressed in N but when normalized to body weight, no differences were observed between men and women in MFS ($p = 0.82$) and MES [$F(1,75) = 0.004$; $p = 0.95$; η^2=0.00]. The MFS/MES ratio ($p = 0.16$) was also similar between men and women.

A significant correlation between the climbing grade and MFS and the MFS/MES ratio was observed but there was no correlation between the climbing grade and MES. The same results were observed in men and women for MFS, MES and the MFS/MES ratio.

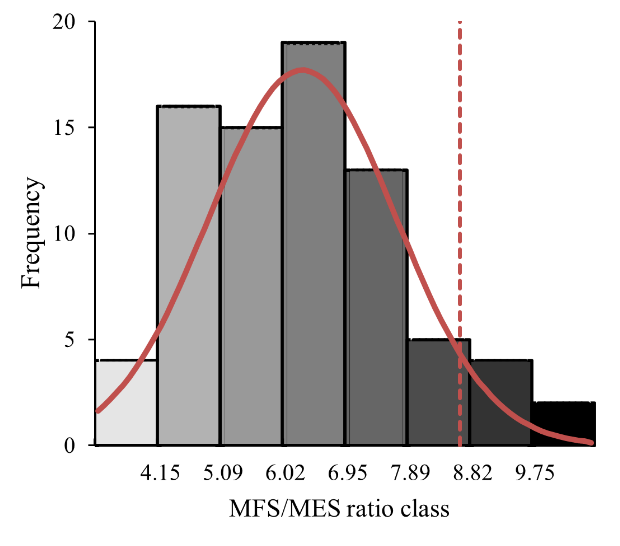

FIGURE 2
Histogram of frequency distribution of the number of participants (men and women combined) by flexor-to-extensor ratio (MFS/MES ratio) classes. The red curve represents the normal distribution with the vertical red dotted line representing the upper limit for $p < 0.05$.

TABLE 2 Descriptive characteristics (mean ± SD) of the participants of each group (control, CTRL; flexor training, TFlex; extensor training, TExt; flexor-extensor training, TPaired).

	CTRL	TFlex	TExt	TPaired	*p*-value
Age (y)	28.5 ± 9.1	24.3 ± 5.3	27.2 ± 7.5	23.3 ± 4.7	0.15
Height (cm)	172.4 ± 9.5	176.8 ± 9.0	168.3 ± 9.6	174.7 ± 9.6	0.31
Body mass (kg)	64.0 ± 8.8	67.5 ± 6.4	62.7 ± 8.3	67.0 ± 10.3	0.61
Red-point grade	18.6 ± 4.8	21.2 ± 3.2	16.6 ± 4.7	19.3 ± 3.5	0.09

Red-point grade means climbing a sport route after inspecting and practising it, and represents the most difficult grade achieved in the past 6 months, converted to the IRCRA scale.
p-values represent results of the one-way ANOVA comparing the four groups.

The eight MFS/MES intervals are shown in Figure 2. Since no significant difference was observed between men and women, the histogram was based on pooled data and made it possible to classify intervals from "very low ratio" to "extreme ratio". The ratios of the lowest class were less than 4.15 while the extreme ratios were above 9.75, meaning that the finger flexors were 9.75 times stronger than the finger extensors in this class. The mean value was 6.27 and the confidence interval was within the range of 5.94 and 6.61. The *Z*-score for a $p < 0.05$ probability corresponded to a value of 8.75.

3.2. Training effects

The anthropometric data and climbing ability of participants involved in the different training groups are summarized in Table 2. No statistical differences were observed between groups for all variables.

MFS, MES and the MFS/MES ratio results before and after training according to the different groups are presented in Table 3. There were significant Time × Group interaction effects for MFS [$F(3,47) = 7.4$; $p < 0.001$; η^2=0.32; 1-β=0.91], MES [$F(3,47) = 6.0$; $p = 0.001$; η^2=0.28; 1-β=0.86] and a tendency in the MFS/MES ratio [$F(3,47) = 1.37$; $p = 0.099$; η^2=0.12; 1-β=0.48]. Post-hoc tests revealed that MFS was greater after training than before in the TFlex and TPaired groups, and MES was greater after training than before in the TExt group, and the MFS/MES ratio seemed to decrease after training in the TExt group.

TABLE 3 Mean ± SD results of maximum finger flexor (MFS) and extensor (MES) strength normalized to body weight (BW) and flexor-to-extensor strength ratio (MFS/MES ratio) before (pre) and after (post) training, according to the groups (control, CTRL; flexor training, TFlex; extensor training, TExt; flexor-extensor training, TPaired).

		CTRL	TFlex	TExt	TPaired
MFS/BW	Pre	1.17 ± 0.26	1.25 ± 0.15	0.99 ± 0.19	1.21 ± 0.14
	Post	1.21 ± 0.27	1.36 ± 0.17*	0.95 ± 0.18	1.34 ± 0.13*
	Difference (%)	3.6 ± 9.8	8.4 ± 4.4[a,c]	−2.3 ± 7.1	11.9 ± 10.5[a,c]
MES/BW	Pre	0.21 ± 0.05	0.18 ± 0.02	0.22 ± 0.06	0.21 ± 0.04
	Post	0.22 ± 0.05	0.20 ± 0.03	0.34 ± 0.12*	0.24 ± 0.02
	Difference (%)	3.7 ± 15.3	10.9 ± 22.8	41.4 ± 31.3[a,b,d]	18.1 ± 30.5
MFS/MES Ratio	Pre	5.84 ± 2.01	7.02 ± 1.14	4.66 ± 1.04	5.95 ± 1.11
	Post	5.96 ± 2.33	6.93 ± 0.93	3.16 ± 1.39	5.72 ± 0.78
	Difference (%)	1.6 ± 15.9	0.9 ± 17.5	−27.8 ± 17.6	−1.9 ± 16.1

[a]Statistical difference with CTRL ($p < 0.05$).
[b]Statistical difference with TFlex ($p < 0.05$).
[c]Statistical difference with Text ($p < 0.05$).
[d]Statistical difference with TPaired ($p < 0.05$).
*Statistical difference between pre- and post-tests ($p < 0.05$).

4. Discussion

The aim of the study was to investigate antagonist muscle adaptation in climbers from the point of view of muscular capabilities. A first objective was to propose an easy-to-perform test to assess the flexor-to-extensor imbalance in climbers' fingers and to observe the strength profiles in their fingers. The second objective was to explore the effectiveness of different types of training on performance and on rebalancing the flexor-to-extensor ratio.

4.1. Effect of level of expertise on capabilities and imbalance in fingers

Our results allowed us to determine a finger strength profile for the climbers, as well as ratio classes that allow us to measure the degree of imbalance between finger flexor and extensor strengths. Our results showed a positive correlation between the finger flexor capacity (MFS) with the climbing level which is in line with previous studies (8). As our sample was mixed-gender, the analysis enabled us to measure any gender-related effect. As no differences were observed between men and women when strength was normalised by body weight, the rest of the analysis was based on pooled data. The gender effect in our study differs from the literature, as Mermier et al. (31) found a higher strength in men than in women, despite body mass normalisation. In their study, the gender difference was explained by a lower climbing level in female participants compared with male participants. However, in our study, the climbing level of women (18.4 ± 4.1) was also lower ($p = 0.013$) than that of men (21.0 ± 4.1). Faced with this problem, we used ANCOVA with climbing level as a co-variate to correct for its effect on the variables analysed. This statistical approach may thus explain the different conclusion compared with Mermier et al. (31) who only performed a t-test without considering the effect of the climbing level. Future studies should thus take into account the climbing level as a co-variate to isolate the main effect of the factors tested and provide robustness in any conclusions.

Contrary to the results for MFS, MES results were not correlated with the climbing level which is in line with the literature (5, 8, 14). This confirms previous findings by Vigouroux et al. (14), who showed that practising climbing develops primarily the flexors, so it is justified to ask whether the balance of the finger flexor-to-extensor ratio should be shifted, especially given the complexity of the hand, which requires the intricate balancing of a whole chain of joints. This equilibrium implies a major action of the finger extensors, as previously shown in other types of grip (32, 33) which, without appropriate capacity, can limit finger force-generating capacity (34).

With regard to the MFS and MES results, the averaged MFS/MES ratio showed a strong imbalance in both men and women which is correlated with the climbing grade level. In our study the ratio revealed that the finger flexors were on average 6.27 times stronger than the finger extensors. This result is similar to the ratio previously observed in the literature for climbers [6.10 in Vigouroux et al. (14)]. A relationship between the MFS/MES ratio and climbing level was also shown, so the more experienced the climber, the more unbalanced the ratio, and the higher the need to rebalance the extensors' capacity. The histogram (**Figure 2**) provides ratio values that allow the imbalance to be considered and classified. For example, a climber with a ratio in the class of 6 (6.02–6.95) could be considered a "standard" climber (where the confidence interval is included). The "extreme" climbers (with a ratio higher than 8.75 defined by the *Z*-score) represented 7.7% of our participants, and are included in the two highest classes of MFS/MES ratio. With such imbalanced results, it is legitimate for climbers and trainers alike to decide whether a rebalancing should be undertaken since the extensors are highly solicited during climbing grips and such an imbalance could either limit performance or lead to overuse and injuries.

The main contribution of this first part is the easy-to-implement method which allows discriminating climbers from a muscular imbalance perspective. Although this method was based on external fingertip force measurements the results were in line with previous studies relying on more complex measurements and evaluating internal muscle capacities, confirming the validity of the present protocol. The main interest is that this method, unlike the one based on modelling by Vigouroux et al. (14), can be implemented in gyms for trainers and climbers. Given the complexity of the biomechanics (23 joint degrees of freedom) and muscles of the hand (more than 40 muscles), determining the capabilities of each muscle does indeed require a modelling approach using electromyography and kinematics, combining efforts on all the 23 joints of the hand under different force application conditions. This time-consuming method would not have been applicable to be consistent with our first objective and to use in daily training.

Few studies have focused on the flexor-to-extensor ratio in the upper limb of climbers, particularly in the shoulders and elbows (30, 31), and some differences have been found compared with non-climbers, but the impact of these consequences on the risk of injury needs to be confirmed as the climbers tested were all uninjured. Based on the method currently proposed, further studies are now needed to establish relationships between the occurrence of finger injuries and the value of the MES/MFS ratio, in order to investigate the pertinence of this ratio in the occurrence of injuries.

4.2. Effect of type of training on capabilities and imbalance in fingers

First of all, similar values in the control group between both pre- and post-tests showed that differences observed in other training groups are not attributed to a familiarization effect with the tests nor to other concomitant activities. Regarding the training effects, the hypothesis that flexor-based training increases MFS was confirmed by our results, which indicated an increase in MFS (+8.4% in the TFlex group and +11.9% in the TPaired group, on average). However, the hypothesis that extensor-based training increases MFS and MES was only partially confirmed: paired training increased MFS but not significantly MES (+18.1%), whereas extensor-only training increased MES (+41.4% in the TExt group on average) but not MFS. Thus, the MFS/MES ratio had a tendency to decrease with the extensor-only training (−27.8%) but seemed to remain stable in the other groups (between −1.9% and +1.6%). The increase in MFS after flexor-based training is in agreement with the literature (22, 26, 27, 35). The training with 80% MFS tested in the current study led to an 8.4% increase in strength. These improvements have been discussed in detail by Devise et al. (22) for this type of training. Briefly, the physiological phenomena activated are probably a combination of neural adaptation processes and metabolic stress that may be effective in increasing muscle strength.

No increase in MFS was observed in the extensor-only training. This differs from the literature focused on other joints, which showed an increase in hand grip (23) and elbow flexion (24) with antagonist training. This difference might be explained by several factors. First, the muscles analysed were not the same, especially as the fingers are at the end of the upper limb chain, so the adaptations may be different. In large muscles, hypertrophy can partly explain a strength gain, but the volume available in the forearms for the finger muscles is more limited and suggests more difficulties for development, which may explain the lack of increase (36). Secondly, the duration of our training protocols was shorter than in previous studies (4 vs. 6 weeks or more) and we can suppose that an increase may appear with a longer training program. Finally, climbers already have a higher initial flexor strength compared with non-climbers, which makes it more difficult to gain strength (22), whereas the population tested in the previous studies (23, 24) were untrained subjects. Thus, these effects would depend on the type of population studied, and it would appear that agonists in a trained population (i.e., with higher initial strength) would be less sensitive to strength gain.

The increase in MFS in the paired training is consistent with the literature concerning the APS training (28). This type of training was chosen because it might be beneficial for both strength development and injury prevention. As this type of training is an alternation of exercises involving the coupling of agonists and antagonists, it has the advantage of enhancing acute performance on agonists in a relatively short period of time [significant effects after 4-weeks of training (24)] and to be less-time consuming than traditional resistance training. Reported effects on antagonist strength are rarer but improvements may be expected as a previous study (37) has shown an increase in both flexor and extensor forearm strength in recreationally trained individuals. However, no significant increase in MES was observed in the paired training of our study, despite an average increase of 18.1%, which could be attributed to relatively high inter-individual variability. As MES is not correlated with climbing level, it cannot be the type of population (with a potentially higher initial MES) that affects our result. However, our results are similar to those of Fink et al. (38) who found no increase in one repetition-maximum for triceps, although the significance of their findings was questioned due to relatively large confidence intervals. It may also be that our training was not sufficiently optimum to be significant, but could probably be improved by simply changing the volume and/or rest periods during the training sessions.

There seemed to be a tendency for the MFS/MES ratio to decrease in the extensor-only training (−27.8%), due to a significant increase in MES without an increase in MFS. Again, the variability was relatively high. The mean ratio after the extensor-only training (3.16) was 47% lower than in the control group, close to or even lower than that found in non-climbers in the literature [3.66 in Vigouroux et al. (14)]. It can be assumed that extensor-based training may activate the same physiological phenomena as flexor-based training and as mentioned above. The effects of extensor-based training should be confirmed by an intervention longer than 4 weeks or with a higher training volume.

In the other training groups (the TFlex and TPaired groups), the MFS/MES ratio did not decrease so the flexor-to-extensor imbalance remained high. Although MFS increased, the ratio did not increase either, which means that MES must increase slightly, not enough to be significant but enough to keep the ratio similar. A certain amount of work was therefore done by the co-contraction of the finger extensors, which are the antagonist muscles, and are involved in the maintenance and stability of the joints (14, 33). However, the additional work on the extensors in the paired training was not sufficient as it did not increase the MES: it seems better to separate the training of the flexors from that of the extensors in order to obtain the best benefits.

From a practical point of view, the main conclusion is that improving MES is not obvious. Even if the extensors are highly engaged during climbing grip, TFlex or TPaired training is not suitable for improving their level. Only the TExt training over four weeks has been validated to rapidly enhance MES. Further studies with a longer training period should be conducted to explore whether this has a significant effect on the finger flexor-to-extensor ratio. In addition, the training volume of the TExt is only 15 min per session, so that it can be quickly and easily incorporated into a “classic” climbing training routine, making it potentially acceptable to climbers. It should be noted that the load applied in our study (>70% MES) is of high intensity to produce MES benefits. This training intensity is probably higher than that used in the popular exercise relying on elastic bands to train finger extensors. The amount of force exerted with elastic bands is not known and not constant throughout the extension phase. Unfortunately, to our knowledge, no studies have reported information on the effects of elastic band training on MES, but it can be expected that this exercise does not produce sufficient resistance and intensity to improve strength benefits (39).

4.3. Limitations and perspectives

This study presents some inherent limitations that should be considered. First of all, our results should be confirmed with higher-elite climbers as we only tested climbers from intermediate to elite climbers. In addition, our study lacked a population of non-climbers to exactly understand the adaptations associated with climbing. As a further analysis, it would be interesting to investigate the level of activation of the finger flexors and extensors before and after training using electromyography. This would highlight the neuromuscular adaptations that may have occurred and clarify the mechanisms that explain the strength gains whereas, in the current study, only assumptions of the phenomena can be made. In addition, the relationship between the MFS/MES ratio and the injury rate is only speculative given the current state-of-the-art. Further studies should thus focus on measuring the finger strength profile of previously injured climbers to provide more information. Furthermore, conducting a longitudinal study of climbers who have undergone rebalancing training and those who have not, and then observing the incidence of injury in both groups using the proposed assessment method would be a step forward in understanding injury prevention. Future research is therefore needed on this topic.

5. Conclusion

Our study proposed an easy-to-implement method and provided the basis for some reference values for finger strength, especially in the extensors. It has made it possible to classify climbers according to their MFS/MES ratio, which can help climbers and trainers to assess climbers and personalise training. The results obtained suggest that climbing at higher grade levels is associated with an increasingly imbalanced flexor-to-extensor ratio in climbers. Finally, our results showed that training the finger flexors increased the MFS and left the same imbalance as it does not benefit the extensor muscle groups. On the other hand, combining some flexor-extensor training in the way we did (combined in the same training exercise) only improved the MFS. On the contrary, extensor-only training improved extensor capacities and thus reduced the flexor-to-extensor imbalance, but this reduction did not lead to any improvement in maximum finger strength. Although further studies are required, the results of this study thus suggest that exclusively utilizing extensor-based training shows promise in reducing the flexor-to-extensor imbalance. This study was a first step in exploring the issue of antagonist muscle adaptation in climbers and therefore provided the basis for assessment and training to further investigate the potential implication of hand extensor strength and flexor-to-extensor imbalance on injury prevention and 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 humans were approved by Comité d'éthique pour la recherche en science et technologie du sport et des activités physiques: IRB00012476-2020-19-11-69. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

LV, MD, and LP concepted the work, wrote the initial draft and carried out the experiments. MD, LV, and BG wrote the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

LV reports his involvement in the development of SmartBoard in "ScienceForClimbing (SFC)" firm, and his current position as scientific advisor. 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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References

1. Fuss FK, Niegl G. Biomechanics of the two-handed dyno technique for sport climbing. *Sports Eng.* (2010) 13(1):19–30. doi: 10.1007/s12283-010-0052-1

2. Quaine F, Martin L, Leroux M, Blanchi JP, Allard P. Effect of initial posture on biomechanical adjustments associated with a voluntary leg movement in rock climbers. *Arch Physiol Biochem.* (1996) 104(2):192–9. doi: 10.1076/apab.104.2.192.12887

3. Watts P, Newbury V, Sulentic J. Acute changes in handgrip strength, endurance, and blood lactate with sustained sport rock climbing. *J Sports Med Phys Fitness.* (1996) 36(4):255–60. PMID: 9062048.

4. Saul D, Steinmetz G, Lehmann W, Schilling AF. Determinants for success in climbing: a systematic review. *J Exerc Sci Fit.* (2019) 17(3):91–100. Available at: https://linkinghub.elsevier.com/retrieve/pii/S1728869X19300723 doi: 10.1016/j.jesf.2019.04.002

5. Grant S, Hynes V, Whittaker A, Aitchison T. Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *J Sports Sci.* (1996) 14(4):301–9. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=7613530&lang=fr&site=ehost-live doi: 10.1080/02640419608727715

6. Philippe M, Wegst D, Müller T, Raschner C, Burtscher M. Climbing-specific finger flexor performance and forearm muscle oxygenation in elite male and female sport climbers. *Eur J Appl Physiol*. (2012) 112(8):2839–47. doi: 10.1007/s00421-011-2260-1

7. Quaine F, Vigouroux L, Martin L. Finger flexors fatigue in trained rock climbers and untrained sedentary subjects. *Int J Sports Med*. (2003) 24(6):424–7. doi: 10.1055/s-2003-41174

8. Baláš J, Pecha O, Martin AJ, Cochrane D. Hand–arm strength and endurance as predictors of climbing performance. *Eur J Sports Sci*. (2012) 12(1):16–25. doi: 10.1080/17461391.2010.546431

9. Laffaye G, Collin JM, Levernier G, Padulo J. Upper-limb power test in rock-climbing. *Int J Sports Med*. (2014) 35(08):670–5. doi: 10.1055/s-0033-1358473

10. Sylvester AD, Christensen AM, Kramer PA. Factors influencing osteological changes in the hands and fingers of rock climbers: osteological changes in rock climbers. *J Anat*. (2006) 209(5):597–609. doi: 10.1111/j.1469-7580.2006.00640.x

11. Schreiber T, Allenspach P, Seifert B, Schweizer A. Connective tissue adaptations in the fingers of performance sport climbers. *Eur J Sports Sci*. (2015) 15(8):696–702. doi: 10.1080/17461391.2015.1048747

12. Schweizer A. Biomechanical properties of the crimp grip position in rock climbers. *J Biomech*. (2001) 34(2):217–23. Available at: https://www.sciencedirect.com/science/article/pii/S0021929000001846 doi: 10.1016/S0021-9290(00)00184-6

13. Vigouroux L, Quaine F, Paclet F, Colloud F, Moutet F. Middle and ring fingers are more exposed to pulley rupture than index and little during sport-climbing: a biomechanical explanation. *Clin Biomech*. (2008) 23(5):562–70. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0268003307002999 doi: 10.1016/j.clinbiomech.2007.12.009

14. Vigouroux L, Goislard de Monsabert B, Berton E. Estimation of hand and wrist muscle capacities in rock climbers. *Eur J Appl Physiol*. (2015) 115(5):947–57. doi: 10.1007/s00421-014-3076-6

15. Vigouroux L, Quaine F, Labarre-Vila A, Moutet F. Estimation of finger muscle tendon tensions and pulley forces during specific sport-climbing grip techniques. *J Biomech*. (2006) 39(14):2583–92. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0021929005004033 doi: 10.1016/j.jbiomech.2005.08.027

16. Calmels P, Minaire P. A review of the role of the agonist/antagonist muscle pairs ratio in rehabilitation. *Disabil Rehabil*. (1995) 17(6):265–76. doi: 10.3109/09638289509166646

17. Rochcongar P. Évaluation isocinétique des extenseurs et fléchisseurs du genou en médecine du sport : revue de la littérature. *Ann Readapt Med Phys*. (2004) 47(6):274–81. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0168605404001047 doi: 10.1016/j.annrmp.2004.05.013

18. Peters P. Orthopedic problems in sport climbing. *Wilderness Environ Med*. (2001) 12(2):100–10. Available at: https://linkinghub.elsevier.com/retrieve/pii/S1080603201707016 doi: 10.1580/1080-6032(2001)012[0100:OPISC]2.0.CO;2

19. Phillips KC, Sassaman JM, Smoliga JM. Optimizing rock climbing performance through sport-specific strength and conditioning. *Strength Cond J*. (2012) 34(3):1–18. Available at: https://journals.lww.com/00126548-201206000-00001 doi: 10.1519/SSC.0b013e318255f012

20. Lutter C, Tischer T, Hotfield T, Frank L, Enz A, Simon M, et al. Current trends in sport climbing injuries after the inclusion into the olympic program. Analysis of 633 injuries within the years 2017/18. *Muscle Ligaments and Tendons J*. (2020) 10(02):201. Available at: http://www.mltj.online/current-trends-in-sport-climbing-injuries-after-the-inclusion-into-the-olympic-program-analysis-of-633-injuries-within-the-years-2017-18/ doi: 10.32098/mltj.02.2020.06

21. Lucado AM. Scapular muscle imbalance: implications for shoulder pain and pathology. *Phys Ther Rev*. (2011) 16(5):356–64. doi: 10.1179/1743288X11Y.0000000039

22. Devise M, Lechaptois C, Berton E, Vigouroux L. Effects of different hangboard training intensities on finger grip strength, stamina, and endurance. *Front Sports Act Living*. (2022) 4:862782. doi: 10.3389/fspor.2022.862782/full

23. Shimose R, Matsunaga A, Muro M. Effect of submaximal isometric wrist extension training on grip strength. *Eur J Appl Physiol*. (2011) 111(3):557–65. doi: 10.1007/s00421-010-1675-4

24. MacKenzie SJ, Rannelli LA, Yurchevich JJ. Neuromuscular adaptations following antagonist resisted training. *J Strength Cond Res*. (2010) 24(1):156–64. Available at: https://journals.lww.com/00124278-201001000-00023 doi: 10.1519/JSC.0b013e3181bd4317

25. Draper N, Giles D, Schöffl V, Konstantin Fuss F, Watts P, Wolf P, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: international rock climbing research association position statement. *Sport Technol*. (2015) 8(3–4):88–94. doi: 10.1080/19346182.2015.1107081

26. Medernach JPJ, Kleinöder H, Lötzerich HHH. Fingerboard in competitive bouldering: training effects on grip strength and endurance. *J Strength Cond Res*. (2015) 29(8):2286–95. Available at: https://journals.lww.com/nsca-jscr/FullText/2015/08000/Fingerboard_in_Competitive_Bouldering__Training.26.aspx doi: 10.1519/JSC.0000000000000873

27. Levernier G, Laffaye G. Four weeks of finger grip training increases the rate of force development and the maximal force in elite and top world-ranking climbers. *J Strength Cond Res*. (2019) 33(9):2471–80. doi: 10.1519/JSC.0000000000002230

28. Robbins DW, Young WB, Behm DG, Payne WR. Agonist-antagonist paired set resistance training: a brief review. *J Strength Cond Res*. (2010) 24(10):2873–82. Available at: https://journals.lww.com/00124278-201010000-00041 doi: 10.1519/JSC.0b013e3181f00bfc

29. Scott DW. Sturges' rule. *WIRES Comp Stat*. (2009) 1(3):303–6. doi: 10.1002/wics.35

30. Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd ed Hillsdale, N.J: L. Erlbaum Associates (1988). 567.

31. Mermier CM, Janot JM, Parker DL, Swan JG. Physiological and anthropometric determinants of sport climbing performance. *Br J Sports Med*. (2000) 34(5):359–65. doi: 10.1136/bjsm.34.5.359

32. Charissou C, Amarantini D, Baurès R, Berton E, Vigouroux L. Effects of hand configuration on muscle force coordination, co-contraction and concomitant intermuscular coupling during maximal isometric flexion of the fingers. *Eur J Appl Physiol*. (2017) 117(11):2309–20. doi: 10.1007/s00421-017-3718-6

33. Goislard De Monsabert B, Rossi J, Berton É, Vigouroux L. Quantification of hand and forearm muscle forces during a maximal power grip task. *Med Sci Sports Exerc*. (2012) 44(10):1906–16. Available at: https://journals.lww.com/00005768-201210000-00011 doi: 10.1249/MSS.0b013e31825d9612

34. Caumes M, Goislard De Monsabert B, Hauraix H, Berton E, Vigouroux L. Complex couplings between joints, muscles and performance: the role of the wrist in grasping. *Sci Rep*. (2019) 9(1):19357. Available at: https://www.nature.com/articles/s41598-019-55443-w doi: 10.1038/s41598-019-55443-w

35. López-Rivera E, González-Badillo JJ. The effects of two maximum grip strength training methods using the same effort duration and different edge depth on grip endurance in elite climbers. *Sport Technol*. (2012) 5(3–4):100–10. doi: 10.1080/19346182.2012.716061

36. España-Romero V, Watts PB. Strength: volume ratio for the forearm in climbers and non-climbers. *Age (Omaha)*. (2012) 25(9.6):21–1.

37. Huff W, Clark K, Kim H, Reed M. *The effects of agonist-antagonist paired set vs. traditional set training on forearm strength*. In: *International Journal of Exercise Science: Conference Proceedings*. (2018). p. 57.

38. Fink J, Schoenfeld BJ, Sakamaki-Sunaga M, Nakazato K. Physiological responses to agonist–antagonist superset resistance training. *J Sci Sport Exerc*. (2021) 3(4):355–63. doi: 10.1007/s42978-020-00092-z

39. Fink J, Kikuchi N, Yoshida S, Terada K, Nakazato K. Impact of high versus low fixed loads and non-linear training loads on muscle hypertrophy, strength and force development. *SpringerPlus*. (2016) 5(1):698. doi: 10.1186/s40064-016-2333-z

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Risk factors and injury prevention strategies for overuse injuries in adult climbers: a systematic review

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Introduction: Climbing is an increasingly popular activity and imposes specific physiological demands on the human body, which results in unique injury presentations. Of particular concern are overuse injuries (non-traumatic injuries). These injuries tend to present in the upper body and might be preventable with adequate knowledge of risk factors which could inform about injury prevention strategies. Research in this area has recently emerged but has yet to be synthesized comprehensively. Therefore, the aim of this study was to conduct a systematic review of the potential risk factors and injury prevention strategies for overuse injuries in adult climbers.

Methods: This systematic review was conducted in accordance with the PRISMA guidelines. Databases were searched systematically, and articles were deemed eligible based upon specific criteria. Research included was original and peer-reviewed, involving climbers, and published in English, German or Czech. Outcomes included overuse injury, and at least one or more variable indicating potential risk factors or injury prevention strategies. The methodological quality of the included studies was assessed with the Downs and Black Quality Index. Data were extracted from included studies and reported descriptively for population, climbing sport type, study design, injury definition and incidence/prevalence, risk factors, and injury prevention strategies.

Results: Out of 1,183 records, a total of 34 studies were included in the final analysis. Higher climbing intensity, bouldering, reduced grip/finger strength, use of a "crimp" grip, and previous injury were associated with an increased risk of overuse injury. Additionally, a strength training intervention prevented shoulder and elbow injuries. BMI/body weight, warm up/cool downs, stretching, taping and hydration were not associated with risk of overuse injury. The evidence for the risk factors of training volume, age/years of climbing experience, and sex was conflicting.

Discussion: This review presents several risk factors which appear to increase the risk of overuse injury in climbers. Strength and conditioning, load management, and climbing technique could be targeted in injury prevention programs, to enhance the health and wellbeing of climbing athletes. Further research is required to investigate the conflicting findings reported across included studies, and to investigate the effectiveness of injury prevention programs.

Systematic Review Registration: https://www.crd.york.ac.uk/, PROSPERO (CRD42023404031).

KEYWORDS

climbing, bouldering, overuse injuries, risk factors, injury prevention, systematic reveiw, climbing injuries

1. Introduction

Participation in climbing is growing rapidly, especially given its recently attained status as an Olympic sport (1). There are several unique disciplines of climbing, including traditional and sport climbing (practised outdoor), bouldering and lead climbing (practised indoor), and ice climbing, which is also practised outdoor, but indoor ice walls are available (2, 3). Each discipline is known to have its own specific performance demands and risk of injury (4, 5). Injury incidence rates for both traumatic and overuse injuries have been reported around 4.2 injuries per 1,000 climbing hours (6), indicating a similar injury risk profile to sports such as baseball and handball (7). The point prevalence of all injuries in climbers has been reported at 22.8% (8), whilst the one year prevalence of rock-climbing injuries appears to be around 50% (9) The majority of overuse injuries seem to occur in the upper extremities, whereas lower-extremity injuries are more commonly associated with falls (9). Acute lower-extremity injury seems to be particularly prevalent in bouldering, whereby nearly two-thirds of injuries treated in an emergency department and obtained whilst bouldering were located in the lower extremities (10). Injuries in climbing can be classified as both acute and overuse. Acute injuries are typically related to falling or environmental exposure such as rock falls, whereas persistent overuse injuries arise due to repetitive stress without adequate recovery, where one clear and exact traumatic cause for pain or structural deficit cannot be identified (11). Some injuries occur whilst overstraining in a single move, for example a finger pulley rupture when exerting high levels of force in a crimp grip against a hold (11). Such injuries would typically be defined as acute in nature, although the effects of preceding repetitive overuse and fatigue on the injured tissue cannot be ruled out. Most injuries in climbing are thought to be overuse in origin, with up to 93% of injuries defined as such (6). It would therefore appear pertinent to categorize injury risk as either traumatic or overuse, considering that the aetiology and risk factors associated with each category are known to be distinct (5, 6, 12). Injury prevention strategies and risk factor mitigation for traumatic injuries has mainly focused on adequate safety standards and training, equipment use, and type of climbing (12), whereas risk factors for overuse injuries seem more related to appropriate load management and training programming, particularly relating to the upper extremities (5, 13). A previous systematic review by Woollings et al., (2015) found that age, increasing years of climbing experience, higher climbing grade, high chronic training loads, and participating in lead climbing are potential risk factors for injury in sport climbing and bouldering (5). However, this analysis included both traumatic and overuse injuries. Concentrating solely on overuse injuries may be more insightful for practitioners, as some of the risk factors are likely modifiable and related to physical training programming (5, 14). Since the review by Woollings et al., (2015) literature in this area has been reviewed critically (13, 14) but not systematically, and research interest has grown significantly in recent years. An updated systematic review of the literature is therefore appropriate, to revise and synthesize existing knowledge. Moreover, this systematic analysis should identify more specific risk factors and thus support the development of injury prevention strategies to reduce overuse injuries in climbers. This knowledge is vital for coaches, clinicians, and the athletes themselves as more and more individuals are likely to push the limits of training in the pursuit of Olympic gold. Therefore, the aim of this study was to conduct a systematic review of the literature, relating to risk factors and injury prevention strategies for overuse injuries in adult climbers.

2. Methods

This systematic review was pre-registered in the international prospective register of systematic reviews (PROSPERO) (ID: CRD42023404031). Additionally, the review was conducted in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (15) (see **Supplementary Material File S1**).

2.1. Sources

The databases (PubMed, Web of Science and the Cochrane Library) along with the websites (The International Federation of Sport Climbing (https://cdn.ifsc-climbing.org/index.php/home-mobile), The International Rock Climbing Research Association (IRCRA) (https://www.ircra.rocks), UIAA—The International Climbing and Mountaineering Federation (https://theuiaa.org), The Beta Angel Project (https://beta-angel.com), and The Crag (https://www.thecrag.com/home) were searched for studies addressing risk factors and injury prevention of overuse injuries in climbers. The search date was 1st March 2023. The bibliographies of included studies were also searched for further relevant publications.

2.2. Search strategy

The key terms of “climbing”, “injury”, “risk factors”, and “injury prevention” were combined with the Boolean Operators “AND”/”OR” to search the selected databases. Truncation of search terms and MeSH terms were applied, to maximize the reach of the search. An example of the search strategy conducted in the database PubMed can be seen in **Table 1**, and the search strings for additional databases can be found in **Supplementary Material File S2**. Identified studies were exported into an electronic reference manager (Mendeley Desktop 1.19.8), and duplicates were removed semi-automatically with manual checking. The eligibility of identified records was then determined according to strict eligibility criteria.

2.3. Eligibility criteria

Studies were included for analysis based upon the following criteria: (1) Original data published in peer-reviewed journals,

TABLE 1 Details of search strategy conducted in pubMed.

Category	Terms
Climbing	["Climb*"(Title/Abstract)] OR ["Boulder*"(Title/Abstract)] OR ["Mountaineering"(MeSH Terms)]
Injury	["Wounds and injuries"(MeSH Terms)] OR ["Athletic Injuries"(MeSH Terms)] OR ["Injur*"(Title/Abstract)] OR ["Overuse"(Title/Abstract)]
Risk factors	["Risk Factors"(MeSH Terms)] OR ["Protective Factors"(MeSH Terms)]
Injury prevention	["Prevention Program" (Title/Abstract)] OR ["Train*" (Title/Abstract)]
(Human subjects)	NOT (Animals)

Categories of "climbing", "injury" and ("risk factors" OR "injury prevention") were combined with the Boolean Operator "AND".

(2) Adult climbers (mean age of sample >18 years old) at all levels and in all disciplines of climbing, (3) Study designs should be prospective, cross-sectional, retrospective, cohort, randomized controlled trials, case-control or case-series, (4) Published in the language of English, German, or Czech, (5) Studies should investigate overuse injuries (studies exclusively investigating acute/traumatic injuries were excluded), and additionally at least one potential risk factor or injury prevention strategy. Solely epidemiological studies or investigations into conservative treatment, injections, surgery and rehabilitation of injuries were excluded.

2.4. Selection process

Potential studies were screened independently by two reviewers and included according to the aforementioned eligibility criteria. Initially, titles and abstracts of identified studies were screened for eligibility. Upon inclusion, the full-text articles of studies were sought for further screening, and disagreements regarding study inclusion were arbitrated by a third author.

2.5. Data collection

Relevant parameters were manually extracted from the included studies and entered into a single table. Data was extracted for study design, participant characteristics and sample size, injury definition and incidence/prevalence, types of overuse injuries identified, risk factors and/or injury prevention strategies studied, and the results of associations between risk factors/prevention strategies and injury with statistical findings. In some cases, studies investigated all forms of injury occurrence including overuse and traumatic aetiologies. Where possible, overuse injuries were isolated and identified in relation to associated risk factors and prevention strategies. Reported climbing grades of participants were converted into the IRCRA comparative grading scale (16), to allow for easier comparison and interpretation of the included samples. To assess the methodological quality of the included studies, two independent reviewers conducted the Downs and Black questionnaire (17). The checklist scores studies out of 32 points and is referred to as "Study Quality Score" (SQS; x/32) in the results and discussion.

2.6. Data synthesis

The included studies were highly heterogenous in terms of objectives, methodology, and outcomes, and thus, a meta-analysis would not have been appropriate. Therefore, the data was synthesized descriptively, whereby trends in risk factors and prevention measures were interpreted qualitatively with reference to the methodological quality of the identified studies. Risk factors and injury prevention strategies were grouped into "modifiable" and "nonmodifiable" to assist with interpretation of the findings.

3. Results

3.1. Identification of studies

The results of the study selection process can be seen in Figure 1. Overall, 1,183 records were identified for screening. A total of 83 full-text reports were assessed for eligibility, of which 49 were excluded mainly because a risk factor wasn't studied, or no overuse injuries were mentioned. After complete screening, 34 studies were included in the final analysis.

3.2. Methodological quality assessment

The quality of included studies according to the Downs and Black criteria ranged from 8 to 20 out of a possible 32 points (mean: 14.4 points), indicating a large range of study quality (see Table 2). The quality of most studies overall was quite low, as 64.7% of studies were cross-sectional designs. The remainder of the studies were prospective designs plus two randomized controlled trials, and these studies generally obtained higher quality scores. The majority of studies performed particularly poorly in ratings of participant blinding (an inherent issue in many areas of sports medicine), randomization, and control of confounding factors which could have influenced outcomes.

3.3. Participants

The characteristics of all included participants across all studies can be seen in Supplementary Material File S3 in the "sample characteristics" column. A total of 10,049 participants were included within this systematic review across 34 studies. The average age of all participants was 30.2 years (ranging from 19 to 54 years). Males were disproportionately represented when considering all studies. Regarding climbing discipline, participants could be categorized as follows: rock climbers (nine studies), sport climbers (eight studies), mixed discipline (13 studies), boulderers [two studies (18, 28)], and ice climbers [one

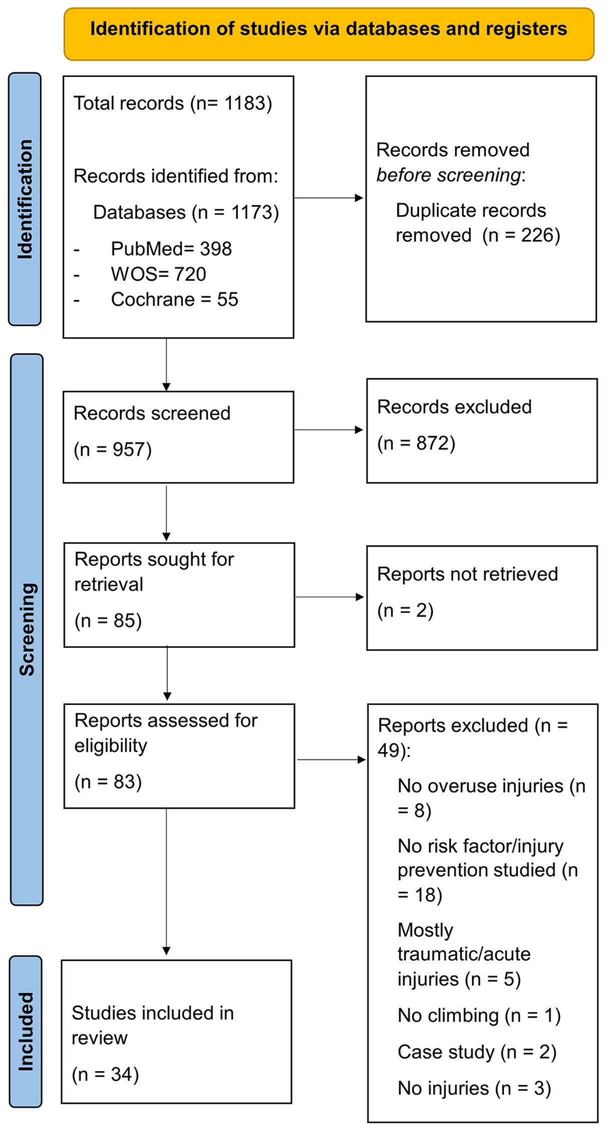

FIGURE 1
PRISMA flow diagram.

study (2)]. IRCRA climbing grades scored an average of 17.4 in all studies (intermediate to advanced level) and ranged from 1 (lower grade) to 29 (higher elite).

3.4. Injury prevalence and incidence

The prevalence and incidence of injuries described within the individual studies can be found in Table 3. The reported numbers are extremely varied, probably due to the differences in populations and methodologies across the 34 studies. The incidence proportion ranged from 26 injuries per 100 participants to 300 injuries per 100 participants, whereas point/time prevalence ranged from 15% to 81%. These injury rates range across a diverse period from 6 months to whole career. Fifteen of the included studies investigated climbing injuries at specific anatomical sites, namely foot injuries/alterations (21, 23, 29), back pain (47), injuries of the shoulders (19, 30), elbow injuries (31), the fingers and hands (22, 32, 34, 43), Duputryen's disease (33), and upper extremity injuries (8, 36, 41). The remaining 19 studies investigated climbing injuries more broadly, and nine of these studies contained clear definitions of overuse injury within them (6, 9, 18, 25, 27, 35, 39, 40, 45, 46). Upper extremity injuries appear to be the most prevalent and well-studied across all included investigations.

3.5. Risk factors and injury prevention strategies

A total of 73 risk factors or injury prevention strategies were studied in the 34 included studies. For reasons of brevity, only the most prevalent of them are presented in the results section, divided into modifiable and nonmodifiable risk factors, though details of the remaining findings can be found in **Supplementary Material File S3**.

3.6. Modifiable risk factors and injury prevention strategies

3.6.1. Body weight and body mass index (BMI)

Eight studies researched body weight and/or BMI (6, 8, 18, 26, 28, 32, 35, 37). Of these, three prospective studies (1–3 years in length) with relatively high study quality scores (SQS) (17/32–19/32) found no association between body weight or BMI and climbing injury (8, 18, 35). Additionally, three cross-sectional studies also showed no associated risk of climbing injury with BMI (26, 28, 37), whilst one cross-sectional study with a study quality score of 16/32 did indicate increased risk of injury with increased BMI (6). Furthermore, a single study determined that increased BMI was associated with a higher risk of hand injuries, although the data was cross-sectional (SQS: 14/32) (32).

3.6.2. Type of climbing

A total of 11 studies investigated the type of climbing and associations with injury (6, 8, 9, 24, 25, 27, 28, 39, 44, 46, 47). Overall, three studies indicated that bouldering as a climbing activity was associated with an increased risk of injury, when compared with other forms of climbing (6, 46, 47). In addition, one further study found that bouldering increased the risk of injury in a univariate analysis ($p = 0.046$), but not in a secondary multivariate analysis (8). Bouldering frequency was also associated with overuse injury in two further studies (9, 27). In two studies, outdoor injuries were more prevalent than indoors, namely 61% vs. 27% in boulderers (28), and 74% of outdoor male climbers (25). Two studies showed that traditional climbing was not associated with injuries, whilst other forms of climbing such as lead and sport were (27, 39). Finally, one study showed no associations between type of climbing and injury risk, although the study had a relatively low SQS and sample size (11/32; $n = 50$) (44).

TABLE 2 Methodological quality assessment of the included studies according to downs and black.

Study author name & year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Q25	Q26	Q27	Downs black score (/32)
Auer et al. (18)	1	1	1	0	0	1	1	0	0	1	1	1	0	0	0	1	1	1	0	1	0	1	0	0	0	1	5	19
Backe et al. (6)	1	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	5	16
Beeler et al. (19)	1	1	1	0	0	1	1	0	1	1	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	5	17
Bollen et al. (20)	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	5	9
Buda et al. (21)	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	5	15
Carmeli et al. (22)	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	5	13
Cobos-Moreno et al. (23)	1	0	1	0	0	1	1	0	1	1	0	0	0	0	0	1	0	1	0	0	1	1	0	0	0	1	5	16
Gerdes et al. (24)	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	5	15
Grønhaug et al. (25)	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	5	13
Grønhaug et al. (26)	1	1	1	0	1	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	5	15
Jones et al. (9)	1	1	1	0	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	0	1	13
Jones et al. (27)	1	1	1	0	0	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	1	0	0	0	0	5	20
Josephson et al. (28)	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	5	14
Killian et al. (29)	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	5	11
Kozin et al. (30)	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	0	5	18
Kozin et al. (31)	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	0	5	18
Lion et al. (32)	1	1	1	0	0	1	1	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	5	14
Logan et al. (33)	1	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	5	12
Lutter et al. (34)	1	1	1	0	0	1	1	0	1	1	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	5	17
Lutter et al. (35)	1	0	1	0	0	1	1	0	1	0	1	1	0	0	0	1	0	1	0	1	1	1	0	0	0	0	2	14
Nelson et al. (36)	1	1	1	0	0	1	1	0	1	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	5	16
Neuhof et al. (37)	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	5	15
Orth et al. (38)	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	1	0	1	0	1	1	0	0	0	1	0	5	15
Paige et al. (39)	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5	8
Pieber et al. (40)	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	5	15
Rohrbough et al. (41)	1	1	1	0	0	1	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	10
Runer et al. (2)	1	1	1	0	1	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	5	15
Schäfer et al. (42)	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	1	5	11
Schöffl et al. (43)	1	1	1	0	0	1	1	0	1	1	0	0	0	0	0	1	0	1	0	1	1	1	0	0	0	1	5	18
Shahram et al. (44)	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	5	11
Stelzle et al. (45)	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	5	12
van Middelkoop et al. (8)	1	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	1	1	0	1	1	1	0	0	0	1	5	19
Wright et al. (46)	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	5	10
Zielinski et al. (47)	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	5	15

TABLE 3 Injuries and epidemiological data from included studies.

Study author name & year	Injury prevalence, incidence rates (IR) or incidence proportions (IP)
Auer et al. (18)	15% incurred overuse injury over 12 months
Backe et al. (6)	IR of 4.2 injuries per 1,000 h of climbing
Beeler et al. (19)	71% career prevalence of shoulder pain
Bollen et al. (20)	Not reported
Buda et al. (21)	Not reported
Carmeli et al. (22)	Not reported
Cobos-Moreno et al. (23)	73.59% prevalence of foot injuries or alterations
Gerdes et al. (24)	Career IP of 131 per 100 participants
Grønhaug et al. (25)	IP of 58 injuries per 100 participants over past 6 months
Grønhaug et al. (26)	IP of 58 injuries per 100 participants over past 6 months
Jones et al. (9)	IP of 50.2 injuries per 100 participants over past 12 months
Jones et al. (27)	IP of 137 per 100 participants over 12 months
Josephson et al. (28)	IP 103 per 100 participants (outdoor climbing), IP 127 per 100 participants (indoor climbing)
Killian et al. (29)	81% point prevalence of pain/discomfort in feet
Kozin et al. (30)	Shoulder injuries: IR of 3.2 per 1,000 athlete exposures in control group vs. IR of 0.5 per 1,000 athlete exposures in injury prevention training group
Kozin et al. (31)	Elbow injuries: IR of 1.8 per 1,000 athlete exposures in control group vs. IR of 0.5 per 1,000 athlete exposures in injury prevention training group
Lion et al. (32)	IP of 67.4 hand injuries per 100 participants in last 3 years
Logan et al. (33)	19.5% point prevalence of Duputryen's disease
Lutter et al. (34)	IP of 93.5 per 100 participants
Lutter et al. (35)	IP of 94.4 overuse injuries per 100 participants over 3 year period
Nelson et al. (36)	IP of 90 per 100 participants for upper extremity injuries
Neuhof et al. (37)	IP of 28.5 per 100 participants
Orth et al. (38)	Not reported
Paige et al. (39)	IP of 63 injuries per 100 participants over last five years
Pieber et al. (40)	Career IP of 194 injuries per 100 participants
Rohrbough et al. (41)	Career IP of 300 injuries per 100 participants
Runer et al. (2)	IR of 9.8 injuries per 1,000 exposure hours over one winter season
Schäfer et al. (42)	Not reported
Schöffl et al. (43)	Finger stress reactions in 8/10 national level climbers and 3/10 recreational climbers over fiver-year period
Shahram et al. (44)	70% of climbers experienced injury
Stelzle et al. (45)	Career IP of 30 overuse injuries per 100 participants
van Middelkoop et al. (8)	IP of 13.04 per 1,000 climbing hours over one year
Wright et al. (46)	IP of 44 overuse injuries per 100 participants
Zielinski et al. (47)	IP of 26 mild back pain cases per 100 participants

3.6.3. Climbing volume

Eight studies measured climbing volume in some form, as a potential risk factor for injury (6, 8, 21, 22, 35–37, 48). A single 5-year prospective study with a relatively high SQS (18/32) suggested that hours of training per week and training units per week were significantly associated with finger stress reactions (48). This is contradicted by evidence in two different longitudinal prospective studies (SQS: 14/32 and 19/32), showing that there were no significant associations between climbing time per month/per week and the development of a climbing injury (8, 35). Five cross-sectional investigations revealed an increased risk of injury with increased climbing volume (6, 21, 22, 36, 37), in particular for recurrent ankle sprains potentially relating to chronic ankle instability (21), and injures of the wrist/fingers (22). Nelson et al., (2017) reported that the odds of sustaining an injury in people climbing every week were 2.49 times higher (95% CI: 1.27–4.90) compared to those who climb at most once a month (36).

3.6.4. Climbing intensity

A total of 21 studies investigated climbing intensity and its relationship to injury, usually measured by climbing grade or level of climbing (e.g., intermediate vs. elite climbers) (2, 8, 9, 19, 21, 23, 25, 27, 29, 32, 33, 35–37, 40, 42, 44–48). Except for one prospective study (SQS: 14/32) (35), and a retrospective survey studying specifically injuries of the foot (SQS: 11/32) (29), the remaining 19 studies indicated some level of association between climbing intensity and an increased risk of injury, and the direction of this relationship was linear and positive (i.e., increased intensity = increased injuries). This evidence is supported by two longitudinal prospective studies (SQS: 18/32 and 19/32), specifically for finger stress injuries (48), and injuries of the entire upper extremity (8). Higher climbing intensity was associated with injuries in specific anatomical areas of the foot in three cross-sectional studies (21, 23, 33), the low back (47), and with degenerative changes in the shoulder (19). A single prospective study over one winter season highlighted that intermediate ice climbers were more likely to get injured than advanced ice climbers (2), however this finding is likely specific to ice climbers and probably alludes to the prevalence of traumatic injuries in the intermediate cohort as a result of lower skill.

3.6.5. Strength and conditioning

Nine studies researched strength and conditioning measures as ether a risk factor or preventative strategy against climbing injuries (8, 22, 28, 30–32, 38, 42). Two studies reporting from the same randomized controlled trial (SQS: 18/32) showed that an injury prevention program based upon closed chain eccentric and strength exercises performed 3–4 times per week for one year, could reduce the likelihood of shoulder injuries (30) and elbow injuries (31). Additionally, prospective evidence (SQS: 14) suggests that weight training can reduce injuries in boulderers, although regular yoga practice had no positive effect (28). Cross-sectional evidence showed that the injured hand in climbers had weaker grip strength than the contralateral hand (22). An additional cross-sectional investigation adds weight to these findings (38) (SQS: 15/32), illustrating 7% mean deficits in maximal voluntary isometric contraction of the previously injured finger flexors. In contrast, prospective data (SQS: 19/32) indicates that higher strength of the middle finger and campus board training of the fingers is predictive of injury in the upper extremities (8). A different one-year prospective study (SQS: 19/32) found that fingerboard training was not associated with an increased risk of injury in boulderers (18). A single study examined cardiovascular training as preventive measure against hand injuries, and found no significant association (32). Finally, a single study discussed weak spinal musculature, strength training, and pull-up technique as indicators for climbing injury (42).

3.6.6. Other prevention measures

Two longitudinal prospective studies (SQS: 19/32) found that finger taping is not an effective intervention for the prevention of injuries in boulderers (18, 28). Meanwhile, one of these prospective studies indicated that wrist taping might have a protective effect (28). Three studies (two of which were prospective designs) indicated that performing a warm-up has no impact on the prevalence of climbing injuries (8, 28, 32), whilst a separate prospective study (SQS: 19/32) actually reported increased odds of injury when conducting a finger-specific warm-up (18) though this finding was attributed to confounding variables not measured within the study design. Performing a cool-down appeared to have no effect on injury in a single cross-sectional study (32), whilst a prospective study (8) (SQS: 19/32) showed that cooling-down was associated with increased risk of injury. Stretching was non-protective against climbing injury in two studies (28, 32). Two studies discussed the repetitive use of a "crimp grip" as a potential risk factor for injuries of the hand and fingers (20, 45), and found a significant association with injury risk. A single study reported a strong correlation between shoe size reduction and neurological symptoms in the foot e.g., tingling, although shoe size reduction was not correlated with pain or discomfort (SQS: 11/32) (29). Lastly, hydration was investigated in a single-study and found not to be associated with injury risk in climbers (32).

3.7. Nonmodifiable risk factors

3.7.1. Age and years of climbing experience

Age and years of experience are considered together, as they are likely somewhat colinear and may confound each other e.g., older people are more likely to have more years climbing experience. A total of 12 studies considered age as a risk factor for climbing injury, whilst ten studies examined years of climbing experience. Five studies identified older age as a significant risk factor for the development of climbing injury (6, 8, 22, 40, 41), whereby one of these studies was a higher-quality prospective study investigating upper extremity injuries only (8) (SQS: 19/32). Conflictingly, six studies (9, 18, 35–37, 46) including two prospective studies in boulderers (18) (SQS: 19/32) and a broad population of climbers (35) (14/32) found no significant relationship with increasing age and risk of climbing injury. Although, Lutter et al., (2019) only included a sample of four people in the 65 + years group (35). Interestingly, a single study indicated a higher risk of forearm bone marrow edema in younger climbing populations compared to their older peers, as measured via magnetic resonance imaging (34). Regarding years of climbing experience, two prospective studies propose that development of bone marrow edema in the hand is associated with increasing years of experience (34) (SQS: 17/32), and that male climbers who report more years of experience also have an increased risk of injury (35) (SQS: 14/32). Additionally, there is further cross-sectional evidence indicating increased risk of medial epicondylitis (41), injuries of the foot (21, 23), and general musculoskeletal injury (37), with increasing years of climbing experience. However, an additional four studies revealed no association between increasing years of climbing experience and injury risk (6, 9, 18, 28), whereby two of these were prospective investigations in boulder specific populations (18, 28) (SQS: 14/32; 19/32). It should be noted that the average age of participants in these two studies was relatively young (24.7–30 years).

3.7.2. Sex

13 studies examined biological sex as a risk factor for climbing injury and provided conflicting results (6, 8, 9, 21, 22, 25, 28, 34, 35, 37, 40, 41, 46). A total of seven studies discovered a significant relationship between male sex and the risk of injury (6, 21, 22, 25, 35, 40, 46). One of these studies was conducted in a prospective design over a three-year period (35) (SQS: 14/32), and showed a male to female ratio of 3:1 in terms of injury rate, whereby males also had significantly higher climbing levels and years of experience which could be considered as confounding factors. One study added nuance to the results, indicating that male sex is indeed a risk factor for chronic elbow and finger injuries, but that females are at greater risk of chronic ankle injuries (SQS: 13/32) (25). In contrast, six studies suggested no relationship between biological sex and injury risk (8, 9, 28, 34, 37, 41), and three of these studies were prospective designs with relatively high quality scores (8, 28, 34) (SQS: 14/32–19/32). These studies were conducted to determine risk factors on hand bone marrow edema (34) and general injury risk in boulderers (28) and a broad climbing population (8).

3.7.3. Previous injury

A total of four studies explored previous injury as a risk factor for the development of future injury or reinjury (18, 22, 27, 28). Three prospective studies with relatively high quality scores (SQS: 14/32–20/32) indicated a history of prior injury to be a significant predictor of future injury and/or reinjury (18, 27, 28). Jones et al., (2015) reported a 63% average probability for reinjury in climbers reporting a previous overuse injury, which was particularly evident for the fingers. In support of this data, Josephson et al., (2007) specifically indicated that a history of finger injury was predictive of a reinjury. A single cross-sectional study on 37 participants (22) (SQS: 13/32) contradicts the above findings, showing no relationship between past and current injury.

4. Discussion

The aim of this study was to conduct a systematic review of the potential risk factors and injury prevention strategies for overuse injuries in adult climbers. A total of 34 studies reporting on 73 risk factors or injury prevention strategies were included in the final analysis. The methodological quality of the included studies was variable (SQS: 8/32–20/32) and bias is likely to have impacted the findings in several studies. The methods of defining injury and risk factors or injury prevention strategies was extremely diverse, so overall conclusions drawn from the reviewed evidence should be treated with caution. For modifiable risk factors associated with injury, some key findings from the evidence can be stated. Strong evidence from prospective and cross-sectional studies indicates that increased climbing intensity is associated with an increased risk of injury, whereas the relationship between climbing volume and injury is much less clear. Strong evidence both prospectively and cross-sectionally suggest that BMI and/or body weight are not associated with an increased risk of injury. Regarding type of climbing, there is moderate evidence that bouldering might result in more injuries, when compared to other disciplines of climbing. An injury prevention strength training program was able to prevent elbow and shoulder injuries in two randomized controlled trials (RCT) (though on the same cohort), and there is weak evidence from cross-sectional studies that reduced grip/finger strength is associated with risk of injury. Limited evidence suggests that warm up/cool downs, stretching, taping and hydration have no relationship with climbing injury, whereas repetitive use of a "crimp grip" and shoe size reduction might be associated with injury. Considering nonmodifiable risk factors, the evidence for age/years of climbing experience and its association with injury was conflicting across studies. Evidence for the association between biological sex and climbing injury was equally conflicting. Meanwhile, strong prospective evidence suggests that previous injury is highly predictive of sustaining future climbing injuries.

4.1. Modifiable risk factors

4.1.1. BMI/body weight not associated with overuse injury risk

In a previous systematic review by Woollings et al., (2015), the authors concluded that a higher BMI was likely to be associated with increased risk of injury in climbers. However, this conclusion was primarily based on data from Backe et al., (2009) due to its methodological rigor compared to other studies in the analysis. Since this review was published, three prospective investigations in a total of 1,138 climbers (8, 18, 35) have subsequently reported no association between increased BMI/ body weight and risk of climbing injury. This strong evidence, supported by additional cross-sectional findings (26, 28, 37), suggests that practitioners working with climbing athletes should avoid strong recommendations on weight loss strategies in the pursuit of injury prevention. Furthermore, weight loss programs are commonly initiated in the pursuit of performance goals, however, associations between reduced BMI and improved climbing performance also seem limited (26). Therefore, such programs should be implemented with extreme caution, especially considering the risk of poor bone health and associated disorders in athletic populations (49). Hence, the health of the climbing athlete should be prioritized above all else (50). It should be acknowledged that weight loss strategies in the pursuit of performance goals will likely continue to be a staple in sports performance, especially in sports such as climbing where the strength to body weight ratio could still be assumed to influence performance for some athletes. Additionally, the data from Gronhaug (2019) showing no effect of low BMI on climbing performance is only cross sectional and retrospective, which weakens the findings substantially.

4.1.2. Bouldering is potentially a greater risk factor for injury

Bouldering appears to be a risk factor for the development of climbing injury when compared to other disciplines such as lead climbing, as indicated by evidence in six studies (6, 8, 9, 27, 46, 47). However, the majority of the studies are cross-sectional in design, therefore strong conclusions cannot be drawn. Nonetheless, this contrasts with previous findings from Woollings et al., (2015) who suggested that lead climbing was associated with an increased risk of injury in climbers. The conflicting results can potentially be explained on two fronts. Firstly, some of the evidence in the current study has emerged since the publication of this previous systematic review. Secondly, the focus of the current study was overuse injuries, whereas the review from Woollings et al., (2015) also included all traumatic injuries by methodology. It could be speculated that lead climbing might result in more traumatic injuries due to the higher risk of larger falls, compared to bouldering which might be associated with a higher amount of overuse related injuries, and traumatic injuries to the leg/ankle during falling. Bouldering is typified by repetitive intense bouts of dynamic climbing, and this specific pattern of highly demanding effort may put climbers at a greater risk of developing an overuse injury (18). Practically, boulderers should be encouraged to take sufficient rest periods between intense bouts of climbing to allow for recovery and mitigate fatigue.

4.1.3. A relationship between climbing volume and injury risk is unclear

The amount of time spent climbing (climbing volume) was shown to be associated with finger stress injuries in one prospective study (48), though the sample size was small with only 20 participants (SQS: 18/32). This is contrasted in two prospective studies (8, 35) ($n = 198$; $n = 434$), which showed no relationship between total climbing volume and general injury risk in climbers (SQS: 14/32; 19/32). It might be important to note that the average age of the sample in the study by Schöffl et al., (2007) (48) was much younger (20 to 21 years old) than in the other two prospective studies (32 to >65 years old), perhaps indicating that large climbing volume may be a risk factor for younger climbing athletes specifically. Despite further evidence from five cross-sectional studies suggesting an association between increased volume and injury risk (6, 21, 22, 36, 37), it is difficult to state that a clear relationship exists in the context of findings from this review. The conflicting results on training volume in the current study support previous conclusions published in a systematic review by Woollings et al., (2015). The discrepancy in findings from the included studies could be explained by variation in the methodologies of reporting training volume, whereby information collected in the form of questionnaires is known to be subject to recall and/or response bias. Future studies could incorporate wearable sensor technology to monitor training volume, which might enable more accurate measurement of time spent training (51). Additionally, it could be considered that training volume may also offer a protective stimulus against injury (52), which might also explain the paradoxical findings. When applied consistently, large training volumes will induce physiological adaptations in athletes which prepare them for their sport and competition, and therefore might actually assist in the prevention of injuries (52). Whilst it must be acknowledged that increased training volume has been suggested to be associated with injury risk in athletes (53), it has equally been debated whether sudden and rapid spikes in training volume may be responsible for the increased injury risk, as opposed to training volume when considered as a consistent variable over a period of time (54). The results of the current study and others (5, 9, 55), indicate that future studies should be conducted to investigate the relationship between training volume and climbing overuse injuries, with an enhanced focus on the quality of the data collected.

4.1.4. Climbing intensity is associated with risk of overuse injury

Climbing intensity was usually measured indirectly via climbing level or grade, whereby a higher grade indicates a higher intensity. A total of 19 studies showed an association between increased climbing intensity and an increased risk of overuse injury (2, 8, 9, 19, 21, 23, 25, 27, 32, 33, 36, 37, 40, 42, 44–48), whereby two of the studies were prospective (8, 48) in a total of 454 climbers (SQS: 18/32 and 19/32). A single prospective study conflicted with this evidence (35) (SQS: 14/32), though this research included a much older population of athletes compared to other studies. This may have confounded the findings as older athletes generally reported lower climbing grades. The findings of the current study support previous work by Woollings et al., (2015), who also described a relationship between increased climbing intensity/grade and an increase in injury risk, and this association has been discussed in other reviews in the literature (14). High intensity training maintained over long periods of time (52) or when introduced abruptly during the training process (54) appears to increase the likelihood of sustaining an overuse injury in athletes, and this risk likely exists in climbers. This result underlines the need for training to be programmed and monitored in a sensible and accurate way, in accordance with currently known best practice in training periodization and planning (52, 56, 57). Approaches should emphasize a balanced training paradigm, which includes periods of intense training sessions to elicit the desired physiological adaptations, counteracted with “easier” sessions which allow for adequate recovery (52, 56). Research in this area specifically for climbers is notably scarce, and more studies are required with a focus on more valid methodological approaches for measuring climbing “intensity”. People working in climbing could adopt the “Climbing Intensity Score” (=climbing grade/level × climbing volume), as suggested by Logan et al., (2005). Such a score may provide a more comprehensive measurement of the total load experienced by climbing athletes and help to inform future climbing studies and load management strategies.

4.1.5. Strength and conditioning for injury prevention

Two RCTs conducted on the same study cohort, reported that closed chain eccentric and strength exercises performed 3–4 times per week for one year, could reduce the likelihood of shoulder injuries (30) and elbow injuries (31) (SQS: 18/32). This is the first and seemingly only study which has implemented an injury prevention program in climbers and showed positive effects of a strength and conditioning program on injury reduction. Strength and neuromuscular training programs are broadly supported in the literature as an injury prevention modality in multiple sports (55), and it has been shown in a recent systematic review and meta-analysis that climbing-specific resistance training can also improve climbing performance (58). Therefore, it would seem appropriate to implement strength training programs in climbers. However, the results of the two included studies in this review had a relatively small sample size ($n = 84$) focusing on injuries of the elbows and shoulders (30, 31). Correspondingly, these findings cannot be applied to injuries of the fingers, which is known to be the most common site of injury in climbers (14). Furthermore, there is cross-sectional evidence in two studies that the injured hand is weaker than the contralateral healthy hand (22, 38), and an additional two prospective studies showed conflicting findings regarding finger strength and injury risk (8, 18). The prospective study by van Middelkoop et al., (2015) reported that increased strength of the middle finger and campus board training was actually predictive of injury risk. However, this might be understood as confounded noise in the data, whereby people with previous injuries to the fingers have adopted specific finger flexor training modalities in an attempt to prevent reinjury. This highlights the need for future RCTs investigating injury prevention programs specifically for the hand and fingers in climbers.

4.1.6. Taping, warm up/cool down, and stretching mostly ineffective for injury prevention

Two high-quality prospective trials including a total of 658 climbers showed that taping did not protect against overuse injury risk (18, 28). Josephsen et al., (2007) did reveal that wrist taping could have a beneficial effect for boulderers, although confidence limits for the incidence rates indicated a weak effect. Taping is widely adopted in climbing gyms as means to prevent injury, but the results of this review cannot support its use. Warm-ups and cool-downs are commonly implemented in climbers to reduce the risk of overuse injury. However, based upon data from four studies (8, 18, 28, 32), two of which were prospective studies (8, 18), both warming up or cooling down had no protective effect against overuse injuries. The ritual of a warm-up or cool-down is likely to have other effects on athletic physiology, and there is some evidence that it may improve athletic performance (59). However, based upon the results of this review and others similar (5), traditional warm-ups or cool-downs cannot be recommended with the explicit goal of reducing overuse injury risk. Another commonly practiced injury prevention technique is stretching, usually performed prior to climbing in a static or dynamic manner. Two studies included in this review (28, 32) including one prospective investigation (28) indicate that stretching offers no protective effect against risk of overuse injury. This finding is commonly reported across other sporting disciplines (55) and supports results of a previous systematic review in climbing (5). Given evidence that static stretching doesn't confer a beneficial effect on muscle performance, and may even have a negative effect at longer duration stretch routines (>60 s) (60), it would seem problematic to advise climbers to engage with a stretching routine prior to training sessions and competition.

4.2. Nonmodifiable risk factors

4.2.1. Relationship between age, years of climbing experience, and injury risk inconclusive

Results from this review indicate conflicting findings, when considering age and years of climbing experience as a risk factor for overuse injury. There is strong prospective evidence in a sample of 434 climbers that increasing age might exacerbate injury risk (8) (SQS: 19/32), which is contrasted by two prospective studies including a total of 704 climbers indicating no increased risk of injury with older age (18, 35) (SQS: 19/32, 14/32) ($n = 229$). Furthermore, two prospective studies showed a positive relationship between increased years of climbing experience and injury (34, 35), which conflicts with two prospective studies showing no relationship (18, 28) ($n = 658$). The mixed findings might be attributed to the large variety of injuries included within this review (see **Table 3**), whereby age and years of climbing experience might be a risk factor for certain injuries, but not for others. In a systematic review, Woollings et al., (2015) concluded that older age was a risk factor for injury in climbing, however, they also suggested that certain injuries may be more prevalent in younger populations when compared to older climbers. To this point, a recent prospective study included in this review indicated that younger climbers may be at a higher risk of bone marrow edema (34), although there were only 31 participants included in the study. This may be especially relevant for the physis of the proximal inter-phalangeal joint during adolescent growth, and practitioners should be vigilant for these issues in younger climbers. An additional consideration might be that older climbers tend to "self-moderate" the intensity of their climbing, by selecting lower grades as they age. This seems to be the pattern in the prospective analysis of Lutter et al., (2019), though this is only speculation and would require further study to verify this claim.

4.2.2. Association between sex and injury risk conflicting

The findings relating biological sex to injury risk are also very conflicting. One prospective study with 198 participants showed that males were more likely to obtain an injury at a 3:1 ratio compared to females (35) (SQS: 14/32). However, in this sample males also reported higher climbing levels and years of experience when compared to females, which have also been discussed as risk factors for overuse injury. A cross-sectional study indicated that males are more at risk for chronic elbow and finger injuries, whereas females appear to have a higher risk of chronic ankle injuries (SQS: 13/32) (25). The author highlights that this may be due to climbing shoe design which is typically male-centric, therefore, shoes designed specifically for female feet should be developed and tested in future studies. In this same paper, male sex was seen to interact with bouldering grade, whereby a higher prevalence of chronic injuries was found in males with higher bouldering grades, however this interaction was not as obvious in females. In fact, the highest prevalence of injuries was amongst the male outdoor climbing group (74%), which is speculated to be reflective of the increased risk-taking behaviours of males when compared to females, especially when climbing outdoors. In contrast, three prospective studies with a total of 617 participants reported no differences for injury risk between the male and female sexes (8, 28, 34) (SQS: 14/32–19/32). Sex-specific differences in injuries have been revealed to some degree in team sports (61), though the differences seem marginal. It should also be noted that most of the studies included samples that were disproportionately male-biased, and therefore future research needs to be mindful of conducting research in female climbing populations. According to this review, there is conflicting evidence regarding sex-specific differences in risk factors for overuse injuries in climbers. In future studies, biological sex should be studied alongside other interacting factors, such as climbing grade and type of climbing e.g., indoors vs. outdoors, so as to reveal how these factors might coalesce and effect injury risk.

4.2.3. Previous injury predicts future injury

Three relatively high quality prospective studies (18, 27, 28) (SQS: 14/32–20/32) identify previous injury as a risk factor for future injury or reinjury. This supports evidence in other sports (62), whereby the mechanism is supposed to occur in altered neuromuscular physiology associated with the injured anatomical site and potentially unresolved structural pathology in the local tissue. However, some studies included within the current review are not clear whether participants reinjured the same specific anatomical site that was injured previously, or whether injury risk is more generally heightened in individuals who have obtained previous injuries. These details should be the subject of future investigations. Nonetheless, it would be advised that climbers who have previously acquired an overuse injury should be aware of the increased risk of reinjury and follow the advice of their healthcare practitioner, and potentially implement a secondary injury prevention program with appropriate load management. Return to sport guidelines in climbing post-injury have yet to be deciphered, but there is some data available which could help inform decision-making (63, 64).

4.3. Limitations

It is important to acknowledge that this study has several limitations. Firstly, the primary limitation is that this systematic review can only make conclusions based upon the available data, and their chosen methodological approach. For example, all studies included in this review only examined the independent effects of chronological age, climbing experience, training volume and intensity, yet an overuse injury is likely the interactive effect of these factors. For example, the overall training load is a combination of volume and intensity, and an abrupt increase in training load is likely tolerable with a relatively low risk in well trained individuals, but a higher risk for overuse injury in untrained inexperienced climbers. Any conclusions on these interactive nuances cannot be made with the current level of evidence. Secondly, this systematic review focused on adult climbers and only studies researching this population were included. However, some studies also included participants younger than 18 years old, so this demographic was not entirely excluded from the analysis. Nevertheless, the mean age of all participants included was around 31 years old, so the large majority of climbers studied were very likely adults. Additionally, the aim of this review was to study overuse injuries only, as opposed to traumatic injuries. Several studies reported data on all types of climbing injuries, without specifically mentioning distribution of overuse or traumatic injuries within their research. Therefore, it is likely that some of the risk factors included in the analysis are related to traumatic injuries, which does limit the interpretation of the findings to some degree. Best efforts were made to isolate overuse injuries wherever possible. Future studies should attempt to categorize injuries more transparently so that better conclusions can be drawn. Finally, the participants included in this review were highly heterogenous, in terms of type of climbers, age, injuries, and the risk factors studied. This results in a large variation in the nature of our findings and makes it difficult to apply the information to specific groups. However, this methodology was chosen to obtain a broad range of data on climbing athletes, so as to synthesize the currently available data in a single review.

4.4. Conclusions

Within this systematic review, several risk factors and injury prevention strategies were identified for climbing athletes, some of which are modifiable. Modifiable risk factors are likely to be most relevant for coaches and clinicians working with climbers, as they can be changed and may prove as useful targets for injury prevention strategies. There is evidence that increased climbing intensity and bouldering are associated with a higher risk of overuse injury, and training for climbers should be planned and monitored in accordance with these findings. Climbing volume appears to be less relevant as a risk factor in general but might be a risk factor in specifically younger populations, and it would still seem pertinent to monitor training volume in addition to training intensity until future research can clarify this relationship. It is generally recommended that future prospective trials are required to validate the impact that training programming can truly have on injury risk reduction in climbers. Additionally, strength and conditioning training appears to be a successful strategy for mitigating injury risk in the shoulders and elbows. However, future intervention trials are necessitated to verify these results and to study prevention in other anatomical areas e.g., the fingers. BMI and body weight appear to have no relationship with overuse injury risk; therefore, aggressive weight loss programs are not useful in the pursuit of injury reduction. The nonmodifiable risk factors of age/years of experience and sex seem to have a conflicting relationship with overuse injury risk, therefore further research is required to clarify differences in climbing injury between younger and older climbing athletes, as well as males and females. A previous climbing injury appears to be a strong predictor of future injury. Climbing athletes who have suffered a prior overuse injury are recommended to complete a comprehensive rehabilitation program with a healthcare professional. This could potentially address associated deficits that might lead to future cases of injury. Finally, the risk factors and injury prevention strategies identified within the current literature are overwhelmingly related to physical therapeutics, training, load management, age, and sex. There is a paucity of information on psychosocial factors, sleep, and nutrition, although it is well documented that these aspects are likely to be associated with overuse injuries (65–67). Future climbing researchers are encouraged to investigate these variables in the context of overuse injury prevention in climbers, to shed more light on these issues and hopefully improve the health of climbing athletes.

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.

Author contributions

AQ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MZ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – review & editing. MG: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – review & editing. TJ: Conceptualization, Resources, Supervision, Writing – review & editing. HM: Conceptualization, Methodology, Resources, Software, Supervision, Writing – review & editing. MC: Validation, Writing – review & editing. JL: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1269870/full#supplementary-material

References

1. Lutter C, El-Sheikh Y, Schöffl I, Schöffl V. Sport climbing: medical considerations for this new Olympic discipline. *Br J Sports Med.* (2017) 51(1):2–3. doi: 10.1136/bjsports-2016-096871

2. Runer A, Lampl K, Neunhäuser D, Runer F, Frick N, Seitlinger G, et al. A 1-year prospective analysis of ice climbing injuries. *Clin J Sport Med Off J Can Acad Sport Med.* (2017) 27(2):161–7. doi: 10.1097/JSM.0000000000000326

3. Woollings KY, McKay CD, Kang J, Meeuwisse WH, Emery CA. Incidence, mechanism and risk factors for injury in youth rock climbers. *Br J Sports Med.* (2015) 49(1):44–50. doi: 10.1136/bjsports-2014-094067

4. Saul D, Steinmetz G, Lehmann W, Schilling AF. Determinants for success in climbing: a systematic review. *J Exerc Sci Fit.* (2019) 17(3):91–100. doi: 10.1016/j.jesf.2019.04.002

5. Woollings KY, McKay CD, Emery CA. Risk factors for injury in sport climbing and bouldering: a systematic review of the literature. *Br J Sports Med.* (2015) 49 (17):1094–9. doi: 10.1136/bjsports-2014-094372

6. Backe S, Ericson L, Janson S, Timpka T. Rock climbing injury rates and associated risk factors in a general climbing population. *Scand J Med Sci Sports.* (2009) 19 (6):850–6. doi: 10.1111/j.1600-0838.2008.00851.x

7. Gimigliano F, Resmini G, Moretti A, Aulicino M, Gargiulo F, Gimigliano A, et al. Epidemiology of musculoskeletal injuries in adult athletes: a scoping review. *Med.* (2021) 57(10):1118. doi: 10.3390/medicina57101118

8. van Middelkoop M, Bruens ML, Coert JH, Selles RW, Verhagen E, Bierma-Zeinstra SMA, et al. Incidence and risk factors for upper extremity climbing injuries in indoor climbers. *Int J Sports Med.* (2015) 36(10):837–42. doi: 10.1055/s-0035-1547224

9. Jones G, Asghar A, Llewellyn DJ. The epidemiology of rock-climbing injuries. *Br J Sports Med.* (2008) 42(9):773–8. doi: 10.1136/bjsm.2007.037978

10. Muller M, Heck J, Pfluger P, Greve F, Biberthaler P, Cronlein M. Characteristics of bouldering injuries based on 430 patients presented to an urban emergency department. *Inj J Care Inj.* (2022) 53(4):1394–400. doi: 10.1016/j.injury.2022.02.003

11. Sims LA. Upper extremity injuries in rock climbers: diagnosis and management. *J Hand Surg Am.* (2022) 47(7):662–72. doi: 10.1016/j.jhsa.2022.01.009

12. Rauch S, Wallner B, Strohle M, Dal Cappello T, Maeder MB, Ströhle M, et al. Climbing accidents-prospective data analysis from the international alpine trauma registry and systematic review of the literature. *Int J Environ Res Public Health.* (2020) 17(1):203. doi: 10.3390/ijerph17010203

13. Cole KP, Uhl RL, Rosenbaum AJ. Comprehensive review of rock climbing injuries. *J Am Acad Orthop Surg.* (2020) 28(12):e501–9. doi: 10.5435/JAAOS-D-19-00575

14. Jones G, Johnson MI. A critical review of the incidence and risk factors for finger injuries in rock climbing. *Curr Sports Med Rep.* (2016) 15(6):400–9. doi: 10.1249/JSR.0000000000000304

15. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ.* (2021) 372:n71. doi: 10.1136/bmj.n71

16. Draper N, Giles D, Schöffl V, Konstantin Fuss F, Watts P, Wolf P, et al. Comparative grading scales, statistical analyses, climber descriptors and ability grouping: international rock climbing research association position statement. *Sports Technol.* (2016) 8(3–4):88–94. doi: 10.1080/19346182.2015.1107081

17. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Heal.* (1998) 52:377–84. doi: 10.1136/jech.52.6.377

18. Auer J, Schoffl VR, Achenbach L, Meffert RH, Fehske K. Indoor bouldering-a prospective injury evaluation. *WILDERNESS Environ Med.* (2021) 32(2):160–7. doi: 10.1016/j.wem.2021.02.002

19. Beeler S, Pastor T, Fritz B, Filli L, Schweizer A, Wieser K. Impact of 30 years' high-level rock climbing on the shoulder: an magnetic resonance imaging study of 31 climbers. *J Shoulder Elb Surg.* (2021) 30(9):2022–31. doi: 10.1016/j.jse.2020.12.017

20. Bollen SR. Soft tissue injury in extreme rock climbers. *Br J Sports Med.* (1988) 22 (4):145–7. doi: 10.1136/bjsm.22.4.145

21. Buda R, Di Caprio F, Bedetti L, Mosca M, Giannini S. Foot overuse diseases in rock climbing: an epidemiologic study. *J Am Podiatr Med Assoc.* (2013) 103 (2):113–20. doi: 10.7547/1030113

22. Carmeli E, Shuruk S, Sheklow SL, Masharawi Y. Incidence of hand injuries in wall climbers: a comparison between adolescent adults and young adults. *Biol Sport.* (2002) 19(4):283–94.

23. Cobos-Moreno P, Astasio-Picado Á, Gómez-Martín B. Epidemiological study of foot injuries in the practice of sport climbing. *Int J Environ Res Public Health.* (2022) 19(7):4302. doi: 10.3390/ijerph19074302

24. Gerdes EM, Hafner JW, Aldag JC. Injury patterns and safety practices of rock climbers. *J Trauma.* (2006) 61(6):1517–25. doi: 10.1097/01.ta.0000209402.40864.b2

25. Grønhaug G. Self-reported chronic injuries in climbing: who gets injured when? *BMJ Open Sport Exerc Med.* (2018) 4(1):e000406. doi: 10.1136/bmjsem-2018-000406

26. Gronhaug G. Lean and mean? Associations of level of performance, chronic injuries and BMI in sport climbing. *BMJ Open Sport Exerc Med.* (2019) 5(1): e000437. doi: 10.1136/bmjsem-2018-000437

27. Jones G, Llewellyn D, Johnson MI. Previous injury as a risk factor for reinjury in rock climbing: a secondary analysis of data from a retrospective cross-sectional cohort survey of active rock climbers. *BMJ Open Sport Exerc Med.* (2015) 1(1):1–5. doi: 10.1136/bmjsem-2015-000031

28. Josephsen G, Shinneman S, Tamayo-Sarver J, Josephsen K, Boulware D, Hunt M, et al. Injuries in bouldering: a prospective study. *Wilderness Environ Med.* (2007) 18(4):271–80. doi: 10.1580/06-WEME-OR-071R1.1

29. Killian RB, Nishimoto GS, Page JC. Foot and ankle injuries related to rock climbing. The role of footwear. *J Am Podiatr Med Assoc.* (1998) 88(8):365–74. doi: 10.7547/87507315-88-8-365

30. Kozin S, Cretu M, Kozina Z, Chernozub A, Ryepko O, Shepelenko T, et al. Application of closed kinematic chain exercises with eccentric and strength exercises for the shoulder injuries prevention in student rock climbers: a randomized controlled trial. *Acta Bioeng Biomech.* (2021) 23(2):159–68. doi: 10.37190/ABB-01828-2021-01

31. Kozin S, Kozina Z, Jagiello M, Joksimovic M. Injury prevention of student rock climbers based on the formation of rational technique of movements: a randomized control trial. *Phys Educ Students.* (2021) 25(5):307–18. doi: 10.15561/20755279.2021.0507

32. Lion A, van der Zwaard BC, Remillieux S, Perrin PP, Buatois S. Risk factors of hand climbing-related injuries. *Scand J Med Sci Sports.* (2016) 26(7):739–44. doi: 10.1111/sms.12505

33. Logan AJ, Mason G, Dias J, Makwana N. Can rock climbing lead to dupuytren's disease? *Br J Sports Med.* (2005) 39(9):639–44. doi: 10.1136/bjsm.2004.015792

34. Lutter C, Hochholzer T, Bayer T, Schöffl V. Rock climbing-related bone marrow edema of the hand: a follow-up study. *Clin J Sport Med Off J Can Acad Sport Med.* (2018) 28(4):382–8. doi: 10.1097/JSM.0000000000000463

35. Lutter C, Hotfiel T, Tischer T, Lenz R, Schoffl V. Evaluation of rock climbing related injuries in older athletes. *WILDERNESS Environ Med.* (2019) 30(4):362–8. doi: 10.1016/j.wem.2019.06.008

36. Nelson CE, Rayan GM, Judd DI, Ding K, Stoner JA. Survey of hand and upper extremity injuries among rock climbers. *Hand*. (2017) 12(4):389–94. doi: 10.1177/1558944716679600

37. Neuhof A, Hennig FF, Schöffl I, Schöffl V. Injury risk evaluation in sport climbing. *Int J Sports Med*. (2011) 32(10):794–800. doi: 10.1055/s-0031-1279723

38. Orth D, Slebioda N, Cavada A, van Bergen N, Deschle N, Hoozemans M. Persistent unilateral force production deficits following hand injury in experienced climbers: a reliability and retrospective injury study. *Wilderness Environ Med*. (2022) 34(1):22–30.

39. Paige TE, Fiore DC, Houston JD. Injury in traditional and sport rock climbing. *Wilderness Environ Med*. (1998) 9(1):2–7. doi: 10.1580/1080-6032(1998)009[0002:IITASR]2.3.CO;2

40. Pieber K, Angelmaier L, Csapo R, Herceg M. Acute injuries and overuse syndromes in sport climbing and bouldering in Austria: a descriptive epidemiological study. *Wien Klin Wochenschr*. (2012) 124(11–12):357–62. doi: 10.1007/s00508-012-0174-5

41. Rohrbough JT, Mudge KM, Schilling RC. Overuse injuries in the elite rock climber. *Med Sci Sports Exerc*. (2000) 32(8):1369–72. doi: 10.1097/00005768-200008000-00002

42. Schäfer J, Gaulrapp H, Pförringer W. Acute and chronic overuse injuries in extreme sport-climbing. *Sportverletz Sportschaden*. (1998) 12(1):21–5. doi: 10.1055/s-2007-993330

43. Schoffl VR, Schoffl I, Schöffl VR, Schöffl I. Finger pain in rock climbers: reaching the right differential diagnosis and therapy. *J Sports Med Phys Fitness*. (2007) 47(1):70–8.

44. Shahram A, Farzad A, Reza R. A study on the prevalence of muscular-Skeleton injuries of rock climbers. *Facta Univ Ser Phys Educ Sport*. (2007) 5(1):1–7.

45. Stelzle FD, Gaulrapp H, Pforringer W. Acute injuries and chronic overuse syndroms due to rock climbing on artificial climbing walls. *Sportverletzung-sportschaden*. (2000) 14(4):128–33. doi: 10.1055/s-2000-8951

46. Wright DM, Royle TJ, Marshall T. Indoor rock climbing: who gets injured? *Br J Sports Med*. (2001) 35(3):181–5. doi: 10.1136/bjsm.35.3.181

47. Zieliński G, Zięba E, Wilkowicz W, Byś A, Ginszt M, Libera O, et al. Influence of regular climbing on depression, generalized anxiety and lower back pain. *Ann Agric Environ Med*. (2021) 28(3):463–8. doi: 10.26444/aaem/124189

48. Schoffl VR, Hochholzer T, Imhoff AB, Schoffl I. Radiographic adaptations to the stress of high-level rock climbing in junior athletes - a 5-year longitudinal study of the German junior national team and a group of recreational climbers. *Am J Sports Med*. (2007) 35(1):86–92. doi: 10.1177/0363546506293256

49. Hoenig T, Ackerman KE, Beck BR, Bouxsein ML, Burr DB, Hollander K, et al. Bone stress injuries. *Nat Rev Dis Prim*. (2022) 8(1). doi: 10.1038/s41572-022-00352-y

50. Turocy PS, DePalma BF, Horswill CA, Laquale KM, Martin TJ, Perry AC, et al. National athletic trainers' association position statement: safe weight loss and maintenance practices in sport and exercise. *J Athl Train*. (2011) 46(3):322–36. doi: 10.4085/1062-6050-46.3.322

51. Sperlich B, Aminian K, Düking P, Holmberg HC. Editorial: wearable sensor technology for monitoring training load and health in the athletic population. *Front Physiol*. (2020) 10:474046. doi: 10.3389/fphys.2019.01520

52. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med*. (2016) 50(5):273–80. doi: 10.1136/bjsports-2015-095788

53. Sugimoto D, Jackson SS, Howell DR, Meehan WP, Stracciolini A. Association between training volume and lower extremity overuse injuries in young female athletes: implications for early sports specialization. *Phys Sportsmed*. (2019) 47(2):199–204. doi: 10.1080/00913847.2018.1546107

54. Windt J, Zumbo BD, Sporer B, Macdonald K, Gabbett TJ. Why do workload spikes cause injuries, and which athletes are at higher risk? Mediators and moderators in workload–injury investigations. *Br J Sports Med*. (2017) 51(13):993–4. doi: 10.1136/bjsports-2016-097255

55. Stephenson SD, Kocan JW, Vinod A V, Kluczynski MA, Bisson LJ. A comprehensive summary of systematic reviews on sports injury prevention strategies. *Orthop J Sport Med*. (2021) 9(10):23259671211035776. doi: 10.1177/23259671211035776

56. Hamlin MJ, Wilkes D, Elliot CA, Lizamore CA, Kathiravel Y. Monitoring training loads and perceived stress in young elite university athletes. *Front Physiol*. (2019) 10(JAN):34. doi: 10.3389/fphys.2019.00034

57. Heard C, Willcox M, Falvo M, Blatt M, Helmer D. Effects of linear periodization training on performance gains and injury prevention in a garrisoned military unit. *J Mil Veterans Health*. (2020) 28(3):23.

58. Stien AN, Riiser A, Matthew P. Effects of climbing- and resistance-training on climbing-specific performance: a systematic review and meta-analysis. *Biol Sport*. (2023) 40(1):179–91. doi: 10.5114/biolsport.2023.113295

59. McCrary JM, Ackermann BJ, Halaki M. A systematic review of the effects of upper body warm-up on performance and injury. *Br J Sports Med*. (2015) 49(14):935–42. doi: 10.1136/bjsports-2014-094228

60. Kay AD, Blazevich AJ. Effect of acute static stretch on maximal muscle performance: a systematic review. *Med Sci Sports Exerc*. (2012) 44(1):154–64. doi: 10.1249/MSS.0b013e318225cb27

61. Zech A, Hollander K, Junge A, Steib S, Groll A, Heiner J, et al. Sex differences in injury rates in team-sport athletes: a systematic review and meta-regression analysis. *J Sport Heal Sci*. (2022) 11(1):104–14. doi: 10.1016/j.jshs.2021.04.003

62. Fulton J, Wright K, Kelly M, Zebrosky B, Zanis M, Drvol C, et al. Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sports Phys Ther*. (2014) 9(5):583.

63. Lum ZC, Park L. Rock climbing injuries and time to return to sport in the recreational climber. *J Orthop*. (2019) 16(4):361–3. doi: 10.1016/j.jor.2019.04.001

64. Schöffl V, Schöffl I, Flohé S, El-Sheikh Y, Lutter C, Schoffl V, et al. Evaluation of a diagnostic-therapeutic algorithm for finger epiphyseal growth plate stress injuries in adolescent climbers. *Am J Sports Med*. (2022) 50(1):229–37. doi: 10.1177/03635465211056956

65. Clemente FM, Afonso J, Costa J, Oliveira R, Pino-Ortega J, Rico-González M. Relationships between sleep, athletic and match performance, training load, and injuries: a systematic review of soccer players. *Healthcare (Basel)*. (2021) 9(7):808. doi: 10.3390/healthcare9070808

66. Buscemi V, Chang WJ, Liston MB, McAuley JH, Schabrun SM. The role of perceived stress and life stressors in the development of chronic musculoskeletal pain disorders: a systematic review. *J Pain*. (2019) 20(10):1127–39. doi: 10.1016/j.jpain.2019.02.008

67. Close GL, Baar K, Sale C, Bermon S. Nutrition for the prevention and treatment of injuries in track and field athletes. *Int J Sport Nutr Exerc Metab*. (2019) 29(2):189–97. doi: 10.1123/ijsnem.2018-0290

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Lower back pain in young climbers: a retrospective cross-sectional study

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Objective: The popularity of sport climbing has been growing since its inclusion in the Olympic Games program, which led to more people practicing it on recreational, amateur, and professional levels. Strenuous climbing training sessions and competitions might lead to frequent and serious musculoskeletal injuries and complaints among competitive climbers. This study aimed to investigate the prevalence of low back pain (LBP) and to explore the influence of various risk factors on LBP in adolescent climbers.
Methods: The sample included 180 competitive climbers (46.6% males) aged 13–19 years competing in under-16 (48.3%) or under-20 categories. Data collection was carried out using the Nordic Musculoskeletal Questionnaire (NMQ) and the Graded Chronic Pain Scale (GCPS).
Results: A total of 74.4% of the entire sample of participants (male = 75%; female = 74%) reported lower back complaints throughout the past twelve months, and only 15.5% during the last seven days. A major part of complaints was classified as low intensity-low disability (Grade I, 62.8%; male = 72.6%; female = 54.2%). Under-20 competitors reported a small but significantly higher percentage of almost all NMQ measures compared to under-16 athletes.
Conclusions: This study found a relatively high prevalence of LBP, although complaints were of limited severity and did not affect climbers' regular training practice. Moreover, climbers did not differ in LBP prevalence according to sex, while climbers from the older age group reported higher complaints and seeking medical attention than younger climbers. Future studies should prospectively monitor the influence of climbing on LBP in youth climbers.

KEYWORDS
chronic injuries, injury surveillance, sport climbing, youth athletes, well-being

Introduction

Climbing is a fast-growing sport. According to the International Federation of Sport Climbing (IFSC), 35 million climbers were estimated worldwide in 2015, while in 2018, the number rose to 44.5 million (IFSC 2018). Numerous studies have reported a variety of injuries as a result of climbing activities (1, 2). Climbing places extreme loads mostly on the upper extremities, followed by the lower extremities and the rest of the body, which means that no anatomic location is spared from climbing-related injury (2). The most prevalent injuries occur to the upper extremities, with fingers, elbows, and shoulders representing 80% of chronic injuries in climbing (1). Specifically, a study on

667 active climbers noted that two of three climbers had chronic injury, and the most prevalent injury sites were fingers (41.3%), shoulder (19.4%), and elbow (17.7%) (3). Moreover, the most common acute injuries are a result of a fall involved lower extremity (4).

Interestingly, gender differences concerning the injury site and injury prevalence have been reported, with the most frequent injury sites for females being fingers, shoulder, and wrist, and for males fingers, elbow, and shoulder (3). Moreover, one study on 1962 climbers from different countries aged 32.82 ± 9.4 years reported that females had a higher incidence of injuries compared to males, which was explained by the anatomical differences between sexes, e.g., male athletes reported twice the incidence of hand ligament injuries (5). Also, level of climbing experience and the overall training frequency have been reported as general predictors of injury in sports (i.e., a higher years of training experience and training hours led to a higher incidence of injuries), and similar was reported in climbers (6). The age at which climbers begin to compete has decreased during the last 10 years, meaning that adolescents are engaged in structured training programs which place enormous stress on the skeleton that is still immature (7, 8). Also, adolescents are more prone to injury due to adolescent growth spurts, differences in maturity status, and non-linearity of growth (7). Interestingly, older age (more than 15 years of age) and previous injuries were reported as one of the main risk factors in climbing, which means that adolescents should be monitored over time to try to prevent more serious injuries (9).

Most climbing-related injuries are from chronic overuse (19%–33%), acute atraumatic (28%), and 10%–39% are acute traumatic as a result of falls (5, 10). Thus, previous studies focused mainly on acute and chronic injuries, while musculoskeletal complaints are poorly studied in climbers. Musculoskeletal complaints are important because they are often underdiagnosed but can cause significant pain and reduced function (11). Low back pain (LBP) is one of the most common complaints worldwide (12). Indeed, it is estimated that more than 80% of the population would report LBP at some point during a lifetime (13). This represents a frequent disability condition leading to being unable to work and representing a social and economic burden (14). One of the most advocated preventions of LBP is physical activity (15). However, it has been proven that LBP and physical activity have a U-shaped relationship, meaning that too little or too much activity could be harmful to the health condition of the spine (14). Thus, as athletes are partaking in strenuous and vigorous-intensity physical activity, they are considered extremely susceptible to developing chronic LBP (16). Indeed, 10%–15% of all sports-related complaints are low back injuries and complaints (17). Moreover, adolescents have a greater risk of developing spinal problems as their musculoskeletal system is not mature and they are still undergoing excessive height growth (18). It has been reported that LBP is a common problem among children and adolescents (70%–80% lifetime prevalence before 20 years of age), and one of the risk factors for LBP in this age group is sports participation (19, 20). LBP among youth athletes should be taken seriously as it is usually associated to structural injuries such as spondylolysis and injuries to the posterior parts of the spine (21). Thus, LBP should be monitored and treated especially among young athletes who are still in the developmental life phase.

The impact of competitive climbing on LBP is debated; there are studies showing potential benefits but repetitive falls, unphysiological postures and very high lumbar muscles activation could represent potential risk factors. Namely, since climbing includes repetitive falls (i.e., falls on the mat during bouldering or in the rope during sport climbing), the stress which those falls put on the spine could be seen as potentially harmful (8). Moreover, other potential mechanisms are the prolonged high activation of paraspinal muscles and quadratus lumborum, and unphysiological postures that could lead to disc rotation and compression (22, 23). Indeed, there is a well-known postural dysfunction called “climbers back” which describes a postural adaptation of increased thoracic kyphosis which places the climber’s body under unequally distributed forces on the musculoskeletal system (22). On the other side, a study on 30 patients aged 27.90 ± 6.08 years reported that climbing had a positive effect on LBP (24). However, this study involved a group of non-climbing people with LBP and a group of lower than amateur level participants. Previous research reported that only 5.3% of climbers had trunk pain which included LBP, making it less common than in the general (non-climbing) population (25, 26). However, as the climbing style changes due to the increased difficulty of the courses and a greater demand for spectacularism, the way of steep and three-dimensional wall architecture and dynamic moves (e.g., jumps that involve coordinated moves of feet and arms), injury patterns are changing correspondingly (8). Specifically, among 633 injuries within years 2017/18, there was a decrease in upper extremity injuries and increase of lower extremity injuries compared to studies observing periods of 1998–2001 and 2009–2012 (8).

Even though the most common injury sites in climbing are at the upper extremities, investigating other body parts in more detail is need, especially among younger populations, who are still in their growth and development phase (27). Thus, the main aim of this investigation was to determine the prevalence and severity (i.e., intensity and disability) of LBP in adolescent climbers. As sex, age, climbing volume, and years of experience are considered factors that influence higher susceptibility to injuries (6), the aim was also to investigate the influence of these factors on LBP in adolescent climbers.

Materials and methods

Study design

This study had a retrospective cross-sectional design, data were collected in sport clubs at the end of the competition season through online questionnaires. Participants completed the questionnaires independently and individually. The study rationale and informed consent formed the first pages of the package. Recruitment was carried out sending e-mail to sport clubs associated to the FASI (Italian Federation of Sport Climbing). Athletes were subsequently contacted via social networks or by telephone.

Study population

Participants were members of climbing sport clubs from 15 regions in Italy. A total of 180 adolescent competitive climbers (84 males and 96 females), aged 13–19 years, participated in the study. They were divided into two age categories, U-16 and U-20, according to the International Federation of Sport Climbing (IFSC) rules 2023 Ver. no. 1.1 (IFSC rules 2023, https://cdn.ifsc-climbing.org/images/Website/2023_IFSC_Rules_112.pdf, Accessed on 10.7.2023.).

Assessment tools

The questionnaire included three parts: (1) Demographic characteristics, training and competing background (questions related to the number of seasonal/daily competitions and training sessions); (2) the Nordic Musculoskeletal Questionnaire (NMQ), Italian version (28, 29) and (3) The Graded Chronic Pain Scale (GCPS), Italian version (30, 31).

The NMQ explores the prevalence of musculoskeletal complaints, restrictions while performing normal activities and the need for medical attention during the last twelve months and the last seven days, respectively. In addition, this questionnaire contains an illustration of a body map showing the location of the pain area.

The GCPS is composed of questions related to pain intensity and disability, to assess the severity of LBP during the last 6 months prior to completing the questionnaire. It is compiled of seven questions as answers were provided on a scale from 0 (e.g., "no pain" or "no interference/change") to 10 (e.g., "pain as bad it could be" or "unable to carry on any activity/extreme change"). Pain intensity and disability scores were calculated, and 5 grades of severity were assigned. Grade 0 (pain-free); Grade I (low disability-low intensity); Grade II (low disability-high intensity); Grade III (high disability-moderately limiting); Grade IV (high disability-severely limiting).

Statistical analysis

Demographic characteristics and training/competition related parameters were presented as number of cases and percentages. The GCPS scores were expressed as mean ± SD. The measures were presented for the total sample and for the subgroups divided by sex and age category (U16 and U20). To assess the potential sex and age category differences as percentages, the Pearson's Chi Square tests were used. An independent sample *t*-test was used to assess the sex and age category differences. For the relationships between the GCPS scores, Spearman's correlational analysis was conducted. Statistical Package for the Social Sciences—IBM SPSS Statistics for Windows, V.28.0 (IBM) was used for all the analysis performed with the statistical significance level set at $p < 0.05$.

TABLE 1 Participants' characteristics.

Variable	Total (n = 180)	Male (n = 84)	Female (n = 96)
Age	15.79 ± 2.08	16.35 ± 1.90	15.31 ± 2.11
Height (cm)	164.56 ± 9.82	170.14 ± 9.01	159.68 ± 7.69
Weight (kg)	53.22 ± 9.95	58.15 ± 9.77	48.91 ± 7.93
Body mass index (kg/m^2)	19.49 ± 2.06	19.95 ± 1.95	19.08 ± 2.07
Years of practice	5.64 ± 3.07	5.62 ± 3.16	5.66 ± 3.01
Seasonal competitions	7.94 ± 4.91	7.69 ± 4.81	8.16 ± 5.00
Weekly hours of training	8.20 ± 3.98	8.95 ± 4.23	7.54 ± 3.63
Number of training sessions per week	3.22 ± 0.96	3.37 ± 0.98	3.09 ± 0.93

Results

Participants' characteristics including demographic and anthropometric characteristics and sports variables are summarized by sex in **Table 1**.

The NMQ-related results are showed in **Table 2**. A total of 74.4% of the entire sample of participants reported lower back complaints throughout the past twelve months and only 15.5% during the last seven days. Furthermore, 22.2% of the participants reported that they have been restricted in normal everyday activities within the last 12 months, and 19.4% noted that their lower back complaints needed medical attention throughout the past twelve months. No significant differences were observed between males and females in terms of each NMQ measure.

Climbers competing in U16 category reported significantly higher prevalence of lower back complaints during the last 12 months compared to U20 age group (83.9% and 65.6%, respectively, $p = 0.008$). However, competitors U20 demonstrated higher percentage of lower back complaints within the last seven days in relation to U16 age category climbers (21.5% and 9.2%, respectively, $p = 0.038$). Additionally, athletes competing in the older age category demonstrated greater incidence of restrictions in normal activities throughout the last twelve months than their younger counterparts (25.8% and 12.6%, $p = 0.041$). Similarly, U20 climbers reported higher need for medical attention during the last 12 months than athletes competing in U16 category (30.1% and 13.8%, $p = 0.014$).

TABLE 2 Overview of the nordic musculoskeletal questionnaire (NMQ)-based results and differences between sexes and age groups.

NMQ measure	Overall $n = 180$	Male $n = 84$	Female $n = 96$	X^2 (df). p	U16 $n = 87$	U20 $n = 93$	X^2 (df). p
Lower back complaints during the last 12 months	134 (74.4%)	63 (75%)	71 (74%)	n.s.	73 (83.9%)	61 (65.6%)	6.99 (1). 0.008
Lower back complaints during the last 7 days	28 (15.5%)	14 (16.7%)	14 (14.6%)	n.s.	8 (9.2%)	20 (21.5%)	4.29 (1). 0.038
Restricted in normal activities during the last 12 months	40 (22.2%)	16 (19%)	24 (25%)	n.s.	11 (12.6%)	24 (25.8%)	4.17 (1). 0.041
Required medical attention during the last 12 months	35 (19.4%)	16 (19%)	19 (19.8%)	n.s.	12 (13.8%)	28 (30.1%)	6.01 (1). 0.014

All NMQ-related measures are expressed as absolute numbers and the percentage proportion on the overall group/subgroups (number of affected climbers/number of climbers per group × 100). Levels of significance for sex are based on Pearson chi-square tests. n.s.: not significant at $p < 0.05$; U-16: under 16 years; U-20: under 20 years.

TABLE 3 Overview of the graded chronic pain scale (GCPS) scores and differences between sexes and categories.

GCPS score	Overall $n = 180$	Male $n = 84$	Female $n = 96$	z (df). p	U16 $n = 87$	U20 $n = 93$	X^2 (df). p
Pain intensity	19.6 ± 18.5	17.5 ± 15.3	21.9 ± 20.9	n.s.	18.0 ± 18.3	21.6 ± 18.7	n.s.
Disability score	7.5 ± 13.4	6.4 ± 14.0	8.4 ± 12.9	n.s.	6.3 ± 10.7	8.6 ± 15.5	n.s.
GCPS classification							
Grade 0 pain free	48 (26.7%)	19 (22.6%)	29 (30.2%)	n.s.	29 (33.3%)	19 (20.4%)	n.s.
Grade I Low intensity-low disability	113 (62.8%)	61 (72.6%)	52 (54.2%)	n.s.	52 (59.8%)	64 (68.8%)	n.s.
Grade II High intensity-low disability	13 (6.1%)	1 (1.2%)	12 (10.4%)	9.31 (1). 0.002	5 (5.75%)	8 (8.6%)	n.s.
Grade III High disability-moderately limiting	2 (2.8%)	1 (1.2%)	1 (4.2%)	n.s.	1 (1.15%)	1 (1.1%)	n.s.
Grade IV High disability-severely limiting	1 (0.6%)	1 (1.2%)	0 (0%)	—	0 (0%)	1 (1.1%)	—

GCPS scores are expressed as mean ± SD. GCPS classifications are expressed as absolute numbers and the percentage proportion of the overall group/subgroups (number of affected climbers/number of climbers per group×100). Levels of significance for sex and category differences are based on Mann-Whitney tests and Pearson chi-square tests, respectively.
n.s.: not significant at $p < 0.05$; U-16: under 16 years; U-20: under 20 years.

The results related to GCPS are showed in **Table 3**. There were no significant differences between the two age category groups (U16 and U20) in terms of GCPS scores and grades. However, female athletes reported higher Grade II (high intensity-low disability) percentage compared to males (10.4% and 1.2%, respectively, $p = 0.002$).

No significant correlation was observed between GCPS and sport practice-related questions (years of practice, seasonal competitions, weekly hours of training, training sessions per week), neither in the case of stratification of training attributes nor in stratification by gender.

Discussion

This study aimed to determine the prevalence and severity of LBP with respect to sex and age category. We found a relatively high prevalence of LBP in young climbers, mainly classified as low-intensity or pain-free. Climbers did not differ in LBP prevalence according to sex. Concerning age groups, younger climbers reported significantly higher prevalence of lower back complaints during the last 12 months, while older climbers demonstrated higher percentage of lower back complaints within the last seven days, greater incidence of restrictions in normal activities throughout the last twelve months, and higher need for medical attention during the last 12 months. The relationship between lower back complaints severity and training attributes was not significant for the total sample nor sex- or age-stratified.

The prevalence of low back pain in adolescent climbers

We observed a relatively high prevalence of LBP during the last 12 months in Italian young climbers. However, concerning the GCPS classification, most of the LBP was classified as pain-free and low intensity, and low disability, which means that LBP was not that severe and intense to affect climbers' regular competing and training sessions.

We observed low LBP severity, suggesting low adverse back loading, which is in agreement with the relatively low percentage of spine injuries reported in the literature. Specifically, several studies investigated climbing-related chronic injuries by observing the whole body, which includes low back and LBP complaints. Specifically, a study on 667 climbers aged 26–40 years recorded that 385 climbers had chronic injuries, from which only 11 climbers (2.9%) had LBP (3). Similarly, a study on 836 climbers aged 34.1 ± 11.1 years noted that only 11 cases (1.2%) of LBP have been reported, out of 911 total injuries (32). In a relatively recent comprehensive review of climbing injuries, it was reported that injuries of the spine account for 1.9%–7.1% of all climbing injuries (2). The study which focused on investigating LBP in climbers aged 29 ± 7 years found that 26% of included climbers reported mild LBP (33). It must be emphasized that the previously mentioned study used the Oswestry Low Back Pain Disability Index (which demonstrated good validity and reliability) categorizing LBP intensity into mild, moderate, and severe, which means that the reported LBP led to light or no restrictions at all (34).

Noteworthy, the prevalence and severity of LBP in other sports is significantly higher than in climbers. Precisely, in a study on 1,114 elite German athletes aged 20.9 ± 4.8 years, the lifetime prevalence of LBP was 89%, prevalence during the last 12 months was 81%, and prevalence during the last 3 months was 68% (16). It has to be noted that the prevalence of LBP differed according to sports disciplines, with athletes involved in waterpolo (100%), fencing (100%), rowing (96.4%), gymnastics (93.8%), and dance (95.5%) having the highest rates of LBP (16, 17). Also, a study on athletes involved in repetitive overhead activities (i.e., volleyball, handball, tennis) reported that the lifetime prevalence of LBP was 85%, and the prevalence during one year was 75% (35). On the other side, the prevalence of LBP during one year was reported to be lower (50%–65%) in different sports among elite athletes, for instance in cross-country skiers and rowers (36, 37).

Considering youth athletes, LBP is also a common complaint as 10%–15% of youth athletes report LBP, but this percentage varies according to sports (e.g., 27% of college football, and 86% of rhythmic gymnasts) (21). Adolescent athletes involved in sports that have repetitive extension, flexion, and rotation of the spine (e.g., gymnastics, soccer, dance) are the most susceptible to injuries in the lower back (17). Furthermore, a study on adolescent alpine skiers aged 15–18 years, that used a similar methodology as our study, reported that 80.3% of skiers suffered LBP during the last 12 months, and 50.7% during the last 7 days, which is a higher prevalence than in our study (38). Moreover, LBP among young alpine skiers was in 21.8% of cases classified as high intensity/low disability, which is of significantly higher prevalence than in our study (6%). Also, the characteristic pain intensity was higher in alpine skiers compared to climbers (37.53 ± 18.00 and 19.60 ± 18.50, respectively), so was the disability score (13.27 ± 14.59 and 7.50 ± 13.40) (36).

Therefore, we could speculate that young climbers display lower LBP complaints compared to athletes participating in other sports, as climbing might facilitate the improvement in motor control and coordination (39), and the strength development without a functional overload. Due to these factors, climbing might be beneficial for preventing and treating LBP. Previous studies focused on investigating the positive effects of climbing (i.e., therapeutic climbing) on LBP, but mostly in non-athletic population (39). Indeed, the impact of climbing on patients with LBP has been evaluated on patients divided into climbing groups, who practiced climbing exercises for 8 weeks, and the control group, who did not practice climbing (24). Patients in the climbing group displayed a reduction in the size of disc protrusion and a reduction in overall back pain compared to the control group (24). Authors of that study theorized that climbing offers closed-chain muscle exercise which improves muscle control and posture, resulting in less pain (24). However, studies that investigated the effects of therapeutic climbing on back pain included a non-climbing population and activity was at low intensity. Thus, prospective studies on competitive climbers are needed to prove the hypothesis of the beneficial effects of climbing on LBP.

Sex differences in the prevalence of low back pain and the relationship between lower back complaints severity and training attributes

The results of our study did not show sex differences in the prevalence of LBP. Also, there were no sex-specific associations between LBP and training attributes. Previous studies reported controversial results regarding the relationship between LBP and sex in athletes (16). Some studies reported that females are more likely to report LBP (40, 41), while other studies found higher rates of LBP for males (42, 43). Sex differences in LBP and other musculoskeletal injuries in athletes are influenced by numerous factors. Specifically, males might be exposed to higher loads in some sports disciplines because they have higher training volume and higher loads during strength training, or they might have different rules (e.g., game duration) (16). Also, females have a menstrual cycle that sometimes prevents them from partaking in training sessions and reduces overall training volume (44). Additionally, a study on adolescents aged 11–19 years with chronic pain conditions noted differences in pain tolerance between sexes (i.e., females reported lower pain threshold than males) and pain-coping strategies (i.e., females used more social support while males engaged in behavioural distraction) (45).

Overall, our results showed no sex differences in LBP severity and no associations with training attributes which could be explained by the specificity of sport. A recent study on a similar cohort of young climbers investigated gender differences in generic- (countermovement and squat jump, grip strength) and specific-fitness test (power slap test and Draga foot lift) of youth climbers and found no differences in climbing-specific-fitness profiles comparing males and females, while there were sex differences in the generic-fitness profile (46). Authors suggested that climbing requires specific abilities similar in males and females, which could be the reason why we did not detect differences in LBP between sexes (46). This theory could be further confirmed by a review study that investigated injury risk factors in climbers which reported that six studies found no differences in injury risk between males and females, accounting for whole-body injuries (6). Thus, we could hypothesize that, due to the specificity of climbing and similar loads, males and females do not differ in the prevalence and intensity of LBP.

Age differences in the prevalence of low back pain and the relationship between lower back complaints severity and training attributes

Our results showed age differences in NMQ low back complaints among youth competitive climbers, with older climbers reporting a higher incidence of LBP during the last 7 days and a greater occurrence of seeking medical attention than younger climbers. Similar to the results of our study, a study on Canadian youth climbers aged 11–19 years reported that adolescent climbers (15–19 years) have 11.3 times greater risk of injuries compared to younger climbers aged 11–14 years (9). Moreover, a study on a large sample of young athletes involved in combat sports, game sports, explosive strength sports, and endurance sports found that younger athletes (11–13 years) had 2%–4% of LBP while the prevalence increased to 12%–20% in older athletes (14–17 years) (47). Thus, from the results of the NMQ, it could be concluded that older climbers are more predisposed to experience LBP. What is somewhat surprising and confusing is the result that younger climbers reported a higher incidence of LBP during the last 12 months. We could speculate that younger climbers were less accurate in reporting results regarding the 12-month recall period.

Our results noted that climbers did not differ in LBP severity according to age groups and there were no LBP associations with training attributes. These results could be explained in light of similar performance levels in different age groups (48). In our study, younger (U16) climbers had only one year of training experience less than older (U20) climbers (5.05 years and 6.19 years of climbing practice, respectively). Thus, the small difference in the years involved in climbing practice and exposure to training-induced musculoskeletal stress could be the reason for not recording differences in LBP severity between younger and older adolescents.

Limitations and strengths

The main limitation of the study is its cross-sectional design, unable to determine causality. Moreover, the limitation is that injuries were self-reported and retrospective, which could potentially lead to recall bias. We were also unable to categorize the incidence of LBP according to a specific climbing discipline, this is due to the fact that climbers in our study competed in all the three disciplines, as required by the rules of the climbing federation for the U16 and U20 age categories. An additional limitation is that it was not possible to determine the climbing level expressed through the highest climbed grade (both sport climbing routes and boulders). This is due to youth climbers not frequently (or at all) climbing outdoors where there are graded climbing routes or boulders, as they most commonly practice indoors.

The main strength of the study is related to the novelty of the information collected. To date, we still know little about the prevalence of LBP in young climbers; investigating musculoskeletal complaints in adolescent athletes could lead to detecting injury risks, so that appropriate preventive actions and effective treatment programs can be planned.

Practical implications

Young climbers in this study reported lower LBP complaints compared to young athletes participating in other sports, this could be due to a combination of specific factors, such as motor control and coordination and muscle strength improvement. It might therefore appear that climbing might be beneficial for preventing and treating LBP. Whether this can be true for recreational climbing, on the other hand it is important to consider that the style of climbing competitions has been changed profoundly in recent years into more dynamic and physically demanding. This trend might lead into increased prevalence and severity of musculoskeletal conditions, and within these of LBP, in athletes. Therefore, the results of this study can be used to disseminate the message that it is important to adopt preventive strategies for LBP, which should be regularly implemented into training routine. Also, prospective evaluation of LBP should be applied in future research and coaching practice with the aim of monitoring LBP and preventing more serious complaints and injuries.

Conclusion

The results of this study showed that there was a relatively high prevalence of LBP in young climbers, but it was mainly classified as low-intensity or pain-free. Furthermore, climbers did not differ in LBP prevalence according to sex and a significant but small difference in age groups was recorded. According to the results, it could be theorized that climbing, including competitive climbing, may not be particularly harmful to the lower back. However, the results should be interpreted with caution and no strict conclusions can be drawn due to the cross-sectional nature of the study. Also, considering that the climbing style is changing rapidly to more dynamic movement patterns, especially among competitive climbers, LBP could be expected to become more common than before. Thus, future studies should prospectively monitor the influence of climbing on LBP in youth climbers. This way, coaches would be able to identify risk factors for LBP occurrence and prevent this common health problem.

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 humans were approved by Ethics Committee of the Department of Biomedical Sciences of the University of Padua (HEC-DSB/02-19). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

AC: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. BG: Writing – original draft, Writing – review & editing. RB: Conceptualization, Data curation, Investigation, Writing – original draft. AA: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. FS: Data curation, Investigation, Writing – original draft. RR: Formal analysis, Writing – original draft, Writing – review & editing. DS: Conceptualization, Methodology, Writing – original draft.

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References

1. Grønhaug G, Norberg M. First overview on chronic injuries in sport climbing: proposal for a change in reporting of injuries in climbing. *BMJ Open Sport Exerc Med*. (2016) 2:e000083. doi: 10.1136/bmjsem-2015-000083

2. Cole KP, Uhl RL, Rosenbaum AJ. Comprehensive review of rock climbing injuries. *J Am Acad Orthop Surg*. (2020) 28:501–9. doi: 10.5435/JAAOS-D-19-00575

3. Grønhaug G. Self-reported chronic injuries in climbing: who gets injured when? *BMJ Open Sport Exerc Med*. (2018) 4:e000406. doi: 10.1136/bmjsem-2018-000406

4. Schöffl V, Küpper T. Feet injuries in rock climbers. *World J Orthop*. (2013) 4:218–28. doi: 10.5312/wjo.v4.i4.218

5. Neuhof A, Hennig FF, Schöffl I, Schöffl V. Injury risk evaluation in sport climbing. *Int J Sports Med*. (2011) 32:794–800. doi: 10.1055/s-0031-1279723

6. Woollings KY, McKay CD, Emery CA. Risk factors for injury in sport climbing and bouldering: a systematic review of the literature. *Br J Sports Med*. (2015) 49:1094–9. doi: 10.1136/bjsports-2014-094372

7. Schöffl V, Lutter C, Woollings K, Schöffl I. Pediatric and adolescent injury in rock climbing. *Res Sports Med*. (2018) 26(sup1):91–113. doi: 10.1080/15438627.2018.1438278

8. Lutter C, Tischer T, Hotfiel T, Frank L, Enz A, Simon M, et al. Current trends in sport climbing injuries after the inclusion into the olympic program. Analysis of 633 injuries within the years 2017/18. *Muscles Ligaments Tendons J*. (2020) 10(2):201–10. doi: 10.32098/mltj.02.2020.06

9. Woollings KY, McKay CD, Kang J, Meeuwisse WH, Emery CA. Incidence, mechanism and risk factors for injury in youth rock climbers. *Br J Sports Med*. (2015) 49:44–50. doi: 10.1136/bjsports-2014-094067

10. Jones G, Asghar A, Llewellyn DJ. The epidemiology of rock-climbing injuries. *Br J Sports Med*. (2008) 42:773–8. doi: 10.1136/bjsm.2007.037978

11. Bahr R. No injuries, but plenty of pain? On the methodology for recording overuse symptoms in sports. *Br J Sports Med*. (2009) 43:966–72. doi: 10.1136/bjsm.2009.066936

12. Wu A, March L, Zheng X, Huang J, Wang X, Zhao J, et al. Global low back pain prevalence and years lived with disability from 1990 to 2017: estimates from the global burden of disease study 2017. *Ann Transl Med*. (2020) 8(6):299. doi: 10.21037/atm.2020.02.175

13. Jones GT, Macfarlane GJ. Epidemiology of low back pain in children and adolescents. *Arch Dis Child*. (2005) 90:312–6. doi: 10.1136/adc.2004.056812

14. Heneweer H, Vanhees L, Picavet SJH. Physical activity and low back pain: a U-shaped relation? *Pain*. (2009) 143:21–5. doi: 10.1016/j.pain.2008.12.033

15. Auvinen J, Tammelin T, Taimela S, Zitting P, Karppinen J. Associations of physical activity and inactivity with low back pain in adolescents. *Scand J Med Sci Sports*. (2008) 18:188–94. doi: 10.1111/j.1600-0838.2007.00672.x

16. Fett D, Trompeter K, Platen P. Back pain in elite sports: a cross-sectional study on 1114 athletes. *PLoS One*. (2017) 12:e0180130. doi: 10.1371/journal.pone.0180130

17. Mortazavi J, Zebardast J, Mirzashahi B. Low back pain in athletes. *Asian J Sports Med*. (2015) 6:e24718. doi: 10.5812/asjsm.6(2)2015.24718

18. Kim HJ, Green DW. Adolescent back pain. *Curr Opin Pediatr*. (2008) 20:37–45. doi: 10.1097/MOP.0b013e3282f357fe

19. Kordi R, Rostami M. Low back pain in children and adolescents: an algorithmic clinical approach. *Iran J Pediatr*. (2011) 21:259–70.

20. Wall J, Meehan WP 3rd, Trompeter K, Gissane C, Mockler D, van Dyk N, et al. Incidence, prevalence and risk factors for low back pain in adolescent athletes: a systematic review and meta-analysis. *Br J Sports Med*. (2022) 56:1299–306. doi: 10.1136/bjsports-2021-104749

21. Purcell L, Micheli L. Low back pain in young athletes. *Sports Health*. (2009) 1:212–22. doi: 10.1177/1941738109334212

22. Förster R, Penka G, Bösl T, Schöffl VR. Climber's back–form and mobility of the thoracolumbar spine leading to postural adaptations in male high ability rock climbers. *Int J Sports Med*. (2009) 30:53–9. doi: 10.1055/s-2008-1038762

23. Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. *Spine*. (1996) 21:2640–50. doi: 10.1097/00007632-199611150-00014

24. Schinhan M, Neubauer B, Pieber K, Gruber M, Kainberger F, Castellucci C, et al. Climbing has a positive impact on low back pain: a prospective randomized controlled trial. *Clin J Sport Med*. (2016) 26:199–205. doi: 10.1097/JSM.0000000000000238

25. Pieber K, Angelmaier L, Csapo R, Herceg M. Acute injuries and overuse syndromes in sport climbing and bouldering in Austria: a descriptive epidemiological study. *Wien Klin Wochenschr*. (2012) 124:357–62. doi: 10.1007/s00508-012-0174-5

26. Chen S, Chen M, Wu X, Lin S, Tao C, Cao H, et al. Global, regional and national burden of low back pain 1990–2019: a systematic analysis of the global burden of disease study 2019. *J Orthop Transl*. (2022) 32:49–58. doi: 10.1016/j.jot.2021.07.005

27. Giustino V, Messina G, Patti A, Padua E, Zangla D, Drid P, et al. Effects of a postural exercise program on vertical jump height in young female volleyball players with knee Valgus. *Int J Environ Res Public Health*. (2022) 19(7):3953. doi: 10.3390/ijerph19073953

28. Kuorinka I, Jonsson B, Kilbom A, Vinterberg H, Biering-Sørensen F, Andersson G, et al. Standardised nordic questionnaires for the analysis of musculoskeletal symptoms. *Appl Ergon*. (1987) 18:233–7. doi: 10.1016/0003-6870(87)90010-X

29. Ghersi R, Martinelli S, Richeldi A, Clerici P, Grazioli P, Gobba FM. The Italian version of nordic musculoskeletal standardized questionnaire. *G Ital Med Lav*. (2007) 29:564–6.

30. Von Korff M, Ormel J, Keefe FJ, Dworkin SF. Grading the severity of chronic pain. *Pain*. (1992) 50:133–49. doi: 10.1016/0304-3959(92)90154-4

31. Salaffi F, Stancati A, Grassi W. Reliability and validity of the Italian version of the chronic pain grade questionnaire in patients with musculoskeletal disorders. *Clin Rheumatol*. (2006) 25:619–31. doi: 10.1007/s10067-005-0140-y

32. Schöffl V, Popp D, Küpper T, Schöffl I. Injury trends in rock climbers: evaluation of a case series of 911 injuries between 2009 and 2012. *Wilderness Environ Med*. (2015) 26:62–7. doi: 10.1016/j.wem.2014.08.013

33. Zieliński G, Zięba E, Wilkowicz W, Byś A, Ginszt M, Libera O, et al. Influence of regular climbing on depression, generalized anxiety and lower back pain. *AAEM*. (2021) 28:463–8. doi: 10.26444/aaem/124189

34. Monticone M, Baiardi P, Ferrari S, Foti C, Mugnai R, Pillastrini P, et al. Development of the Italian version of the oswestry disability index (ODI-I): a cross-cultural adaptation, reliability, and validity study. *Spine (Phila Pa 1976)*. (2009) 34 (19):2090–5. doi: 10.1097/BRS.0b013e3181aa1e6b

35. Fett D, Trompeter K, Platen P. Prevalence of back pain in a group of elite athletes exposed to repetitive overhead activity. *PLoS One*. (2019) 14:e0210429. doi: 10.1371/journal.pone.0210429

36. Bahr R, Andersen SO, Løken S, Fossan B, Hansen T, Holme I. Low back pain among endurance athletes with and without specific back loading—a cross-sectional survey of cross-country skiers, rowers, orienteerers, and nonathletic controls. *Spine*. (2004) 29:449–54. doi: 10.1097/01.BRS.0000096176.92881.37

37. Schulz SS, Lenz K, Büttner-Janz K. Severe back pain in elite athletes: a cross-sectional study on 929 top athletes of Germany. *Eur Spine J*. (2016) 25:1204–10. doi: 10.1007/s00586-015-4210-9

38. Carraro A, Gnech M, Sarto F, Sarto D, Spörri J, Masiero S. Lower back complaints in adolescent competitive alpine skiers: a cross-sectional study. *Appl Sci*. (2020) 10:7408. doi: 10.3390/app10217408

39. Liu S, Gong X, Li H, Li Y. The origin, application and mechanism of therapeutic climbing: a narrative review. *IJERPH*. (2022) 19:9696. doi: 10.3390/ijerph19159696

40. Shehab DK, Al-Jarallah KF. Nonspecific low-back pain in Kuwaiti children and adolescents: associated factors. *J Adolesc Health*. (2005) 36:32–5. doi: 10.1016/j.jadohealth.2003.12.011

41. Sato T, Ito T, Hirano T, Morita O, Kikuchi R, Endo N, et al. Low back pain in childhood and adolescence: assessment of sports activities. *Eur Spine J*. (2011) 20:94–9. doi: 10.1007/s00586-010-1485-8

42. Dubravcic-Simunjak S, Pecina M, Kuipers H, Moran J, Haspl M. The incidence of injuries in elite junior figure skaters. *Am J Sports Med*. (2003) 31:511–7. doi: 10.1177/03635465030310040601

43. Ng L, Perich D, Burnett A, Campbell A, O'Sullivan P. Self-reported prevalence, pain intensity and risk factors of low back pain in adolescent rowers. *JSAMS*. (2014) 17:266–70. doi: 10.1016/j.jsams.2013.08.003

44. Findlay RJ, Macrae EHR, Whyte IY, Easton C, Forrest Née Whyte LJ. How the menstrual cycle and menstruation affect sporting performance: experiences and perceptions of elite female rugby players. *Br J Sports Med*. (2020) 54:1108–13. doi: 10.1136/bjsports-2019-101486

45. Keogh E, Eccleston C. Sex differences in adolescent chronic pain and pain-related coping. *Pain*. (2006) 123:275–84. doi: 10.1016/j.pain.2006.03.004

46. Vrdoljak D, Gilic B, Kontić D. Fitness profiling in top-level youth sport climbing; gender differences. *Sport Mont*. (2022) 20:111–6. doi: 10.26773/smj.220617

47. Müller J, Müller S, Stoll J, Fröhlich K, Otto C, Mayer F. Back pain prevalence in adolescent athletes. *Scand J Med Sci Sports*. (2017) 27:448–54. doi: 10.1111/sms.12664

48. Gilic B, Vrdoljak D. Sport-specific performances in elite youth sport climbers; gender, age, and maturity specifics. *Biomed Hum Kinet*. (2023) 15:49–56. doi: 10.2478/bhk-2023-0007

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Nutrition knowledge, weight loss practices, and supplement use in senior competition climbers

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Introduction: Sport climbing has gained increased scientific attention, including studies investigating the dietary habits and nutritional requirements of climbers; however, significant gaps in the literature remain. An assessment of nutritional knowledge, weight loss for competition, and supplement use has not been previously reported in senior competition climbing athletes.

Methods: Fifty climbers (26 male, 24 female; BMI 21.6 ± 1.9; 23.7 ± 5.2 years) participated in the study. Participants answered a 72-item questionnaire, comprised of demographic data and three main sections to assess general and sports nutrition knowledge, weight loss strategies, and supplement use.

Results: The mean nutrition knowledge score was 'average', with considerable individual variation (53.5 ± 11.1 %). There were no significant sex differences in the general (GNK) or sport (SNK) nutrition knowledge scores, or effect of age. Significantly higher knowledge was demonstrated by national vs. international athletes for the GNK scores (11.09 ± 1.58 vs. 9.58 ± 1.75; p = 0.028). Participants scored well in questions concerning protein, carbohydrates, alcohol, and supplements, and conversely, performed poorly in hydration and micronutrient related questions. Less than one-fifth of respondents had access to a dietitian. Forty-six percent of males and 38% of female climbers reported intentional weight loss for competition on at least one occasion. Of those, ~76% reported utilizing concerning practices, including methods that conform with disordered eating and/or eating disorders, dehydration, vomiting, and misuse of laxatives. Approximately 65% of athletes reported using at least one nutritional supplement in the previous 6 months, with 44% reporting multiple supplement use. There was no significant difference in supplement use between sexes or competition level.

Discussion: Due to the established importance of nutritional intake on athlete health and performance, educational support should be employed to improve knowledge in climbers and address shortcomings. Moreover, intentional weight loss for climbing competition is common, with most athletes achieving ~3–8% body weight loss over ≥2 weeks. It is crucial that professionals working with competitive climbers are vigilant in identifying athletes at risk of concerning weight management and establish referral pathways to the appropriate specialist services. High quality intervention trials to assess the efficacy of ergogenic aids in climbing remains inadequate.

KEYWORDS

climbing, nutrition, bouldering, sport climbing, weight loss, competition, supplements

1 Introduction

Climbing as a competitive sport resembling the modern format started in 1985 in Bardonecchia, Italy, and the first competition event on an artificial climbing wall was held the following year (1). Encompassing climbing disciplines of lead, bouldering, and speed, sport climbing has grown to immense popularity since, with over 25 million climbers in around 150 countries worldwide (1). Sport climbing made its debut at the Olympic Games at Tokyo 2020 following previously successful inclusion at the youth games and has been selected to be one of the four new sports of Paris 2024, alongside breaking, surfing, and skateboarding (1).

The most recognized climbing competitions are governed by the International Federation of Sport Climbing (IFSC) and divided into 3 sub-disciplines of indoor climbing; speed, bouldering, and lead. The 2020 Olympic Games event was the first to require senior athletes to compete in all three sub-disciplines, with one overall winner chosen from each sex, however, this has been modified for the Paris 2024 programme, where speed climbing has been allocated an individual medal and will take place as a separate event (1).

Lead climbing takes place on artificial walls which must permit a route of at least 15 m in length and 3 m in width. Climbers must carry their rope as they ascend, clipping into carabiners placed at fixed protection points in the route. Scoring is determined by the furthest hold used in a controlled manner, effectively representing how high up the route the athlete gets before they fail. Attempts in which multiple athletes complete the route or reach the same hold are differentiated using the time taken to complete their attempt. In IFSC competitions, qualification requires athletes to climb on two non-identical routes separated by at least 50 min rest. In scenarios where more than one round takes place in a day, these must be separated by at least 2 h. Lead climbing attempts are notably longer than in other disciplines, lasting from 2 to 7 min with a larger proportion (~38%) spent in static positions (2). To date, few studies have investigated the energy cost and profile of lead climbing, however, the contributions of the aerobic, anaerobic lactic, and anaerobic alactic systems during difficult climbing have been reported as 41.9, 22.3, and 35.8%, respectively (3).

Bouldering is performed without the use of ropes on lower walls with crash mats used for protection. Routes must be designed so that the lower body of the climber should not exceed 3 m above the protection. Athletes are allowed multiple attempts at a route or "problem" within a 5-min period. IFSC competitions require athletes to attempt 5 routes in the qualification round, followed by 4 routes in the semi-final and final rounds. Scoring is determined by the number of problems an athlete completes in each round, alongside the number of attempts made. Athletes typically attempt a problem 3 times, with attempts lasting ~30–40 s, and ~115 s of recovery in between attempt (4). Ascents generally feature low static periods (~25%) and an exercise-to-recovery ratio in the forearm flexors of ~13:1 (4). This could be due to the steeper routes typically used in bouldering combined with the precarious nature of the hand and foot holds which enhance the difficulty of routes, allowing fewer opportunities find stable positions to reduce force through the upper limbs. As the energy release from PCr hydrolysis is significantly reduced after ~10 s of high-intensity exercise (5), it could be assumed that bouldering athletes will rely on larger contributions of the lactate energy systems for the provision of energy; indeed, La Torre et al. (6) reported mean blood lactate levels following national competitions of 6.2–6.9 mmol·L^{-1}.

Speed climbing requires a pair of athletes to race side-by-side to the top of two identical routes set on a 15 m artificial wall. Competitors will make one attempt in each lane separated by a minimum of 5 min, with the winner decided by the lowest aggregate time over the two runs. Since 2007, the IFSC have used a standardized wall and hold configuration for all competitions and world record attempts. IFSC certified speed climbing walls are slightly overhanging (not more than 5 degrees) and feature a route with a difficulty which would be achievable by most recreational climbers. The timing of attempts begins after a countdown of beeps, and the clock is stopped by the athlete striking a mechanical–electrical pad at the top of the route. Athletes are protected from falls using a rope attached at the top of the wall to an auto-belay system. Speed climbing events feature an all-out sprint of powerful and dynamic moves, with elite efforts typically lasting 5–6 s in duration, emplacing the anaerobic demand (7).

Based on the significant discrepancies in the physiological demands of each discipline, it is reasonable to assume a variance in the nutritional requirements and practices of the athletes who specialize in each event (8, 9). In line with growing public interest and participation, sport climbing has gained increased scientific attention, including studies investigating the dietary habits and nutritional requirements of climbers (8, 10–12). Nevertheless, significant gaps in the literature remain, and little is known regarding the existing nutritional knowledge, strategies of weight loss, or supplement use in competition climbers, warranting further research.

The positive influence of an individualized dietary intake on sports performance and recovery is well established and evidenced by the publication of internationally recognized expert consensus statements outlining guidelines for the optimal intake and timing of food, fluid, and supplements (13–15). Despite this, research shows that many athletes, including climbers, have sub-optimal dietary intakes (8, 10, 16); time constraints, financial considerations, limited cooking skills, and access to cooking facilities have been proposed as potential barriers to achieving optimal dietary intakes in athletes (17). Furthermore, cultural background, taste preferences, appetite, attitude toward nutrition, nutrition knowledge, and access to professional support have been highlighted in a review of factors influencing athletes' food choices (18).

A 2011 systematic review of the nutrition knowledge of recreational and elite athletes, reported a positive correlation between general and sport specific nutrition knowledge, and good quality dietary intake (19). Although this relationship appears to be weak to moderate (16, 19), nutrition knowledge is regarded as one of the few modifiable determinants of dietary behaviors (20). Thus, educational interventions centered on addressing gaps in athlete knowledge and adherence to expert guidelines remains a common approach in the support of sports dietitians (18).

Weight loss methods have been anecdotally practiced by climbers for decades, with athletes generally believing that by reducing their body mass they can improve their strength to weight ratio, reduce load on the extremities, and subsequently improve performance. However, there is a lack of published research to support this notion, with most studies finding little impact of body weight on performance among high-level athletes (21, 22). Although research regarding weight loss practices of climbers is scarce, early indications suggest that climbers face similar challenges to athletes in other weight-sensitive sports, which include increased risk of iron deficiency, chronic energy deficiency, and disordered eating (10, 23).

Dietary supplements are used at all levels of sports performance and a prevalence of 40–100% has been reported in athletes depending on the sport, level of competition, method of data collection, and definition of supplements used (24). Gibson-Smith et al. (10) investigated the prevalence of supplement use in climbers, finding that 45% of athletes took supplements, with protein powder, vitamin tablets, and fish oil capsules being the most prevalent, similar to the findings of Sas-Nowosielski and Judyta (25). Peoples et al. (26) found that protein, caffeine, and energy bars were the most commonly used supplements among climbers, with elite climbers being more likely than their intermediate counterparts to use protein and caffeine supplements.

There have been numerous supplement intervention trials in climbers over the last decade to quantify the effect of caffeine, creatine, beta-alanine, and other supplements on climbing performance. However, there is a lack of consistency in methods of measuring climbing "performance", with the vast majority of studies relying on methods with unproven reliability or lacking ecological validity. More specifically, methods of forearm muscle oxygenation (27), campus board exercises (28), arm-crank Wingate tests (29), pull-up repetitions and/or velocity (30), hand grip strength (31), and time to climb boulders and sport routes (32) have all been used in supplement intervention trials, providing little comparative data or indication of which methods are reflective of real-world climbing performance, and which supplements provide the most meaningful change.

An assessment of nutritional knowledge or strategies of weight loss has not been previously reported in climbing athletes. Furthermore, only one previous study has assessed prevalence or sources of influence of supplement use in recreational climbers (33), and none have examined competition climbers specifically. Therefore, the aim of this study was to firstly, assess the current nutrition knowledge of competition climbers and identify gaps which may inform education programs to support health and performance; secondly, develop a greater understanding of the magnitude, sources of influence, and strategies of weight loss in competition climbers; and lastly, to identify the prevalence, rationale, and sources of influence of supplement use in competition athletes.

2 Methods

2.1 Participants

Participants were primarily recruited from the semi-finals stage of two international climbing competitions (CWIF 2019/20, Sheffield, United Kingdom), the 2019 British Bouldering Championship (Sheffield, United Kingdom), and the British Universities & Colleges Sport (BUCS) finals (Sheffield, United Kingdom). An electronic version of the questionnaire was also created and advertised on social media and online climbing forums. Fifty climbers (24 females, 26 males) volunteered to participate. Participants were required to meet the following inclusion criteria: age ≥ 18 years, competing at university/collegiate, national, or international level within the previous 12 months, and actively training for competition. Ethical approval was received from Sheffield Hallam University Research Ethics Committee in January 2019 (ER10121205). Following written study briefings, participants provided written or digital informed consent to participate, and for the data collected to be used freely for publication.

2.2 Questionnaire

Participants answered a 72-item questionnaire, in paper or electronic format. The electronic format was designed and hosted using a bespoke online survey platform developed by the Sports Industry Research Centre (SIRC) at Sheffield Hallam university. The questionnaire was comprised of three main sections to assess sport nutrition knowledge, weight loss strategies, and supplement use. The questions for each section were derived from three pre-validated questionnaires used in previous studies investigating the respective themes of each main section (34–36). Participant demographic data (e.g., sex, nationality, competition level, primary discipline) were also gathered. The questionnaire took approximately 20–40 min to complete and outlined within the participant information sheet. Questions not relevant to an individual participant could be omitted (e.g., if a participant did not partake in intentional weight loss *and/or* consume dietary supplements).

2.2.1 General and sports nutrition knowledge

The Abridged Nutrition for Sport Knowledge Questionnaire (A-NSKQ) is a brief and reliable tool designed and validated by Trakman et al. (36, 37) to assess general nutrition knowledge (GNK) and sports nutrition knowledge (SNK). The A-NSKQ has 37 items (GNK = 17; SNK = 20) and covers the same key topics assessed in the 89-item NSKQ (weight management, macronutrients, micronutrients, supplementation, sport nutrition, and alcohol). However, typical completion time of the A-NSKQ is around half the time required to complete the NSKQ (12 vs. 25 min) with comparable reliability and validity (36), and therefore, deemed more appropriate for use when administered concurrently with additional tools.

2.2.2 Weight loss strategies

A questionnaire used to assess weight loss strategies and concerning dietary habits in mixed martial arts [(34); originally developed and validated by (38)] was modified appropriately for use with climbing athletes. Modifications included adapting terminology to suit the sport of climbing (e.g., disciplines of climbing rather than combat sports) or with the use of generalized language (e.g., weight loss directly before a "competition", rather than "weigh-in"). This section of the questionnaire contained 11 questions including typical pre-competition or competition season weight loss, influences of weight management, and weight loss behaviors.

2.2.3 Nutritional supplement habits

The final section of the questionnaire contained 14 questions to assess nutritional supplement use including reasons for use/nonuse, side effects, sources of influence, and attitudes toward supplementation. These questions were derived from a previous study investigating supplement habits in an athletic population (35).

2.3 Statistical analysis

Statistical analysis was performed using SPSS software (version 24, IBM, United States). Data was checked for homogeneity of

TABLE 1 Anthropometric data.

	Male (n = 26)		Female (n = 24)	
	Mean ± SD	Range	Mean ± SD	Range
Age (years)	24.3 ± 6.0	18.0–37.0	23.1 ± 4.3	18.0–33.0
Mass (kg)	66.9 ± 7.4	54.0–79.0	60.4 ± 7.2	45.0–78.0
Height (cm)	175.7 ± 8.0	160.0–188.0	167.6 ± 4.9	160.0–178.0
BMI	21.6 ± 1.3	18.9–24.4	21.5 ± 2.4	16.9–27.4

BMI: body mass index.

variance using Levene's test, and normality using Shapiro–Wilk's. The differences in variables between groups (e.g., competition level) were analyzed using an independent-samples one-way ANOVA test. Where non-parametric data was identified, the independent-samples Mann–Whitney U test was used. Statistical significance for all tests was set at $p \leq 0.05$. A Spearman's correlation coefficient determined the relationship between data sets (e.g., age and GNK). Correlation values (R) were set as <0.2: weak correlation, 0.5: medium correlation, and > 0.8: strong correlation (39). Supplement use prevalence data were evaluated by sex and competition level using chi-square analyses. Data are presented as means ± standard deviation (SD), unless otherwise stated.

3 Results

3.1 Participant demographics

Participant anthropometric data and demographics are shown in Tables 1, 2. Fifty competition climbers ($n = 26$ male, $n = 24$ female) aged 18–37 (mean age 23.7 ± 5.2 years) participated in the study. The athletes reported a mean competition frequency of 7.6 ± 1.9 in the previous 12 months. Average BMI was 21.6 ± 1.9; a BMI of <18.5, defined as potentially "underweight" (40) was reported in two participants.

TABLE 2 Participant demographics.

	n	% of sample
Age started competitions		
5–9	8	16
10–14	22	44
15–19	9	18
20–24	7	14
>25	4	8
Discipline		
Lead	8	16
Bouldering	34	68
Combined	8	16
Competition level		
University/Collegiate	12	24
National	12	24
International	26	52
Nationality		
United Kingdom	27	54
Other European	12	24
North America	9	18
Other	2	4

3.2 General and sports nutrition knowledge

The mean scores and range on the A-NSKQ are reported in Table 3.

TABLE 3 Mean scores on the A-NSKQ.

	Mean score (%)	Range (%)
Total	53.5 ± 11.1	25.0–75.0
GNK	62.5 ± 12.3	37.5–87.5
SNK	46.7 ± 13.8	15.0–75.0

Mean ± standard deviation, GNK, general nutrition knowledge; SNK, Sports nutrition knowledge.

3.2.1 Individual items and gaps in knowledge

The authors determined a correct response rate of ≥75% or ≤25% to be notable for individual items.

3.2.1.1 Macronutrient knowledge

Items with a notably high correct response rate included, "protein needs can be met by a vegetarian diet without the use of supplements" (82%), "consuming carbohydrate during exercise will assist in maintaining blood glucose levels" (76%), "fat is involved in immunity" (75%), and "a banana is high in carbohydrate" (82%). Conversely, only 19% correctly identified cottage cheese as a "low-fat" food option.

3.2.1.2 Micronutrient knowledge

In regard to micronutrient knowledge, 75% of respondents were able to correctly identify the statement "vitamins provide the body with energy" as false. However, very few athletes correctly answered a question relating to the role of vitamin B in the delivery of oxygen to muscles (7%) or understood an athlete's needs for magnesium and calcium (8%).

3.2.1.3 Hydration

Athlete knowledge on hydration for sports performance was poor; just 22% of the athletes identified the correct hydration strategy during exercise, with only 10% of athletes correctly identifying the reason they should drink during exercise (i.e., to maintain plasma volume).

TABLE 4 History and magnitude of weight loss.

		Male	*n*	Female	*n*
Have you ever lost weight for competition (% yes)		46	12	38	9
At what age did you begin to lose weight for competition? (mean ± SD)		22.4 ± 5.7		19.9 ± 4.8	
Do you attempt to lose weight on the day before or the day of competition? (~% yes)		8	1	12	1
How many times have you lost weight for competition? (~%)	1–2	58	7	12	1
	3–5	25	3	75	7
	6–10	0	0	12	1
	>10	17	2	0	0
How much weight would you typically lose? (%)	<2 kg	0	0	62	6
	2–5 kg	92	11	38	3
	6–10 kg	8	1	0	0
How much time do you lose the weight over? (%)	<48 h	0	0	12	1
	1–2 weeks	17	2	12	1
	2–4 weeks	25	3	45	4
	>1 month	58	7	34	3

3.2.1.4 Alcohol

The highest correct response rate was seen within the alcohol category. Almost all athletes (96%) correctly identified that "alcohol contains calories that can lead to weight gain" and that "alcohol can reduce recovery from injury" (90%).

3.2.1.5 Supplements

Most athletes knew that "supplement labels may contain false or misleading information" (84%), or that taking testosterone is banned in sport (88%).

3.2.2 Individual characteristics and knowledge

3.2.2.1 Sex differences

There were no significant differences between males and females for the GNK (10.10 ± 1.80 vs. 9.70 ± 2.00, $p = 0.34$) or SNK scores (9.40 ± 3.20 vs. 9.30 ± 2.30, $p = 0.79$).

3.2.2.2 3.3.2.2 Competition level

ANOVA analysis demonstrated a significant difference in knowledge scores between competition levels ($p = <0.05$). Bonferroni post-hoc analysis revealed higher nutrition knowledge scores in national vs. international athletes, reaching significance for the GNK scores (11.09 ± 1.58 vs. 9.58 ± 1.75, $p = 0.03$), and almost reaching significance for the SNK scores (11.0 ± 2.14 vs. 8.65 ± 2.83, $p = 0.053$).

3.2.2.3 Access to dietician/nutritionist

Less than one-fifth of respondents (18.4%, $n = 9$) had access to a dietitian. There was no significant difference in the combined scores (GNK + SNK) between groups with or without access to a dietician (20.00 ± 4.77 vs. 19.08 ± 3.90, $p = 0.54$).

3.2.2.4 Age correlation

There was no significant correlation between participant age and GNK, SNK, or combined scores ($R = 0.22$, $p = 0.12$; $R = 0.24$, $p = 0.09$; $R = 0.21$, $p = 0.15$).

3.3 Weight loss practices

3.3.1 History and magnitude of weight loss

The history and magnitude of weight loss is reported in Table 4.

3.3.2 Ranking of influence on weight loss practices

Figure 1 shows the ranking of influence on weight loss practices. The top 3 sources of influence were successful athletes, other competitors, and internet articles, with dietician/nutritionist and coach, ranking 5th and 6th, respectively.

3.3.3 Ranking of prevalence of weight loss practices

Figure 2 shows the ranking of prevalence of weight loss practices.

3.3.4 Prevalence of concerning weight loss practices

Table 5 provides a summary of responses reporting concerning weight loss practices. 76% (16 of 21) of participants who reported intentionally losing weight for competition are practicing concerning weight loss methods, including skipping meals, using a sauna, training in warm clothes, taking laxatives, restricting fluids, or vomiting. The prevalence of concerning weight loss practices appears to be similar between males and females (~75% vs. 78%).

3.4 Supplement use

3.4.1 Prevalence of supplement use

The frequency distribution for the type of nutritional supplements used is shown in Figure 3.

Approximately 65% ($n = 34$) of athletes reported using at least one nutritional supplement in the previous 6 months, with 44% ($n = 22$) reporting multiple supplement use. Of those, ~46% of nutritional supplements (NS) were used daily (at least 4–5 times per week), ~29%

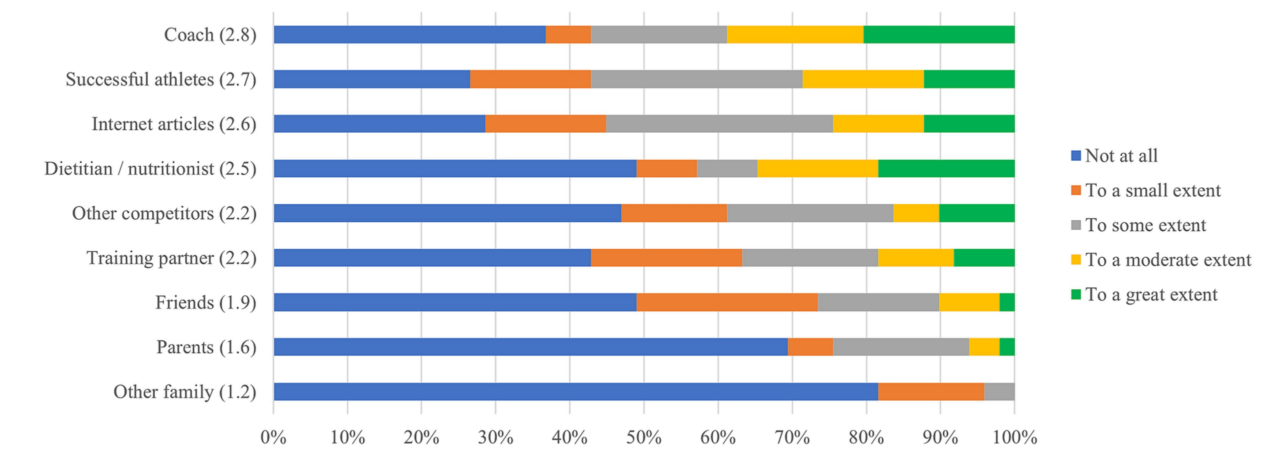

FIGURE 1
Ranking of influence on weight loss practices.

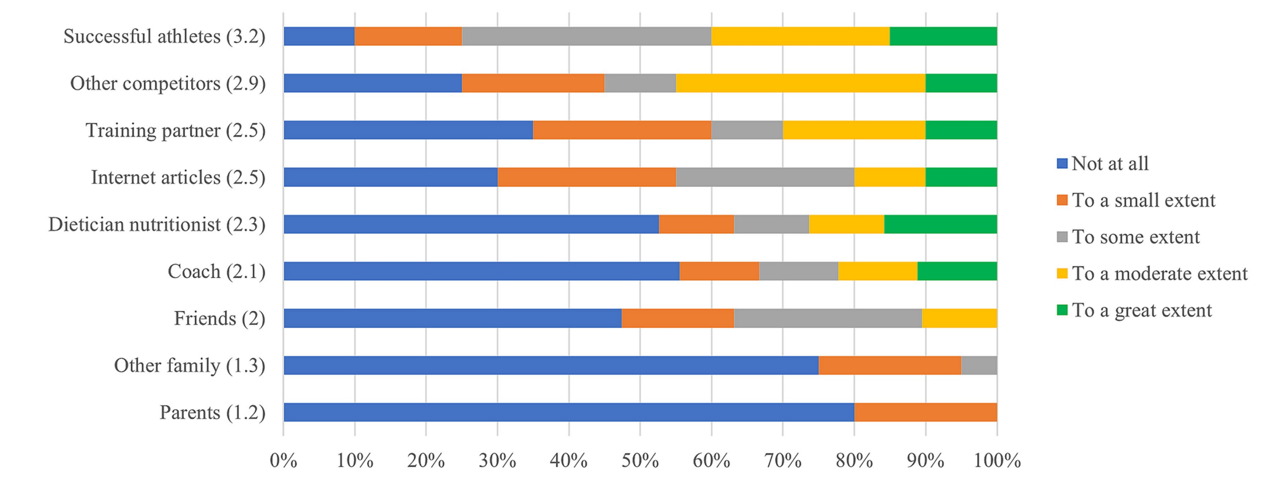

FIGURE 2
Ranking of prevalence of weight loss practices.

TABLE 5 Prevalence of concerning weight loss practices.

	n		
	Male	Female	Total
Skipping meals	9	7	16
Using a sauna	3	1	4
Training in warm clothes	4	0	4
Taking laxatives	3	0	3
Restricting fluids	2	0	2
Vomiting	1	0	1

were used before, during, or after training, ~ 20% used occasionally, and only ~5% were competition specific.

The three most popular supplements used exclusively for health included vitamin D ($n=6$), multivitamins ($n=6$), and fish oil ($n=3$). The three most popular supplements used exclusively for performance included creatine ($n=7$), CHO drinks ($n=4$), and beta-alanine ($n=4$).

The three most common outlets athletes obtained supplements were the internet (36%), health food/sports shops (21%), and pharmacies (19%).

Fourteen percent of all athletes ($n=7$) reported having experienced a negative effect from using nutritional supplements, such as gastrointestinal/digestive problems (protein, BCAA, iron, biotin) and weight gain (creatine). The top 3 reasons reported for non-use of supplements (participants could select more than one answer) were, "I do not need them" ($n=9$), "I do not know enough about them" ($n=14$), and "they are too expensive" ($n=8$).

3.4.2 Comparisons by sex and competition level

There was no significant difference in supplement use between sexes or competition level ($p = >0.05$). Figure 4 indicates the use of NS within the competition levels in this sample.

3.4.3 Ranking of influence on supplement use

Figure 5 shows the ranking of influence on supplement use.

Athletes ranked their coach, successful athletes, and internet articles as their top three sources of influence. Dietitian/nutritionist ranked in

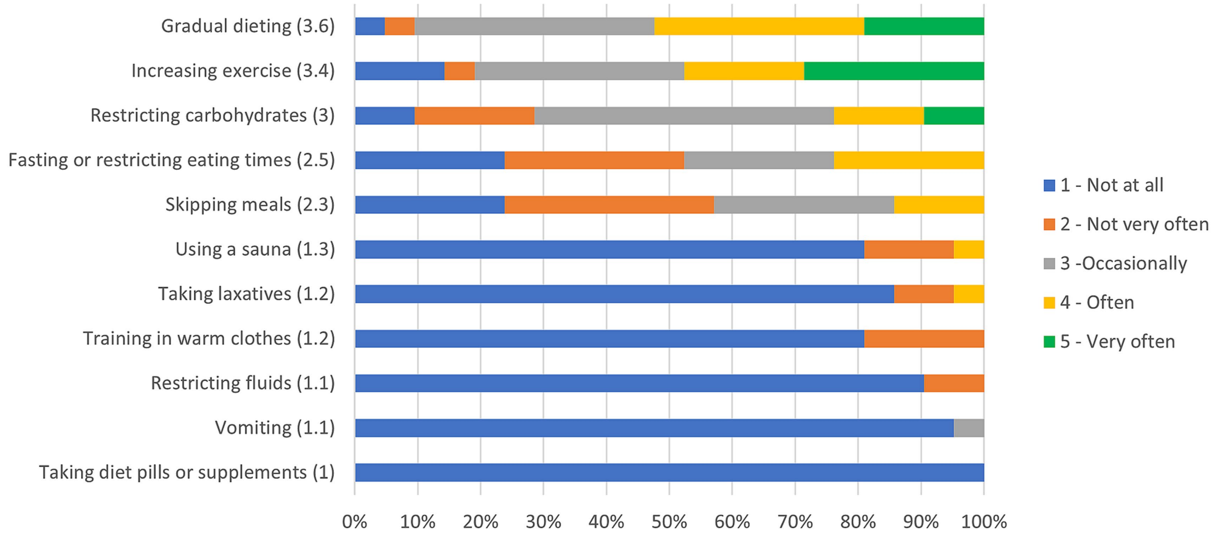

FIGURE 3
Frequency distribution for the type of nutritional supplements used.

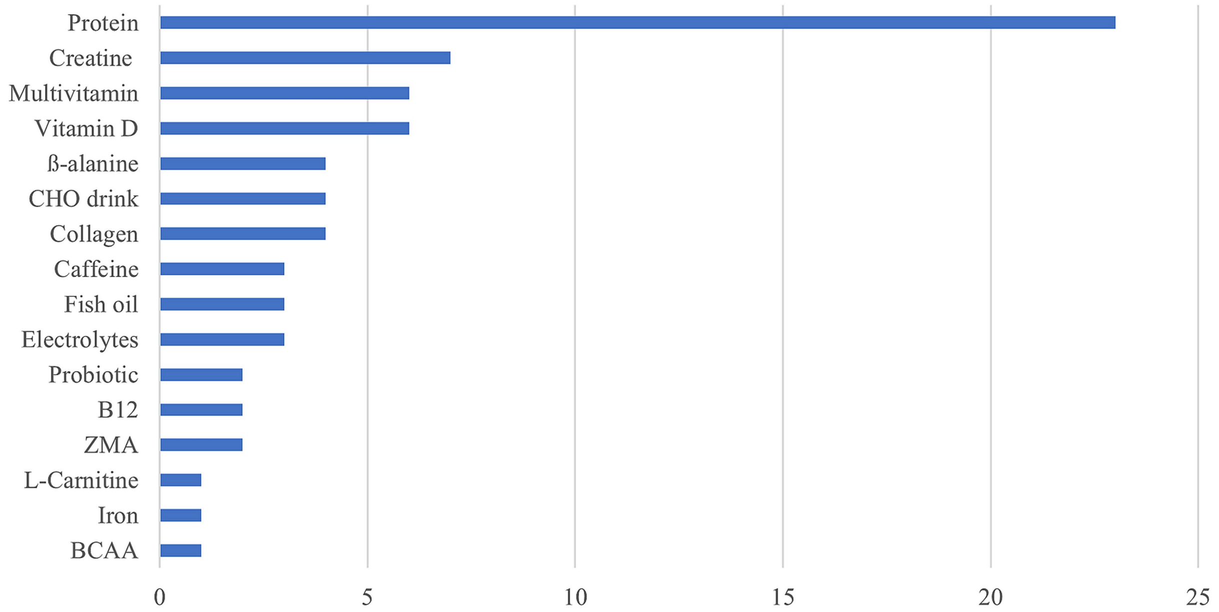

FIGURE 4
Nutritional supplement use within the competition levels in this sample.

4th position, however, only ~18% of athletes reported access to a nutritionist/dietitian. Interestingly, national athletes had greater access to nutritionists/dietitians (25%, $n=3$) compared with international (16%, $n=4$) or collegiate level (17%, n=2). Although, international athletes had greater access to anti-doping information (88%, $n=22$) compared with national (8%, $n=1$) or collegiate level (8%, $n=1$).

3.4.4 Influence of nutrition knowledge

There was no significant difference in sports nutrition knowledge (SNK) (9.76 ± 2.87 vs. 8.4 ± 2.29, $p=0.11$) or general nutrition knowledge (10.21 ± 1.78 vs. 9.26 ± 2.05, $p=0.23$) between supplement users and non-users.

4 Discussion

This is the first study to perform the assessment and evaluation of sports nutrition knowledge, weight loss strategies, and supplement use in competition climbers at collegiate, national, and international level.

4.1 Nutrition knowledge

4.1.1 Knowledge scores

Based on a mean total score of 53.5%, the overall nutrition knowledge of climbers in this study is considered "average,"

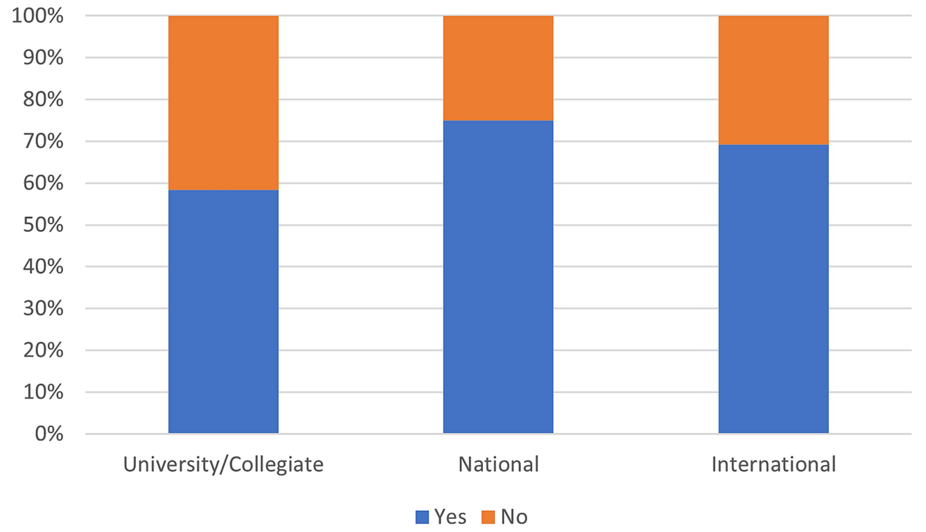

FIGURE 5
Ranking of influence on supplement use.

classified using the scoring system set by Trakman et al. (41). Although no previous data exist in climbing populations, this score is similar, albeit slightly higher than those reported in other sporting populations using the same assessment tool (A-SNKQ), which includes Gaelic games players [46 ± 11.8%, (42)], and a mixed group of Australian football and netball players [47 ± 12%, (36)]. In line with these studies (36, 42), climbing athletes also performed better on the GNK than SNK questions. It is worth noting that there was considerable variation seen in individual scores, particularly in the SNK section with a range of 15–75%, highlighting the need for an individualized approach to athlete support and education.

4.1.2 Individual characteristics and knowledge

4.1.2.1 Sex

Statistical analysis in this sample revealed no significant sex differences for GNK or SNK scores. Previous research assessing sex differences in nutrition knowledge show equivocal results, with some studies suggesting superior knowledge in female athletes (43, 44), whereas other studies, in agreement with the present, show no differences (45, 46).

4.1.2.2 Ability

Although several studies show either no difference in athlete ability level and nutrition knowledge (47, 48), or that higher ability athletes possess greater nutrition knowledge (49, 50), in the present study, post-hoc analysis revealed significantly higher GNK scores in national vs. international level climbers and almost reached significance for the SNK scores. It's plausible that as lower-level athletes are anticipated to train and travel less than their internationally competitive counterparts, they may be able to commit more time to educational reading or continuation of higher education, however, this was not objectively assessed and should be considered in future research.

4.1.2.3 Age

There was no significant correlation between participant age and GNK, SNK, or combined scores. Previous data in athletes supports this finding (44); however, at least one previous study reported a positive influence of age on GNK scores (36) and the larger age span of the participants in the latter (>36 years), may have helped to reveal a trend in that cohort.

4.1.2.4 Access to dietician

Only ~18% of athletes reported access to a nutritionist/dietitian, with no significant impact of access observed within the combined GNK and SNK scores. This could be interpreted several ways; dietitians may not be effective in communicating nutrition information to these subjects, the subjects may not have utilized dietitian services even though they had access, or the nutrition knowledge survey was not a good proxy for nutrition knowledge that the climbers may have gained from a dietitian's services. Regardless, since the athletes overall seemed to have average to poor nutrition knowledge, it seems prudent to facilitate access to a dietitian.

4.1.3 Responses to individual items and gaps in knowledge

4.1.3.1 Alcohol

The highest correct response rate was seen within the alcohol category. Not surprisingly, in a population concerned with weight and body composition, almost all climbers recognized alcoholic drinks as a source of "excess" calories that can lead to weight gain. Many also understood the negative implications of alcohol consumption on recovery, which can include reduced muscle protein synthesis and poor sleep quality (51).

4.1.3.2 Macronutrients

Eighty-two percent of climbers in this sample correctly identified that protein needs can be met by a vegetarian diet without the use of supplements. Although this was not assessed in the present study, previous research suggests a relatively high prevalence of vegan or vegetarian athletes within the climbing community (10). Vegan and vegetarian athletes are able to meet all nutrition needs with appropriate planning to achieve good performance outcomes, with no observable effect of protein source (plant-based whole foods + soy protein isolate supplementation vs. mixed whole foods + whey protein supplementation) in supporting muscle strength and mass accrual in response to resistance training, when adequate amounts of protein (≥ 1.6 g/kg/day) are consumed (52).

The majority of climbers in this sample also correctly identified that "Consuming carbohydrate during exercise will assist in maintaining blood glucose levels." Despite this, current research exploring carbohydrate intake indicates that it is sub-par among adolescent climbers, with 86% of climbing athletes eating below their target carbohydrate intake (8). Similarly, Gibson-Smith (10) reported that adult (>18 years) experienced and elite climbers consumed a daily average intake of 3.7 g/kg of carbohydrate, which is likely inadequate considering the high training volume reported in this study.

4.1.3.3 Micronutrients

Very few athletes correctly answered a question relating to the role of vitamin B in the delivery of oxygen to muscles and were able to correctly identified magnesium and calcium needs, which may have implications for calcium deficiency in higher risk populations, such as vegans (53). Furthermore, there is a positive association between magnesium status and muscle performance, including grip strength, lower-leg power, knee extension torque, ankle extension strength, maximal isometric trunk flexion, rotation, and jumping performance (54); therefore, ensuring magnesium needs are known and met should be a priority for all climbing athletes. Poor micronutrient knowledge has been reported in other athlete groups (36, 55), suggesting this sample of climbers is similar to other athletic populations in terms of their micronutrient nutrition knowledge.

4.1.3.4 Hydration

Athlete knowledge on hydration for sports performance was poor; just 22% of the athletes identified the correct hydration strategy during exercise (i.e., "drink to a plan, based on body weight changes during training sessions performed in a similar climate"), with only 10% of athletes correctly identifying the reason they should drink during exercise (to maintain plasma volume), presenting similar findings to those seen in Australian football and netball athletes (36).

Hydration education could be a method of enhancing climbing performance and preventing adverse events (such as dehydration), which can become apparent with fluid loss as little as 2% of bodyweight during aerobic activity, with impaired repeated anaerobic bouts occurring at ~3% dehydration (56). Interestingly, a recent survey carried in out in climbers (26) reported hydration as one of the "most important" topics, which suggests climbers may feel it is important for performance but unsure how to execute an evidence based hydration strategy.

4.2 Weight loss practices

Forty-six percent of males and 38% of female climbers reported intentional weight loss for competition on at least one occasion. Of those who reported weight loss, 75% of females reported doing this 3–5 times, while 17% of males had lost weight more than 10 times. This suggests that losing weight for competitions is not an uncommon practice. Most athletes lost between two to five kilograms over more than two weeks, which based on the mean data obtained, equates to a ~ 3–8% body weight loss.

Approximately 10% of participants reported losing weight ≤ 48 h prior to competition. This is a concerning number, considering that acute weight loss may hinder climbing performance, especially if it is due to dehydration and/or glycogen depletion (56, 57). The weight loss that occurs in about two to four weeks before competition may include some lean muscle, some adipose tissue, and possibly fluctuations in water and glycogen stores. It is reasonable to assume that if lean mass, water, and glycogen are lost, this may hinder climbing performance. In addition, if climbers are in a repeated state of calorie deficit and low energy availability, it puts them at risk for Relative Energy Deficiency in Sport, comprehensively described by the IOC consensus statement (58).

Alarmingly, ~76% (16 of 21) of participants who reported intentionally losing weight for competition are practicing concerning weight loss methods. Skipping meals was the most common form of concerning weight loss practices (~76%), which is similar to what is seen in combat sport athletes (34). Sports professionals working with climbers may need to discuss with the athlete if it is reasonable, safe, and effective to attempt weight loss. Exploring other areas for potential performance gains within training practices, such as strength, flexibility, endurance, climbing technique, sports psychology, fueling and hydration before, during, and after performing, and route reading strategies, may be more efficacious and prudent than weight loss prior to competition.

Notably, the source of influence around weight-loss were from successful athletes, other competitors, and training partners. These sources, unless adequately qualified, are not considered appropriate to safely navigate a climber through a weight loss phase. This is similar to female physique athletes, where in a recent study 89% of athletes relied on a coach for dieting advice, and 73% relied on another athlete (59). It is interesting to note that many accomplished climbers have spoken out regarding their own anecdotal experiences with disordered eating, which is now supported by the scientific literature. For example, (23) reported 43% of elite female climbers scored as "high risk" for disordered eating, with more recent research suggesting the odds ratio for having an injury may be doubled for those with an eating disorder (60). Aspiring athletes emulating elite climbers may find that they are inadvertently emulating an eating disorder, or disordered eating practices. Some climbers reported losing weight using more extreme concerning practices, such as laxative use, restricting fluids, and vomiting, all of which may lead to performance detriment and carry a high risk for short- and long-term adverse health effects relating to dehydration, malnutrition, and injury.

In addition, the belief that low body weight in climbers already at an appropriate weight will lead to better climbing performance is not supported in the literature. A growing number of studies have failed to observe a correlation between weight, BMI, or body fat levels, and climbing ability (8, 10, 61–64). Conversely, in at least one study in female climbers (65), significantly lower body fat percentage values were reported in the elite group, compared to the lower-advanced ability group (23.3% vs. 29.2%, respectively, d = 0.94). However, the authors noted that these values were substantially higher than those reported in elite female competition athletes almost two decades ago

[(66); semi-finalists 10.7 ± 1.7% and finalists 9.6 ± 1.9%,] despite performing at the same level. This may reflect a shift in the physiological requirements as the sport has evolved, due to the inclusion of more dynamic and strength reliant moves in the setting of competition routes and therefore, demands a greater focus on absolute power development rather than strength-to-weight ratio alone.

This suggests that the widespread notion that weight loss will lead to better climbing performance may need to be re-examined. There are currently no trials examining whether a climber intentionally losing weight results in performance changes, either through acute manipulation of body weight (i.e., fluid loss, low residue diet) or body weight loss from fat or lean muscle stores. It is important to note that the anthropometric profile of climbers at all levels within the current literature is relatively homogeneous; therefore, our current understanding of the influence of body composition on climbing performance is limited and likely does not apply to individuals who have body fat levels that exceed the parameters of "athletic" norms (67).

4.3 Supplement use

Athletes ranked their coach, successful athletes, and internet articles as their top three sources of influence on supplement use. As supplement knowledge appears not to be derived from professional sources, there is higher potential for knowledge to be inaccurate and possibly lead to accidental doping (68). Access to and utilizing dietitians and sports nutrition professionals may be useful for competition athletes to ensure they are taking supplements appropriately, with efficacious dosing and timing strategies, as well as taking clean supplements that comply with WADA and their climbing governing body's rules. Obtaining supplement knowledge from other sources may be detrimental or influenced by a conflict of interest, particularly when coaches or athletes are involved with sponsorships. Financial gain and sponsorship has been reported as one of the reasons to take supplements among athletes (15).

In previous research among experienced, non-competitive climbers, Gibson-Smith et al. (10) reported that 45% of participants used one or more supplements, with a higher prevalence of use in intermediate/advanced level climbers (57.9%) compared to elite/higher-elite level (38.1%). The most common supplements reported in this 2020 study were protein powder, vitamin D, multivitamins, and fish oil; closely aligning with the most popular supplements used by the present cohort. In the present study, prevalence of supplement use was higher than previously reported (65% vs. 45%) and may be due to the increased demands of training and competition, and the increasing normalization of supplement use in elite sport, where the prevalence is reported to be 81–100% (69).

The three most popular supplements used for performance (creatine, CHO drinks, and beta-alanine) have moderate to strong supporting evidence as ergogenic aids (15) and despite a lack of supplement intervention trials in climbers, are reasonable choices for this sport due to their ability to augment anaerobic capacity, which has been suggested as a determinant of climbing performance (8, 11). No significant differences in supplement use between sexes or competition levels suggest that supplement use is not reserved for only certain tiers of competitive level, but rather many athletes across the board are using them.

Eighty-eight percent of international athletes had access to anti-doping information, which is a reasonable indication that they are aware of the risks of doping. However, access was limited in national and collegiate level climbers and may reflect the scarcity of athlete testing in lower levels of competition. Nevertheless, better access to anti-doping information may be indicated for these athletes. The omission of supplement ingredients, contamination with banned substances, and inaccuracies in supplement content has been well documented, and poses a significant risk for inadvertent doping in athletes (68). Reassuringly, most athletes knew that "supplement labels may contain false or misleading information" (84%).

5 Limitations

These self-reported data on anthropometrics, weight loss strategies, and supplements rely on the accuracy of the athletes' memory, accuracy and clarity of the survey questions, and willingness of the athlete to disclose honest information. As with all self-reported data, there may be inaccurate responses and unreliability, both intentional and unintentional (70). The sensitive nature of some questions (i.e., extreme weight loss methods, admitting to supplement use) may also have inhibited some participants from responding, or answering truthfully (71). Furthermore, despite the development of specific tools, the current status of nutrition knowledge in athletes remains difficult to ascertain (20).

The weight loss survey did not ask for weight loss data other than between <48 h before competition through to >1 month. If an athlete is losing a significant amount of weight over the course of 6–12 months, implementing a well-designed periodized nutrition plan (72), and incorporating strategies to promote the preservation of lean mass, this will likely lead to different performance outcomes than an athlete that loses the same amount of weight over the course of 1 month. Furthermore, the weight loss survey did not ask if the participant had ever had an eating disorder. Although the inclusion criteria did include those "in good health with *no chronic illness that may influence eating patterns*," which should exclude those with an active, diagnosed eating disorder, but possibly includes those with disordered eating (no formal diagnosis) or a history of eating disorders/disordered eating. Future studies should consider a more explicit description to avoid doubt.

Finally, while the sample obtained allows an insight into the areas examined, the findings should be considered preliminary and not yet generalized to all climbing athletes until further studies and a larger sample of climbers is captured.

6 Conclusions and recommendations

These findings suggest that the nutritional knowledge of senior competition climbers is "average"; however, significant gaps in knowledge exist, which include topics such as hydration and micronutrients. Due to the established importance of athlete health and performance, educational programs and/or access to educational resources, should seek to address this. While there appears to be no significant effect of sex or age on knowledge scores, large individual variation is demonstrated, further emphasizing the need for individualized educational and practical nutrition support when working with climbing athletes.

Moreover, this study demonstrated that intentional weight loss for climbing competition is common, with most athletes achieving a ~ 3–8% body weight loss. Alarmingly, a large proportion of athletes who lose weight intentionally for competition report utilizing concerning practices that could increase the risk of both acute and chronic health issues. Furthermore, the most common sources of influence around weight-loss were from inappropriate athlete peers, reflecting the lack of access to professional dietitians. It is crucial that coaches and other professionals working with competitive climbers are vigilant in identifying athletes at risk concerning weight management and establish referral pathways to the appropriate specialist services. Nevertheless, this warrants further investigation.

There is currently no data on body weight manipulation in climbers, and no observable relationship in the current literature between body composition and climbing performance. Thus, athletic individuals should explore other elements, such as physical and physiological capacity (e.g., strength, endurance, flexibility), psychological and psychomotor capability (e.g., route reading, sports psychology, technique), and nutritional intake and timing, to promote long term performance development.

Finally, this data suggests that supplement use is higher in competitive vs. non-competitive athletes assessed in previous research; however, the prevalence of use remains below other elite sports. High quality intervention trials to assess the efficacy of ergogenic aids in climbing remains inadequate, although the current choices of athletes can be justified by their established relevant metabolic effects. Future supplement intervention studies should ensure testing protocols are assessed for reliability and reflect valid determinants of climbing performance. A very large proportion of non-users reported "lack of knowledge" around supplements as a reason, further highlighting the lack of access to credible and reliable sources of information.

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 humans were approved by Sheffield Hallam University Research Ethics Committee (ER10121205). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

EG-S: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. RS: Formal analysis, Writing – review & editing. MM: Writing – review & editing. MR: Supervision, Writing – review & editing.

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Conflict of interest

MM was employed by Real Nutrition LLC.

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

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References

1. IOC. *Sport Climbing*. (2021). Available at: https://olympics.com/en/sports/sport-climbing/

2. Billat V, Palleja P, Charlaix T, Rizzardo P, Janel N. Energy specificity of rock climbing and aerobic capacity in competitive sport rock climbers. *J Sports Med Phys Fitness*. (1995) 35:20–4.

3. Bertuzzi RC, Franchini E, Kokubun E, Kiss MM, Kiss MM. Energy system contributions in indoor rock climbing. *Eur J Appl Physiol*. (2007) 101:293–00. doi: 10.1007/s00421-007-0501-0

4. White DJ, Olsen PD. A time motion analysis of bouldering style competitive rock climbing. *J Strength Cond Res*. (2010) 24:1356–60. doi: 10.1519/JSC.0b013e3181cf75bd

5. Hultman E, Greenhaff PL, Ren JM, Söderlund K. Energy metabolism and fatigue during intense muscle contraction. *Biochem Soc Trans*. (1991) 19:347–53. doi: 10.1042/bst0190347

6. La Torre A, Crespi D, Serpiello FR, Merati G. Heart rate and blood lactate evaluation in bouldering elite athletes. *J Sports Med Phys Fitness*. (2009) 49:19–24.

7. Krawczyk M, Rokowski R, Ambroży T, Görner K, Ozimek M, Pociecha M, et al. Evaluation of the level of anaerobic power and its effect on speed climbing performance in elite climbers. *Trends Sport Sci*. (2018) 3:149–58. doi: 10.23829/TSS.2018.25.3-5

8. Michael MK, Joubert L, Witard OC. Assessment of dietary intake and eating attitudes in recreational and competitive adolescent rock climbers: A pilot study. *Front Nutr*. (2019) 6:1–8. doi: 10.3389/fnut.2019.00064

9. Michael MK, Witard OC, Joubert L. Physiological demands and nutritional considerations for Olympic-style competitive rock climbing. *Cogent Med*. (2019) 6:1–13. doi: 10.1080/2331205x.2019.1667199

10. Gibson-Smith E, Storey R, Ranchordas M. Dietary intake, body composition and Iron status in experienced and elite climbers. *Front Nutr*. (2020) 7:122. doi: 10.3389/fnut.2020.00122

11. Smith EJ, Storey R, Ranchordas MK. Nutritional considerations for bouldering. *Int J Sport Nutr Exerc Metab*. (2017) 27:314–24. doi: 10.1123/ijsnem.2017-0043

12. Zapf J, Fichtl B, Wielgoss S, Schmidt W. Macronutrient intake and eating habits in elite rock climbers. *Med Sci Sports Exerc*. (2001) 33:S72. doi: 10.1097/00005768-200105001-00407

13. Burke LM, Castell LM, Casa DJ, Close GL, Costa RJS, Desbrow B, et al. International Association of Athletics Federations Consensus Statement 2019: nutrition for athletics. *Int J Sport Nutr Exerc Metab*. (2019) 29:73–84. doi: 10.1123/ijsnem.2019-0065

14. Kerksick CM, Wilborn CD, Roberts MD, Smith-Ryan A, Kleiner SM, Jäger R, et al. ISSN exercise & sports nutrition review update: research & recommendations. *J Int Soc Sports Nutr*. (2018) 15:38. doi: 10.1186/s12970-018-0242-y

15. Maughan RJ, Burke LM, Dvorak J, Larson-Meyer DE, Peeling P, Phillips SM, et al. IOC consensus statement: dietary supplements and the high-performance athlete. *Br J Sports Med*. (2018) 52:439–55. doi: 10.1136/bjsports-2018-099027

16. Spronk I, Kullen C, Burdon C, O'Connor H. Relationship between nutrition knowledge and dietary intake. *Br J Nutr*. (2014) 111:1713–26. doi: 10.1017/S0007114514000087

17. Heaney S, O'Connor H, Naughton G, Gifford J. Towards an understanding of the barriers to good nutrition for elite athletes. *Int J Sports Sci Coach*. (2008) 3:391–01. doi: 10.1260/174795408786238542

18. Birkenhead KL, Slater G. A review of factors influencing athletes' food choices. *Sports Med*. (2015) 45:1511–22. doi: 10.1007/s40279-015-0372-1

19. Heaney S, O'Connor H, Michael S, Gifford J, Naughton G. Nutrition knowledge in athletes: a systematic review. *Int J Sport Nutr Exerc Metab*. (2011) 21:248–61. doi: 10.1123/ijsnem.21.3.248

20. Trakman G, Forsyth A, Devlin B, Belski R. A systematic review of athletes' and coaches' nutrition knowledge and reflections on the quality of current nutrition knowledge measures. *Nutrients*. (2016) 8:570. doi: 10.3390/nu8090570

21. Mermier CM, Janot JM, Parker DL, Swan JG. Physiological and anthropometric determinants of sport climbing performance. *Br J Sports Med*. (2000) 34:359–65. doi: 10.1136/bjsm.34.5.359

22. Michailov ML, Mladenov LV, Schöffl VR. Anthropometric and strength characteristics of world-class boulderers. *Med Sport*. (2009) 13:231–8. doi: 10.2478/v10036-009-0036-z

23. Joubert LM, Gonzalez GB, Larson AJ. Prevalence of disordered eating among international sport Lead rock climbers. *Front Sports Active Living*. (2020) 2:1–6. doi: 10.3389/fspor.2020.00086

24. Garthe I, Maughan RJ. Athletes and supplements: prevalence and perspectives. *Int J Sport Nutr Exerc Metab*. (2018) 28:126–38. doi: 10.1123/ijsnem.2017-0429

25. Sas-Nowosielski K, Judyta W. Energy and macronutrient intake of advanced polish sport climbers. *J Phys Educ Sport*. (2019) 19:829–32. doi: 10.7752/jpes.2019.s3119

26. Peoples GE, Parker S, Anthony R, Craddock J. Rock climbers' self-reported dietary practices and supplement use in the context of supporting climbing performance. *J Sport Exerc Sci*. (2021) 5:130–8. doi: 10.36905/jses.2021.02.06

27. Fryer S, Giles D, Bird E, Stone K, Paterson C, Baláš J, et al. New Zealand blackcurrant extract enhances muscle oxygenation during repeated intermittent forearm muscle contractions in advanced and elite rock climbers. *Eur J Sport Sci*. (2020) 21:1290–8. doi: 10.1080/17461391.2020.1827048

28. Sas-Nowosielski K, Wyciślik J, Kaczka P. Beta-alanine supplementation and sport climbing performance. *Int J Environ Res Public Health*. (2021) 18:5370. doi: 10.3390/ijerph18105370

29. Doran D, Godfrey A. Effects of creatine supplementation on upper body power output in elite rock climbers. *Biol Sport*. (2001) 18:55–69.

30. Cabañes A, Salinero J, Del Coso J. The ingestion of a caffeine-containing energy drink improves resistance capacity and sport rock climbing performance. *Archivos de Medicina Del Deporte*. (2013) 30:215–20.

31. Potter JA, Hodgson CI, Broadhurst M, Howell L, Gilbert J, Willems MET, et al. Effects of New Zealand blackcurrant extract on sport climbing performance. *Eur J Appl Physiol*. (2020) 120:67–75. doi: 10.1007/s00421-019-04226-2

32. Potter J, Fuller B. The effectiveness of chocolate milk as a post-climbing recovery aid. *J Sports Med Phys Fitness*. (2015) 55:1438–44.

33. Chmielewska A, Regulska-Ilow B. Evaluation of supplement use in sport climbers at different climbing levels. *Nutrients*. (2023) 15:100. doi: 10.3390/nu15010100

34. Barley OR, Chapman DW, Abbiss CR. Weight loss strategies in combat sports and concerning habits in mixed martial arts. *Int J Sports Physiol Perform*. (2018) 13:933–9. doi: 10.1123/ijspp.2017-0715

35. Graham-Paulson TS, Perret C, Smith B, Crosland J, Goosey-Tolfrey VL. Nutritional supplement habits of athletes with an impairment and their sources of information. *Int J Sport Nutr Exerc Metab*. (2015) 25:387–95. doi: 10.1123/ijsnem.2014-0155

36. Trakman GL, Forsyth A, Hoye R, Belski R. Development and validation of a brief general and sports nutrition knowledge questionnaire and assessment of athletes' nutrition knowledge. *J Int Soc Sports Nutr*. (2018) 15:17–8. doi: 10.1186/s12970-018-0223-1

37. Trakman GL, Forsyth A, Middleton K, Hoye R, Jenner S, Keenan S, et al. Australian football athletes lack awareness of current sport nutrition guidelines. *Int J Sport Nutr Exerc Metab*. (2018) 28:644–50. doi: 10.1123/ijsnem.2018-0002

38. Artioli GG, Scagliusi F, Kashiwagura D, Franchini E, Gualano B, Junior AL. Development, validity and reliability of a questionnaire designed to evaluate rapid weight loss patterns in judo players. *Scand J Med Sci Sports*. (2010) 20:e177–87. doi: 10.1111/j.1600-0838.2009.00940.x

39. Ferguson CJ. An effect size primer: a guide for clinicians and researchers. *Prof Psychol Res Pract*. (2009) 40:532–8. doi: 10.1037/a0015808

40. WHO. *Body Mass Index*. (2019). Available at: http://www.euro.who.int/en/health-topics/disease-prevention/nutrition/a-healthy-lifestyle/bodymass-index-bmi

41. Trakman GL, Forsyth A, Hoye R, Belski R. Developing and validating a nutrition knowledge questionnaire: key methods and considerations. *Public Health Nutr*. (2017) 20:2670–9. doi: 10.1017/S1368980017001471

42. Renard M, Kelly DT, Chéilleachair NN, Catháin CÓ. Evaluation of nutrition knowledge in female Gaelic games players. *Sports*. (2020) 8:154. doi: 10.3390/sports8120154

43. Douglas PD, Douglas JG. Nutrition knowledge and food practices of high school athletes. *J Am Diet Assoc*. (1984) 84:1198–02. doi: 10.1016/S0002-8223(21)08322-X

44. Jessri M, Jessri M, RashidKhani B, Zinn C. Evaluation of Iranian college athletes' sport nutrition knowledge. *Int J Sport Nutr Exerc Metab*. (2010) 20:257–63. doi: 10.1123/ijsnem.20.3.257

45. Blennerhassett C, McNaughton LR, Cronin L, Sparks SA. Development and implementation of a nutrition knowledge questionnaire for Ultraendurance athletes. *Int J Sport Nutr Exerc Metab*. (2019) 29:39–45. doi: 10.1123/ijsnem.2017-0322

46. Rosenbloom CA, Jonnalagadda SS, Skinner R. Nutrition knowledge of collegiate athletes in a division I National Collegiate Athletic Association institution. *J Am Diet Assoc*. (2002) 102:418–20. doi: 10.1016/s0002-8223(02)90098-2

47. Andrews MC, Itsiopoulos C. Room for improvement in nutrition knowledge and dietary intake of male football (soccer) players in Australia. *Int J Sport Nutr Exerc Metab*. (2016) 26:55–64. doi: 10.1123/ijsnem.2015-0064

48. Hardy R, Kliemann N, Evansen T, Brand J. Relationship between energy drink consumption and nutrition knowledge in student-athletes. *J Nutr Educ Behav*. (2017) 49:19–26.e1. doi: 10.1016/j.jneb.2016.08.008

49. Heikkilä M, Valve R, Lehtovirta M, Fogelholm M. Nutrition knowledge among young Finnish endurance athletes and their coaches. *Int J Sport Nutr Exerc Metab*. (2018) 28:522–7. doi: 10.1123/ijsnem.2017-0264

50. Spendlove JK, Heaney SE, Gifford JA, Prvan T, Denyer GS, O'Connor HT. Evaluation of general nutrition knowledge in elite Australian athletes. *Br J Nutr*. (2012) 107:1871–80. doi: 10.1017/S0007114511005125

51. Vella LD, Cameron-Smith D. Alcohol, athletic performance and recovery. *Nutrients*. (2010) 2:781–9. doi: 10.3390/nu2080781

52. Hevia-Larraín V, Gualano B, Longobardi I, Gil S, Fernandes AL, Costa LAR, et al. High-protein plant-based diet versus a protein-matched omnivorous diet to support resistance training adaptations: a comparison between habitual vegans and omnivores. *Sports Med*. (2021) 51:1317–30. doi: 10.1007/s40279-021-01434-9

53. Rogerson D. Vegan diets: practical advice for athletes and exercisers. *J Int Soc Sports Nutr*. (2017) 14:36. doi: 10.1186/s12970-017-0192-9

54. Zhang Y, Xun P, Wang R, Mao L, He K. Can magnesium enhance exercise performance? *Nutrients*. (2017) 9:946. doi: 10.3390/nu9090946

55. Turner O, Mitchell N, Ruddock A, Purvis A, Ranchordas M. Elite squash players nutrition knowledge and influencing factors. *J Int Soc Sports Nutr*. (2021) 18:46. doi: 10.1186/s12970-021-00443-3

56. Kraft JA, Green JM, Bishop PA, Richardson MT, Neggers YH, Leeper JD. The influence of hydration on anaerobic performance: a review. *Res Q Exerc Sport*. (2012) 83:282–92. doi: 10.1080/02701367.2012.10599859

57. Murray B, Rosenbloom C. Fundamentals of glycogen metabolism for coaches and athletes. *Nutr Rev*. (2018) 76:243–59. doi: 10.1093/nutrit/nuy001

58. Mountjoy M, Sundgot-Borgen JK, Burke LM, Ackerman KE, Blauwet C, Constantini N, et al. IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. *Br J Sports Med*. (2018) 52:687–97. doi: 10.1136/bjsports-2018-099193

59. Alwan N, Moss SL, Davies IG, Elliott-Sale KJ, Enright K. Weight loss practices and eating behaviours among female physique athletes: acquiring the optimal body

composition for competition. *PLoS One*. (2022) 17:e0262514. doi: 10.1371/journal.pone.0262514

60. Grønhaug G, Joubert LM, Saeterbakken AH, Drum SN, Nelson MC. Top of the podium, at what cost? Injuries in female international elite climbers. *Front Sports Active Living*. (2023) 5:1121831. doi: 10.3389/fspor.2023.1121831

61. Arazi H, Rashidlamir A, Zahed Abolhasani M, Askari Hosseini S. Profiling and predicting performance of indoor rock climbers. *Revista Brasileira de Cineantropometria e Desempenho Humano*. (2018) 20:82–94. doi: 10.5007/1980-0037.2018v20n1p82

62. Grønhaug G. Lean and mean? Associations of level of performance, chronic injuries and BMI in sport climbing. *BMJ Open Sport Exerc Med*. (2019) 5:e000437. doi: 10.1136/bmjsem-2018-000437

63. Saul D, Steinmetz G, Lehmann W, Schilling AF. Determinants for success in climbing: a systematic review. *J Exerc Sci Fit*. (2019) 17:91–00. doi: 10.1016/j.jesf.2019.04.002

64. Sitko S, López I. Performance factors in sport climbing and bouldering: systematic review. *J Sports Train*. (2019) 15:16687.

65. Giles D, Barnes K, Taylor N, Chidley C, Chidley J, Mitchell J, et al. Anthropometry and performance characteristics of recreational advanced to elite female rock climbers. *J Sports Sci*. (2020) 39:48–56. doi: 10.1080/02640414.2020.1804784

66. Watts PB, Martin DT, Durtschi S. Anthropometric profiles of elite male and female competitive sport rock climbers. *J Sports Sci*. (1993) 11:113–7. doi: 10.1080/02640419308729974

67. Wan Nudri WD, Manan WA, Mohamed Rusli A. Body mass index and body fat status of men involved in sports, exercise, and sedentary activities. *Malay J Med Sci*. (2009) 16:21–6.

68. Martínez-Sanz JM, Sospedra I, Ortiz CM, Baladía E, Gil-Izquierdo A, Ortiz-Moncada R. Intended or unintended doping? A review of the presence of doping substances in dietary supplements used in sports. *Nutrients*. (2017) 9:1093. doi: 10.3390/nu9101093

69. Knapik JJ, Steelman RA, Hoedebecke SS, Austin KG, Farina EK, Lieberman HR. Prevalence of dietary supplement use by athletes: systematic review and Meta-analysis. *Sports Med*. (2016) 46:103–23. doi: 10.1007/s40279-015-0387-7

70. Ravelli MN, Schoeller DA. Traditional self-reported dietary instruments are prone to inaccuracies and new approaches are needed. *Front Nutr*. (2020) 7:90. doi: 10.3389/fnut.2020.00090

71. Gnambs T, Kaspar K. Disclosure of sensitive behaviors across self-administered survey modes: a meta-analysis. *Behav Res Methods*. (2015) 47:1237–59. doi: 10.3758/s13428-014-0533-4

72. Stellingwerff T, Morton JP, Burke LM. A framework for periodized nutrition for athletics. *Int J Sport Nutr Exerc Metab*. (2019) 29:141–51. doi: 10.1123/ijsnem.2018-0305

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Recovery markers in elite climbers after the national boulder climbing championship

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This study aimed to investigate recovery markers among elite climbers following the National Boulder Championship. We assessed maximum isometric hand grip strength (HS), forearm swelling (circumference), delayed soreness in forearm muscles, tiredness, and exercise readiness at several time points: pre-competition, immediately post-competition (within 4 min after their last effort), and 12, 24, 48, and 60 h post-competition. Maximum isometric hand grip strength decreased by 6.38 ± 1.32% ($p = 0.006$) post-12 h, returning to pre-competition values post-24 h (all $p > 0.05$). Forearm circumference (FC) increased 1.78 ± 1.77% ($p < 0.001$) post-competition, returning to pre-competition values post-12 h (all $p > 0.05$). Forearm pain (FP) increased post-competition ($p = 0.002$) and post-12 h ($p < 0.001$), returning to pre-competition values post-24 h (all $p > 0.05$). Tiredness increased post-competition ($p < 0.001$), post-12 h ($p < 0.001$), and post-24 h ($p < 0.001$), returning to pre-competition values post-48 h (all $p > 0.05$). Climbing readiness was reduced post-competition ($p < 0.001$), post-12 h ($p < 0.001$), post-24 h ($p < 0.001$), and post-48 h ($p = 0.005$), only returning to pre-competition values post-60 h ($p = 0.189$). Visual analysis of individual data pointed out a relatively small variability in the HS and FC markers, while FP, tiredness, and readiness exhibited larger individual variations. These findings indicate that different recovery patterns exist for the analyzed markers, suggesting that athletes may require up to 60 h after a competition to fully recover and regain their ability to face new competitive challenges.

KEYWORDS

sport climbing, rock climbing, exercise recovery, muscle damage, exercise readiness

1 Introduction

Sport climbing made its debut as an Olympic discipline at the 2020/21 Tokyo Olympic Games (1). Similar to other sports that require a combination of strength and power, the physical demands of training and competitive climbing elicit a range of physiological and metabolic responses in the body, with the magnitude influenced by factors such as the activity's duration, intensity, and frequency (2–5). In the acute phase, overexertion can lead to reduced muscle function, structural damage, and inflammation, often accompanied by subsequent pain, fatigue, and a diminished state of readiness for further exercise. These issues can directly impact an athlete's performance during both competitions and training sessions (6–10).

Sport climbing is categorized into three distinct disciplines: speed, lead, and boulder. The boulder discipline, in particular, involves a series of ascent attempts interspersed by brief periods of rest. Climbers attack routes that are typically around 4 meters in height, often set on more challenging surfaces. This discipline demands a succession of high-intensity bursts of effort to overcome obstacles and reach the top of each route (11). These characteristics require high-intensity, powerful movements, frequent changes in direction, and extensive use of the stretching and shortening cycle. These efforts are often associated with the risk of muscle damage and subsequent declines in performance (12–15).

The potential of climbing to elicit acute performance-reducing psychophysiological responses is enhanced by current models of competition. Sport climbing competitors must perform in qualifying, semi-finals, and finals (depending on the number of participants) on consecutive days and sometimes more than once a day (16). This demanding schedule can become even more exhausting in the context of the current world cup circuit, which often features back-to-back competitions on consecutive weekends (17). Such intensive schedules, with minimal time allocated for recovery, can place substantial strain on athletes and should be the focus of attention for coaches and organizations.

Evaluating an athlete's recovery status involves the assessment of both physiological and psychological factors (18). Therefore, it is crucial to employ methods that can comprehensively investigate both dimensions (18). Various studies have focused on strategies aimed at enhancing and accelerating recovery, and these have gained widespread utilization within sports (7, 8, 12, 15, 19). These strategies can be broadly categorized into regeneration strategies, which apply to physiological aspects, and psychological recovery strategies. In the context of this study, the term "recovery" encompasses both physiological and psychological dimensions (18).

An athlete's performance can be significantly impacted by their state of recovery, which involves a combination of physiological factors, including muscle damage, inflammation, redox state, reduction in energy reserves, and nutritional and hydration status (6, 20, 21). Psychological aspects, such as an increased subjective perception of effort, pain, and tiredness, also play a crucial role (6, 20, 21). For climbing athletes, recovery during and after competitions is a pivotal determinant of sustained performance. Therefore, comprehending the dynamics of recovery following competitive events is essential for designing effective recovery strategies to optimize athlete performance in competitions while also mitigating the risk of overreaching, overtraining, and more serious injuries (6, 7, 12, 19). Thus, our study aims to investigate the temporal changes in both physiological and subjective markers of recovery among elite climbers within the 60 h following the National Boulder Championship. Notably, to the best of our knowledge, multi-day temporal changes in recovery markers among climbers following real or simulated competitions have never been investigated. Thus, being aware of the high level of training of the competitors and possible repeated bout effect occurrence decreasing time to recovery (7, 12, 18), we hypothesized that recovery markers would deteriorate until post-24 h, with progressive recovery up to post-60 h.

2 Materials and methods

This study was approved by the Ethics Committee of the University of Campinas (CAAE: 52244421.4.0000.5404) and conducted in accordance with the Declaration of Helsinki. The participants provided their written informed consent to participate in this study.

2.1 Subjects

The sample consisted of nine climbers from the Brazilian Sport Climbing Team, comprising four men and five women. In this elite group, six of these athletes had also had experience in an international competition. All athletes competed in the Nationals and participated in the week-long evaluation of the Brazilian Sport Climbing Team that took place the week following the championship. The data collections reported in this study were performed during these two events. Sample characteristics are described below (Tables 1, 2).

2.2 Study design

All athletes went through two phases of the National Boulder Championship: Qualifiers, climbing five boulders, in which each

TABLE 1 Athletes' characterization.

	Mean	SD	Minimum	Maximum
Climbing experience (years)	13	3	10	19
Age (years)	28	5	18	34
Body mass (kg)	58.5	8.6	45	72.4
Height (cm)	169.4	6.8	157.5	178.1
Arm span (cm)	174.2	9.9	160.5	191.5
Ape index	1.03	0.02	1	1.08
Lean body mass (kg)	50.3	9.1	39.8	64.4
Body fat (%)	13.7	5.9	6.7	22
Circumferences				
Relaxed arm (cm)	28.4	2.9	24	32.4
Contracted arm (cm)	31.0	3.5	26.2	36.5
Relaxed forearm (cm)	26.5	2.8	23	30.8
Forearm contracted (cm)	27.3	2.7	24	31.1
Relaxed arm–forearm index	1.9	0.9	1	3.8
Contracted arm–forearm index	3.7	1.1	2.2	5.4
Skinfolds				
Subscapular [7f] (mm)	9	2	6	13
Triceps[7f] (mm)	10	5	5	20
Biceps (mm)	4	2	2	9
Chest[7f] (mm)	6	3	3	11
Middle Axillary [7f] (mm)	7	2	5	11
Iliac crest[7f] (mm)	11	4	7	15
Supraspinale (mm)	8	3	5	12
Abdominal[7f] (mm)	11	4	6	17
Front thigh[7f] (mm)	15	9	7	31
Medial calf (mm)	7	5	4	19
Sum (7 folds) (mm)	68	25	43	106
Sum (10 folds) (mm)	87	32	57	137.5

SD, standard deviation; 7f, skinfolds used in the sum of 7 folds; arm–forearm index values calculated by the difference between the arm and forearm measurements. Ape index values calculated by dividing the span by the height. The values for body fat percentage and lean body mass were obtained from the bioimpedance results.

TABLE 2 Athletes' maximum isometric hand grip strength.

	Mean	SD	Minimum	Maximum
Hand grip strength—dominant hand (kgf)	48.6	11.5	38	72
Hand grip strength—dominant hand ($kgf.kg^{-1}$)	0.8	0.1	0.63	1.03
Hand grip strength—non-dominant hand (kgf)	48.1	11.2	37.7	74
Hand grip strength—non-dominant hand ($kgf.kg^{-1}$)	0.8	0.1	0.65	1.04

athlete had 5 min to climb alternated with 5 min of rest; and Finals, approximately 10 h after the Qualifiers, with four boulders, 4 min to climb, and about 20 min of rest. Recovery curve analysis was assessed by dominant maximum isometric hand grip strength (HS), forearm circumference (FC), forearm pain (FP), tiredness, and readiness. These measures were performed in six moments: pre-competition, soon after (post-competition: within 4 min after the last effort), and 12, 24, 48, and 60 h post-competition. On the day of the competition, no intervention/recommendation regarding the practice of physical exercises, nutrient intake, or water was made. For all moments after the competition, the athletes were instructed not to practice exercises for the upper limbs. If they practiced exercises for the lower limbs, it was suggested to do so at low intensity and duration. In addition, they were instructed not to ingest stimulant drinks within 60 h after the competition. Finally, at 60 h post-competition, sample characterization evaluations were carried out. Athletes answered a brief questionnaire about practice time and international competitive experience (World Cup and/or Sport Climbing World Cup) and performed body composition assessments.

2.3 Anthropometric and body composition assessment

Total body mass (BM) (kg) was measured using a digital scale and height (cm) using a stadiometer. Arm and forearm circumference, relaxed and contracted, were measured using a Cescorf anthropometric measuring tape. Trunk and limb skinfolds were measured using a Lange model caliper with 1 mm precision [Cambridge Scientific Instruments (USA)] according to the procedures described by the International Society for the Advancement of Kinanthropometry (2011). The body composition assessment [body fat percentage data (%) and lean mass (kg)] was performed in the morning 60 h post-competition. Athletes fasted and emptied their bladders before the measurement was taken using eight contact electrodes for electrical bioimpedance (Tanita InnerScan 50v, Tokyo, Japan).

2.4 Maximum isometric hand grip strength

The test of maximum isometric muscle strength of the fingers/hand, called maximum isometric hand grip strength (HS), was collected using a Jamar-type dynamometer (Grip Saehan, Hydraulic Hand Dynamometer, SH5001), with support adjustments at the base of the thumb and middle phalanx of the fingers customized for each athlete. At the beginning of each strength test, the participants performed the preparation of the musculotendinous structures by warm-up (22). The warm-up consisted of 10 submaximal and increasing contractions based on the personal and subjective assessment of their strength capacity, namely, 2× 20%, 2× 40%, 2× 60%, 2× 80%, and 2× 90% (except the one measured right after the competition, in which the athletes were already warmed up). Similar warm-up protocols have already been used by our group (23, 24). Then, 3 min after the warm-up, the participants performed three attempts to obtain maximum isometric hand grip strength, with a 2-minute interval between attempts. At the time of the test, the participants stood up, with the dominant hand holding the dynamometer and the arm extended at the side of the body. The participants were asked to squeeze the dynamometer as hard and as fast as possible, with a total duration of 3 s (controlled by the evaluators through a stopwatch). The tests were conducted by an experienced technical member, and strong verbal encouragement was given throughout the test. The average of the three trials was used for the final analysis. For the recovery temporal change analysis, just the dominant hand was assessed, while for sample characterization, both hands were assessed. Maximum isometric hand grip strength values were presented in absolute units (kgf) and relative to body mass, calculated by dividing the absolute hand grip strength by the athlete's body mass ($kgf{\cdot}kg^{-1}$).

2.5 Forearm circumference

The circumference of the forearm was measured to indirectly evaluate muscle edema. First, the point of the largest circumference of the relaxed forearm was marked with a permanent ink pen. Circumference measurement was performed three consecutive times, and the highest value was used for the final analysis (25).

2.6 Delayed-onset muscle soreness

Forearm pain (FP) was evaluated at rest with the use of a visual analog scale (VAS) (26–28). Subjects were instructed to open and close their hand twice and based on the sensation of pain and to mark with a pen on a continuous line (100 mm considered 100%) their perception of pain on a scale from 0 "none" to 10 "a lot of pain!".

2.7 Tiredness and readiness

The tiredness and readiness variables were assessed through self-response to the questions: "How tired are you right now?" and "How ready are you to climb a difficult boulder right now?" Measurements were performed using VAS (26, 27), as performed for FP.

2.8 Statistical analyzes

For the analysis of the recovery curve (measurements over time: pre-competition, post-competition, and 12, 24, 48, and 60 h), one-way analysis of variance (ANOVA) for repeated measures was performed. When appropriate, Dunnett's *post hoc* analysis was used to verify which measurement times after the competition were different from the pre-competition time. Data are reported as mean and standard deviation. The software used for the analysis was STATISTICA 6.0 (StatSoft, Inc., Tulsa, OK, USA). The significance level adopted was $p < 0.05$.

3 Results

Figures 1A,B shows the mean and individual values of HS over the six evaluation times. ANOVA showed the main effect of time ($p = 0.034$). Thus, Dunnett's *post hoc* analysis was performed, indicating a reduction of 6.38 ± 1.32% ($p = 0.006$) in HS at post-12 h compared to pre-competition. Meanwhile, the other time changes in HS post-competition (−2.52 ± 7.53%; $p = 0.452$), post-24 h (−2.93 ± 5.32%; $p = 0.213$), post-48 h (−0.43 ± 8.17%; $p = 0.804$), and post-60 h (−1.50 ± 5.98%; $p = 0.477$) were not different from pre-competition. The visual analysis in Figure 1B shows a small variability of individual HS data behavior throughout the 60 h of recovery. Figures 1C,D shows the mean and individual values of the FC over the six evaluation times. ANOVA showed the main effect of time ($p = 0.001$). Thus, Dunnett's *post hoc* analysis was performed, indicating an increase of 1.78 ± 1.77% ($p < 0.001$) in FC post-competition compared to pre-competition. The other time changes in FC post-12 h (0.07 ± 0.12%; $p = 0.780$), post-24 h (0.18 ± 0.66%; $p = 0.682$), post-48 h (0.12 ± 0.89%; $p = 0.740$), and post-60 h (0.37 ± 1.01%; $p = 0.469$) were not different from pre-competition. The visual analysis in Figure 1D shows a small variability of the individual FC data behavior throughout the 60 h of recovery.

For FP (Figure 2A), ANOVA showed the main effect of time ($p < 0.001$). Therefore, Dunnett's *post hoc* analysis was performed, demonstrating an increase in pain post-competition ($p = 0.002$) and post-12 h ($p < 0.001$) compared to pre-competition. The other time changes in FP post-24 h ($p = 0.224$), post-48 h ($p = 0.730$), and post-60 h ($p = 0.767$) were not different compared to pre-competition. The visual analysis in Figure 2B shows a moderate variability of individual FP data behavior throughout the 60 h of recovery.

Tiredness and readiness for high-intensity bouldering are shown in Figures 2C–F. For tiredness, ANOVA showed the main effect of time ($p < 0.001$), and Dunnett's *post hoc* analysis indicated that post-competition ($p < 0.001$), post-12 h ($p < 0.001$), and post-24 h ($p < 0.001$) were different compared to pre-competition, while post-48 h ($p = 0.129$) and post-60 h ($p = 0.112$) were not different. The climbing readiness ANOVA showed the main effect of time ($p < 0.001$), and Dunnett's *post hoc* analysis indicated that post-competition ($p < 0.001$), post-12 h ($p < 0.001$), post-24 h ($p < 0.001$), and post-48 h ($p = 0.005$)

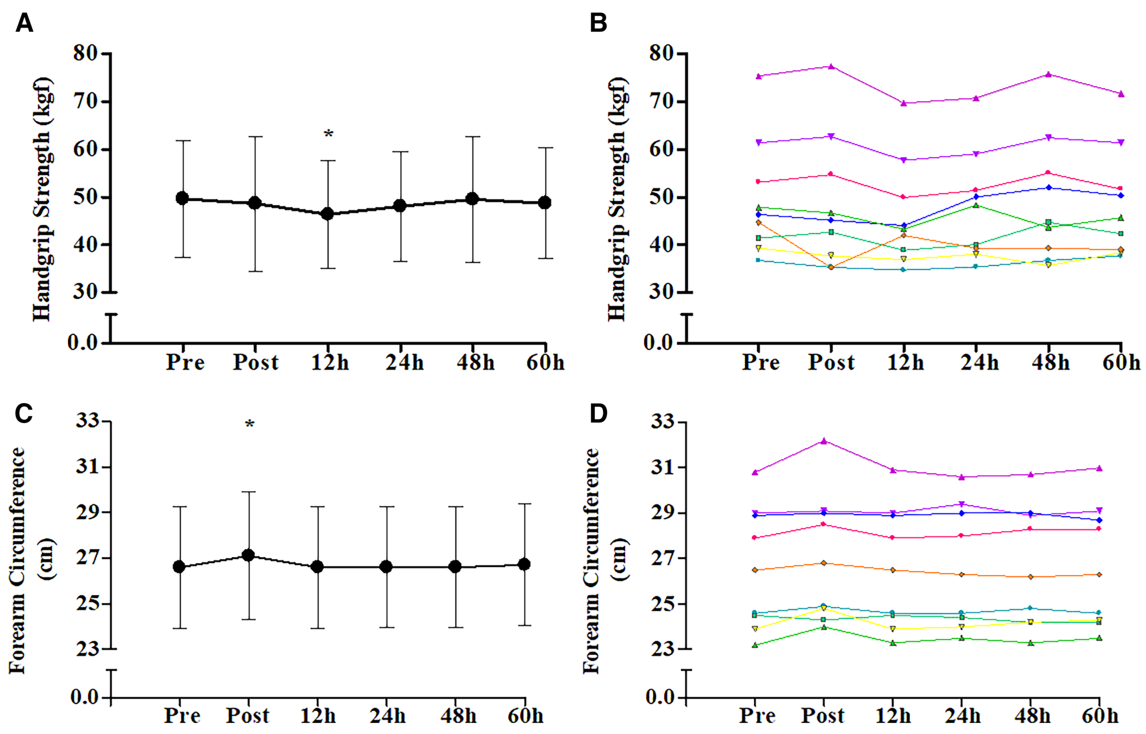

FIGURE 1
Change through time of physiological markers from pre-competition over 60 h post-competition. (A) Maximum isometric hand grip strength mean group values and standard deviation; (B) maximum isometric hand grip strength individual values; (C) forearm circumference mean group values and standard deviation; (D) forearm circumference individual values. *, different compared to pre-competition (Dunnett's *post hoc*; $p < 0.05$).

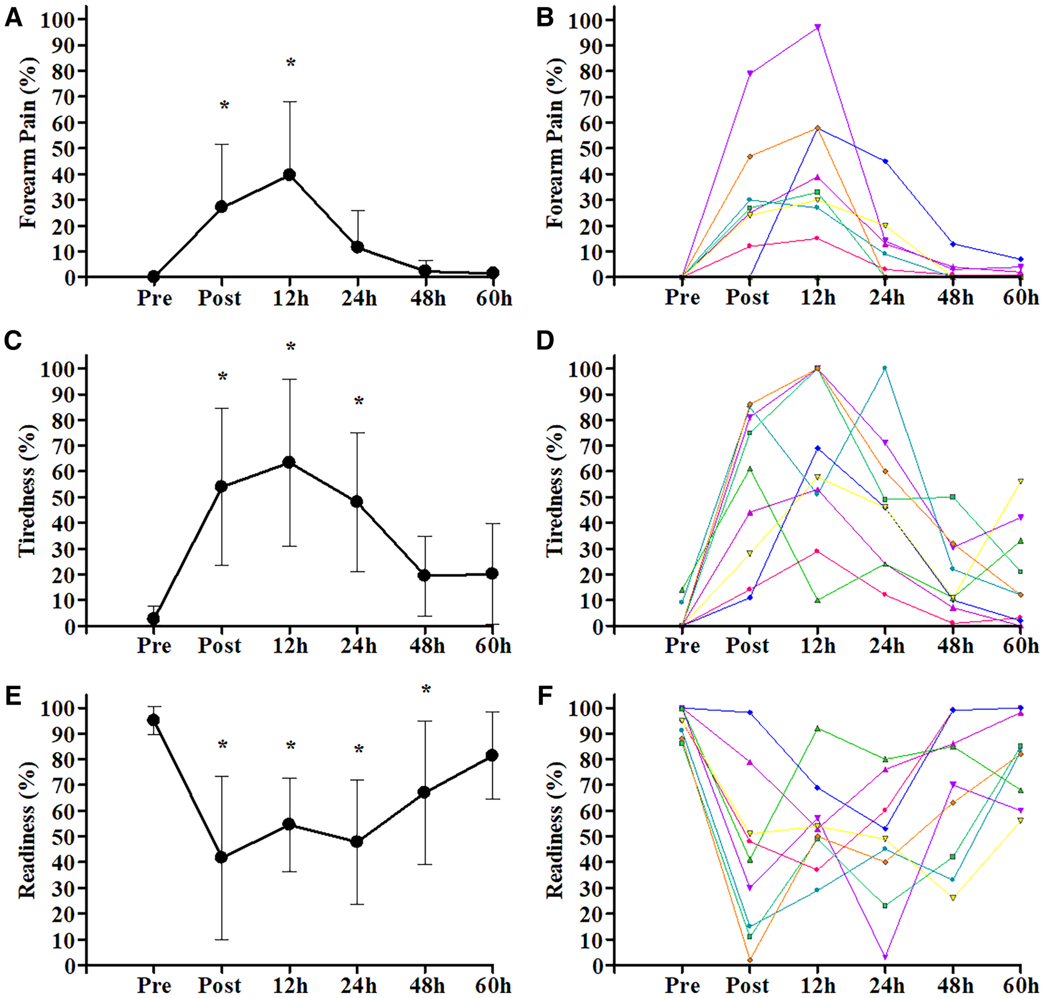

FIGURE 2
Change through time of subjective perceived markers from pre-competition over the 60 h post-competition. (A) Forearm pain mean group values and standard deviation; (B) forearm pain individual values; (C) tiredness mean group values and standard deviation; (D) tiredness individual values; (E) readiness mean group values and standard deviation; (F) readiness individual values. *, different compared to pre-competition (Dunnett's *post hoc*; $p < 0.05$).

were different from pre-competition, with only the time post-60 h ($p = 0.189$) showing no difference compared to the pre-competition. Finally, the visual analysis in Figures 2D,F shows a large variability of individual tiredness and readiness data behavior throughout the 60 h of recovery.

4 Discussion

To the best of our knowledge, this study is the first to investigate recovery markers in elite climbers following a competition. The results reveal that, following a national-level bouldering competition, athletes exhibited a recovery in HS and FP levels within 24 h after the competitive stimulus. In contrast, sensations of tiredness and readiness returned to pre-competition levels at 48 h and 60 h, respectively. These findings, to some extent, deviate from our initial hypothesis. While recovery markers ultimately returned to values similar to the pre-competition state by the 60-h mark, the quickness of the physiological and FP recovery contrasts with our initial expectations. This rapid recovery emphasizes the high training proficiency of the tested athletes and their familiarity with the types of movements encountered in competition. Moreover, it is noteworthy that physiological markers and subjective perceptions did not exhibit a uniform temporal pattern of recovery.

The boulder discipline necessitates brief and intense bursts of effort with limited recovery time between each attempt (29, 30). This highlights the importance of strength and the ability to generate rapid force, particularly from the hands (hand grip), as pivotal factors influencing a climber's performance (31, 32). These types of high-intensity intermittent stimuli, characterized as voluntary and high-magnitude muscle actions, are capable of leading to a reduction in functional muscle capacity, such as in force production, due to fatigue arising from the physiological response to maximal and submaximal voluntary contractions (14, 18, 20) and/or exercise-induced muscle damage (EIMD)

(7, 12, 13). EIMD leading to strength loss is attributed to so-called half-sarcomere non-uniformity, which states that the weakest half-sarcomeres accommodate the majority of finer length adjustment, which becomes weaker as muscle lengthening progresses and advances beyond the point of myofilament overlap, and eventually, microtears develop (22, 33). Repeated stretching increases damaged sarcomeres and exacerbates muscle fiber injury, resulting in membrane breakdown and perforation of mechanically activated channels (22, 33). Damage to junctophilins, proteins that connect t-tubules to the sarcoplasmic reticulum membrane and mediate communication between the calcium release channel and the dihydropyridine receptor, may also contribute to strength losses due to excitation–contraction uncoupling (14, 22, 33). This series of events disrupts the excitation–contraction coupling mechanism and the calcium kinetics originating from the sarcoplasmic reticulum, resulting in a decrease in strength (7, 12, 13, 33). Considering the mechanisms elucidated above, our initial expectations were for a substantial decline in HS, coupled with an increase in FC and FP, persisting for a minimum of 24 h following the competition.

We observed a significant difference in HS 12 h post-competition, returning to the pre-competition value after 24 h. This temporal data behavior shows a small individual variability increasing the confidence that the athletes had their HS recovered post-24 h. Notably, an experimental session comprising three repetitions of maximal climbing efforts, with a 2-minute interval of active recovery between each, demonstrated a reduction in HS (32). Heyman et al. (9) also identified a similar decline in strength after a series of repetitions until voluntary exhaustion in "top rope" climbing. The delayed reduction in strength, occurring post-12 h after the stimulus, may indicate that, in addition to competition-induced fatigue, athletes may experience EIMD. This EIMD can trigger an inflammatory response characterized by leukocyte activation, muscle edema, degradation of muscle function, delayed-onset muscle soreness, increased release of muscle proteins into the interstitial space, elevated circulation, and an increase in muscle temperature. The effects of EIMD and the associated muscle soreness, including a decline in muscle strength, may persist for a duration of 12–72 h post-exertion (7, 12, 13, 33).

Peake et al. (13) conducted a literature review, which revealed that EIMD, leading to swelling and diminished strength, tends to peak between 24 and 72 h following the stimulus. Paulsen et al. (34) established a classification system considering low or negligible muscle damage when the decline in force-generating capacity is less than 20%. Consequently, the relatively minor decrease observed in HS and FP values after 24 h, and FC after 12 h, may likely stem from mechanisms in addition to muscle damage. For instance, the increase in FC after a series of climbing bouts can be attributed to the repetitive isometric contractions of the forearm, leading to a reduction in veins blood flow and an increase in forearm swelling. This, in turn, results in a decrease in strength output as swelling and discomfort intensify when the same muscles are contracted and held repeatedly (35).

The values of FC, an indirect indicator of forearm volume and muscle swelling (Figures 1C,D), indicate a significant increase after the competition, returning to pre-competition values post-12 h. Once again, the temporal data behavior shows a small individual variability, increasing the confidence that the athletes' FC recovery was homogeneous. It is known that strenuous exercise can induce muscle swelling immediately after the stimulus (35), and the persistence of this altered volume accompanied by an inflammatory response is indicative of muscle damage (22, 29, 36–38). Previous studies showed that VO_2 peak climbing exceeded the VO_2 peak obtained on an arm ergometer by 102.2%–108.1%, the peak heart rate achieved varied from 162 to 181 bpm, and lactate concentration ranged between 2.4 and 3.9 $mmol \cdot l^{-1}$ after an effort time ranging from 37.2 to 38.6 s, depending on the technical difficulty of the climbing bout (4). We believe that the changes in FC shown in our study are related to the "muscle pump", a temporary condition that generates muscle swelling described in response to resistance exercise (39). According to Schoenfeld and Contreras (39), high-intensity muscle contractions cause an imbalance in blood supply and drainage in the exercised region. That is due to compression of the veins and preserved normal diameter of the arteries (compression-resistant vascular structure), also leading to an imbalance in the concentration of intramuscular and extramuscular fluids, causing the greatest amount of fluid to be found in the intramuscular space, leading to swelling. This phenomenon has already been described within the practice of climbing (40, 41).

We found that forearm pain experienced a notable reduction within the initial 24 h post-competition. While the individual variability in FP was somewhat greater than that observed for physiological markers, it remained moderate. Nonetheless, the temporal behavior of FP exhibited a similar pattern across individuals, suggesting that although the degree of pain experienced varied among them, the majority demonstrated a significant reduction after the first 24 h. Given that delayed-onset muscle soreness, resulting from muscle damage, typically reaches its peak between 48 and 72 h following the stimulus (42) and that FP did not follow the same temporal pattern as HS, it is plausible that the forearm pain is more likely attributed to minor muscle damages and the breakdown of non-contractile muscle structures rather than substantial muscle damage. Previous studies have highlighted that the fascia is more sensitive than muscle following eccentric contractions (43), which could explain the association between pain and reduced performance, as observed in this study and others (40). A possible explanation for the reduction in force production could be the mechanism of muscle fatigue (44). This phenomenon can manifest at both peripheral and central levels (45). Peripheral fatigue involves intramuscular changes in biochemistry and neuromuscular junctions, while central fatigue is characterized by a decline in neural impulse transmission from the central nervous system to the muscle (43, 45–47). In addition to impairing the ability to generate force, fatigue can be accompanied by sensations of tiredness and exhaustion (45), ultimately constraining high-intensity performance (44, 45).

Repeated muscle contractions can result in the diminished ability to generate or sustain muscle function, a phenomenon commonly referred to as muscle fatigue (48). Fatigue is widely recognized as a critical factor influencing athletic performance, and it comprises a complex event, often characterized by a set of interacting conditions with varying degrees of influence, dependent on the nature of the physical exercise (20, 49). Extensive research has been dedicated to unraveling the fatigue process and its ramifications on performance in physical activities and sports. Nevertheless, a consensus regarding the precise mechanism underpinning this process remains elusive (41–43, 50). In addition to physiological changes, it is vital to pay attention to an athlete's perception of tiredness as it serves as a valuable indicator of their condition (21). Notably, subjective measures capable of gauging tiredness and readiness are typically acquired through verbal feedback and/or the application of specific scales (51, 52). Unlike pain, which often has a precise location, sensations of tiredness, fatigue, and readiness encompass a broader perception of the athlete's overall physical state and their perceived capacity to perform. This subjective dimension adds a layer of subjectivity to the assessment (50–52). Nonetheless, existing literature corroborates that subjective measures are effective in capturing changes in an athlete's well-being as they tend to exhibit greater responsiveness than objective measurements (52). Subjective assessments of athlete recovery, in general, are characterized by their sensitivity and practicality, making them a pivotal component of the recovery–fatigue monitoring process (51).

Unlike FP, the subjective variables, tiredness and readiness (Figures 2C–F), exhibited distinct patterns in this context. Tiredness demonstrated a return to baseline levels around 48 h after the competition, while readiness only reached its initial levels 60 h post-competition. This suggests that athletes might not fully recover from the competitive stimulus when strength and forearm pain recover. These subjective attributes of tiredness and readiness likely account not only for the temporal differences in recovery but also for the considerable variability observed among individuals, emphasizing the importance of individualized assessments and strategies in addressing these aspects. The results obtained for tiredness and readiness led us to believe that they are not entirely linked to local muscle fatigue, given that the forearm has a small muscle mass in relation to the whole. Montull et al. (49) presented a new subjective approach considering that sports performance depends on the athlete's experience and their interactions with the environment. Furthermore, the authors believed that the impairment of these variables may be related to several psychological factors. The studied athletes required at least 60 h of recovery after a competitive stimulus to be fully capable of performing at their maximum performance. The difference in the temporal recovery behavior between physiological markers and subjective markers suggests that for our study there is no strong direct relationship between them, which emphasizes the importance of a holistic understanding of the athlete and the sport, integrating physiological and psychological aspects, considering that both physical and mental factors can influence the athlete's well-being and performance capacity.

This study is not without its limitations. While maximum isometric handgrip strength is recognized as a crucial factor in sport climbing performance, there are other variables, such as rate of force development, finger resistance, and measures related to pulling movements, that could significantly enhance the understanding of the recovery profile of climbers. It is important to note that the maximum isometric handgrip strength measurements were made with a hand dynamometer, and an even more specific strength measurement, such as an instrumented climbing hold, could offer valuable insights. Moreover, it would be intriguing to explore the recovery curve of the non-dominant limb since the intensity imposed on each side can vary non-uniformly based on the characteristics of the climbing routes. In this regard, future research could explore additional variables and employ even more specialized instruments than those used in this study. Furthermore, investigating the temporal changes in recovery variables in other climbing disciplines such as LEAD and SPEED, and following multiple consecutive days of competition, would be of interest and could provide further insights into the recovery requirements in sport climbing.

This study is the first to show the temporal changes in physiological and subjective perceived markers of recovery among elite climbers following a competition. Considering the demanding competition schedules that elite climbers typically face, the findings from this study assume great significance. They offer valuable insights into the evolving recovery patterns of variables pertinent to the preparation and performance of professional sport climbing competitions. This, in turn, can contribute to the mitigation of injury risks arising from physiological and/or psychological stress and potentially prompt a reconsideration of the competition calendar. From a practical standpoint, while physiological markers appear to recover after 24 hours post-competition, allowing athletes to restart physical-oriented training during this period, the more extended temporal patterns and the substantial individual variability observed in subjective markers imply that athletes may require up to 60 hours of recovery to regain their sense of fitness and readiness for competitive endeavors.

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 authors.

Ethics statement

The studies involving humans were approved by Ethics Committee of the University of Campinas (CAAE: 52244421.4.0000.5404). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

AFG: Conceptualization, Methodology, Resources, Investigation, Data curation, Formal Analysis, Writing – review & editing. MGZ: Data curation, Formal Analysis, Validation, Writing – original draft, Writing – review & editing. MCV: Conceptualization, Methodology, Investigation, Writing – original draft. DC: Data curation, Formal analysis, Validation, Writing – Original Draft. PSG: Investigation, Methodology, Data curation, Writing – original draft, Writing – review & editing. RPP: Investigation, Methodology, Data curation, Writing – original draft. AI: Conceptualization, Data curation, Formal Analysis, Supervision, Validation, Writing – review & editing. ACM: Conceptualization, Methodology, Resources, Supervision, Funding acquisition, Writing – review & editing.

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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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References

1. Lutter C, Tischer T, Schöffl VR. Olympic competition climbing: the beginning of a new era-a narrative review. *Br J Sports Med*. (2021) 55(15):857–64. doi: 10.1136/bjsports-2020-102035

2. de Geus B, Villanueva O'Driscoll S, Meeusen R. Influence of climbing style on physiological responses during indoor rock climbing on routes with the same difficulty. *Eur J Appl Physiol*. (2006) 98(5):489–96. doi: 10.1007/s00421-006-0287-5

3. Sheel AW, Seddon N, Knight A, McKenzie DC, Warburton DER. Physiological responses to indoor rock-climbing and their relationship to maximal cycle ergometry. *Med Sci Sports Exerc*. (2003) 35(7):1225–31. doi: 10.1249/01.MSS.0000074443.17247.05

4. Bertuzzi RC, Franchini E, Kokubun E, Kiss MA. Energy system contributions in indoor rock climbing. *Eur J Appl Physiol*. (2007) 101(3):293–300. doi: 10.1007/s00421-007-0501-0

5. MacKenzie R, Monaghan L, Masson RA, Werner AK, Caprez TS, Johnston L, et al. Physical and physiological determinants of rock climbing. *Int J Sports Physiol Perform*. (2020) 15(2):168–79. doi: 10.1123/ijspp.2018-0901

6. Cheng AJ, Jude B, Lanner JT. Intramuscular mechanisms of overtraining. *Redox Biol*. (2020) 35:101480. doi: 10.1016/j.redox.2020.101480

7. Markus I, Constantini K, Hoffman JR, Bartolomei S, Gepner Y. Exercise-induced muscle damage: mechanism, assessment and nutritional factors to accelerate recovery. *Eur J Appl Physiol*. (2021) 121(4):969–92. doi: 10.1007/s00421-020-04566-4

8. Kodejška J, Baláš J, Draper N. Effect of cold-water immersion on handgrip performance in rock climbers. *Int J Sports Physiol Perform*. (2018) 13(8):1097–9. doi: 10.1123/ijspp.2018-0012

9. Heyman E, De Geus B, Mertens I, Meeusen R. Effects of four recovery methods on repeated maximal rock climbing performance. *Med Sci Sports Exerc*. (2009) 41(6):1303–10. doi: 10.1249/MSS.0b013e318195107d

10. Watts PB, Daggett M, Gallagher P, Wilkins B. Metabolic response during sport rock climbing and the effects of active versus passive recovery. *Int J Sports Med*. (2000) 21(3):185–90. doi: 10.1055/s-2000-302

11. Claudia A, Sponar P, Winkler M. Athletes' performance in different boulder types at international bouldering competitions. *Int J Perform Anal Sport*. 2021;21:3, 409–20, doi: 10.1080/24748668.2021.1907728

12. Owens DJ, Twist C, Cobley JN, Howatson G, Close GL. Exercise-induced muscle damage: what is it, what causes it and what are the nutritional solutions? *Eur J Sport Sci*. (2019) 19(1):71–85. doi: 10.1080/17461391.2018.1505957

13. Peake JM, Neubauer O, Della Gatta PA, Nosaka K. Muscle damage and inflammation during recovery from exercise. *J Appl Physiol*. (2017) 122(3):559–70. doi: 10.1152/japplphysiol.00971.2016

14. Allen DG, Westerblad H. Role of phosphate and calcium stores in muscle fatigue. *J Physiol*. 2001;536(Pt 3):657–65. doi: 10.1111/j.1469-7793.2001.t01-1-00657.x

15. Green JG, Stannard SR. Active recovery strategies and handgrip performance in trained vs. Untrained climbers. *J Strength Cond Res*. (2010) 24(2):494–501. doi: 10.1519/JSC.0b013e3181c06af3

16. International Federation of Sports Climbing. (2020). Rule 7.15. v.1.5.1, 2020. Availalbe online at: https://cdn.ifsc-climbing.org/images/World_Competitions/IFSC_Rules_2020_v151_PUBLIC_compressed.pdf (accessed June 29, 2023).

17. International Federation of Sports Climbing. (2023). Calendar 2023. Availalbe online at: https://www.ifsc-climbing.org/index.php/world-competition/calendar (accessed June 30, 2023).

18. Kellmann M, Bertollo M, Bosquet L, Brink M, Coutts AJ, Duffield R, et al. Recovery and performance in sport: consensus statement. *Int J Sports Physiol Perform*. (2018) 13(2):240–5. doi: 10.1123/ijspp.2017-0759

19. Caballero-García A, Córdova-Martínez A. Muscle recovery and nutrition. *Nutrients*. (2022) 14(12):2416. doi: 10.3390/nu14122416

20. Abbiss CR, Laursen PB. Models to explain fatigue during prolonged endurance cycling. *Sports Med*. (2005) 35(10):865–98. doi: 10.2165/00007256-200535100-00004

21. Noakes TD. Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Front Physiol*. (2012) 3:82. doi: 10.3389/fphys.2012.00082

22. Maganaris CN, Baltzopoulos V, Sargeant AJ. Repeated contractions alter the geometry of human skeletal muscle. *J Appl Physiol*. (2002) 93(6):2089–94. doi: 10.1152/japplphysiol.00604.2002

23. Silva M, Gáspari A, Barbieri J, Barroso R, Figueiredo G, Motta L, et al. Far-infrared-emitting fabric improves neuromuscular performance of knee extensor. *Lasers Med Sci*. (2022) 37(5):2527–36. doi: 10.1007/s10103-022-03523-122.

24. Pinto MD, Wilson CJ, Kay AD, Blazevich AJ. Reliability of isokinetic tests of velocity- and contraction intensity-dependent plantar flexor mechanical properties. *Scand J Med Sci Sports*. (2021) 31(5):1009–25. doi: 10.1111/sms.13920

25. Damas F, Nosaka K, Libardi CA, Chen TC, Ugrinowitsch C. Susceptibility to exercise-induced muscle damage: a cluster analysis with a large sample. *Int J Sports Med*. (2016) 37(8):633–40. doi: 10.1055/s-0042-100281

26. Couper MP, Tourangeau R, Conrad FG, Singer E. Evaluating the effectiveness of visual analog scales: a web experiment. *Soc Sci Comput Rev*. (2006) 24(2):227–45. doi: 10.1177/0894439305281503

27. Lau WY, Muthalib M, Nosaka K. Visual analog scale and pressure pain threshold for delayed onset muscle soreness assessment. *J Musculoskeletal Pain*. (2013) 21(4):320–6. doi: 10.3109/10582452.2013.848967

28. Pournot H, Bieuzen F, Duffield R, Lepretre PM, Cozzolino C, Hausswirth C. Short term effects of various water immersions on recovery from exhaustive intermittent exercise. *Eur J Appl Physiol*. (2011) 111(7):1287–95. doi: 10.1007/s00421-010-1754-6

29. White DJ, Olsen PD. A time motion analysis of bouldering style competitive rock climbing. *J Strength Cond Res*. (2010) 24(5):1356–60. doi: 10.1519/JSC.0b013e3181cf75bd

30. Medernach JP, Kleinöder H, Lötzerich HH. Fingerboard em boulder competitivo: efeitos do treinamento na força de preensão e resistência. *J Strength Cond Res*. (2015) 29(8):2286–95. doi: 10.1519/JSC.0000000000000873

31. Stien N, Saeterbakken AH, Hermans E, Vereide VA, Olsen E, Andersen V. Comparison of climbing-specific strength and endurance between lead and boulder climbers. *PLoS One*. (2019) 14(9):e0222529. doi: 10.1371/journal.pone.0222529

32. Valenzuela PL, de la Villa P, Ferragut C. Effect of two types of active recovery on fatigue and climbing performance. *J Sports Sci Med*. (2015) 14(4):769–75.

33. Fatouros I, Jamurtas A. Insights into the molecular etiology of exercise-induced inflammation: opportunities for optimizing performance. *J Inflamm Res*. (2016) 9:175–86. doi: 10.2147/JIR.S114635

34. Paulsen G, Mikkelsen UR, Raastad T, Peake JM. Leucocytes, cytokines and satellite cells: what role do they play in muscle damage and regeneration following eccentric exercise? *Exerc Immunol Rev*. (2012) 18:42–97.

35. Macdonald GA, Manning JW, Bodell NG, Young JC, Schilling BK, Lee SP, et al. Acute handgrip fatigue and forearm girth in recreational sport rock climbers. *Int J Exerc Sci*. (2022) 15(4):834–45.

36. Fleckenstein JL, Canby RC, Parkey RW, Peshock RM. Acute effects of exercise on MR imaging of skeletal muscle in normal volunteers. *AJR Am J Roentgenol*. (1988) 151(2):231–7. doi: 10.2214/ajr.151.2.231

37. Chen TC, Chen HL, Lin MJ, Wu CJ, Nosaka K. Muscle damage responses of the elbow flexors to four maximal eccentric exercise bouts performed every 4 weeks. *Eur J Appl Physiol*. (2009) 106(2):267–75. doi: 10.1007/s00421-009-1016-7

38. Nosaka K, Sakamoto K. Effect of elbow joint angle on the magnitude of muscle damage to the elbow flexors. *Med Sci Sports Exerc*. (2001) 33(1):22–9. doi: 10.1097/00005768-200101000-00005

39. Schoenfeld BJ, Contreras B. The muscle pump: potential mechanisms and applications for enhancing hypertrophic adaptations. *Strength Cond J*. (2014) 36 (3):21–5. doi: 10.1097/SSC.0000000000000021

40. Bergua P, Montero-Marin J, Gomez-Bruton A, Casajús JA. The finger flexors occlusion threshold in sport-climbers: an exploratory study on its indirect approximation. *Eur J Sport Sci*. (2021) 21(9):1234–42. doi: 10.1080/17461391.2020.1827047

41. Feldmann AM, Erlacher D, Pfister S, Lehmann R. Muscle oxygen dynamics in elite climbers during finger-hang tests at varying intensities. *Sci Rep*. (2020) 10 (1):3040. doi: 10.1038/s41598-020-60029-y

42. Hotfiel T, Freiwald J, Hoppe MW, Lutter C, Forst R, Grimet C, et al. Advances in delayed-onset muscle soreness (DOMS): part I: pathogenesis and diagnostics. Delayed onset muscle soreness – Teil I: pathogenese und diagnostik. *Sportverletz Sportschaden*. (2018) 32(4):243–50. doi: 10.1055/a-0753-1884

43. Lau WY, Blazevich AJ, Newton MJ, Wu SS, Nosaka K. Changes in electrical pain threshold of fascia and muscle after initial and secondary bouts of elbow flexor eccentric exercise. *Eur J Appl Physiol*. (2015) 115(5):959–68. doi: 10.1007/s00421-014-3077-5

44. Silva-Cavalcante MD, Couto PG, Azevedo RA, Gáspari AF, Coelho DB, Lima-Silva AE, et al. Stretch-shortening cycle exercise produces acute and prolonged impairments on endurance performance: is the peripheral fatigue a single answer? *Eur J Appl Physiol*. (2019) 119(7):1479–89. doi: 10.1007/s00421-019-04135-4.

45. Wan JJ, Qin Z, Wang PY, Sun Y, Liu X. Muscle fatigue: general understanding and treatment. *Exp Mol Med*. (2017) 49(10):e384. doi: 10.1038/emm.2017.194

46. Amann M, Sidhu SK, Weavil JC, Mangum TS, Venturelli M. Autonomic responses to exercise: group III/IV muscle afferents and fatigue. *Auton Neurosci*. (2015) 188:19–23. doi: 10.1016/j.autneu.2014.10.018

47. Carroll TJ, Taylor JL, Gandevia SC. Recovery of central and peripheral neuromuscular fatigue after exercise. *J Appl Physiol*. (2017) 122(5):1068–76. doi: 10.1152/japplphysiol.00775.2016

48. Fitts RH. Cellular mechanisms of muscle fatigue. *Physiol Rev*. (1994) 74 (1):49–94. doi: 10.1152/physrev.1994.74.1.49

49. Davis JM, Bailey SP. Possible mechanisms of central nervous system fatigue during exercise. *Med Sci Sports Exerc*. (1997) 29(1):45–57. doi: 10.1097/00005768-199701000-00008

50. Knicker AJ, Renshaw I, Oldham AR, Cairns SP. Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Med*. (2011) 41 (4):307–28. doi: 10.2165/11586070-000000000-00000

51. Saw AE, Main LC, Gastin PB. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *Br J Sports Med*. (2016) 50(5):281–91. doi: 10.1136/bjsports-2015-094758

52. Montull L, Slapšinskaitė-Dackevičienė A, Kiely J, Hristovski R, Balagué N. Integrative proposals of sports monitoring: subjective outperforms objective monitoring [published correction appears in Sports Med Open. 2022 May 6;8(1):61]. *Sports Med Open*. 2022;8(1):41. doi: 10.1186/s40798-022-00432-z

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