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Review

Sport climbing performance determinants and functional testing methods: A systematic review

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Abstract

Background: Sport climbing is becoming incredibly popular both in the general population and among athletes. No consensus exists regarding evidence-based sport-specific performance evaluation; therefore, this systematic review is aimed at analyzing determinants of sport climbing performance and evaluation methods by comparing climbers of different levels.

Methods: PubMed, Scopus, and Web of Science were searched up to December 20, 2022. Studies providing the self-reported climbing ability associated with different functional outcomes in groups of climbers of contiguous performance levels were eligible.

Results: 74 studies were finally included. Various methods have been proposed to evaluate determinants of sport climbing performance. Climbing-specific assessments were able to discriminate climbers of different levels when compared to general functional tests. Test validity resulted high for climbing-specific cardiorespiratory endurance as well as muscular-strength, -endurance, and -power; similarly, reliability was good except for cardiorespiratory endurance. Climbing-specific flexibility assessment resulted in high reliability but moderate validity, whereas balance showed low validity. Considerable conflicting evidence was found regarding anthropometric characteristics.

Conclusion: The present analysis identified cardiorespiratory endurance as well as muscular-strength, -endurance, and -power as determinants of sport climbing performance. In contrast, balance, flexibility, and anthropometric characteristics seem to count less. This review also proposes an evidence-based Functional Sport Climbing test battery for assessing performance determinants, which includes tests that have been identified to be valid, reliable, and feasible. While athletes and coaches should rely on evidence-based and standardized evaluation methods, researchers may design specific large-scale trials as a resource for providing additional, homogenous, and comparable data to improve scientific evidence and professionalism in this popular sport discipline.

Keywords: Endurance; Strength; Validity; Reliability

1. Introduction

At the 2020 Tokyo Olympics Games, sport climbing debuted with a format wherein each athlete competes in 3 disciplines (i.e., lead climbing, bouldering, and speed climbing) and their final score reflects the combined results of the 3 competitions.[1] Regulations will change in the 2024 Paris Olympics, wherein there will be 2 competitions (i.e., combined lead climbing and bouldering event, and speed climbing alone).

Since its debut, this unique sport activity has become increasingly popular and is set to become more and more professional. It is characterized by specific functional requirements, and thus various research has aimed to assess and

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monitor climbing-specific fitness, to optimize climbing-specific training, and to develop new training methods.[2–11] Researchers have identified various physiological functions and requirements that potentially determine climbing performance. Of particular interest are assessments of hip flexibility; shoulder, core, and finger muscle strength and endurance;[12–22] grip strength and endurance;[17,23,24] cardiorespiratory endurance;[25] body composition;[26–28] as well as postural balance control.[29]

In the pursuit of identifying performance indicators, many studies investigate differences between climbers and non-climbers or between climbers of different disciplines. For instance, research shows boulder athletes have greater hand-grip and finger strength compared to aerobically trained non-climbers but similar body composition and core endurance.[30] Compared to powerlifters and endurance athletes, sport climbing in particular promotes increased upper body strength.[31,32] Within the climbing context, boulder climbers seem to have greater upper body and finger strength and power compared to lead[19,20,33,34] and speed climbers.[34]

Performance determinants that distinguish the performance level of climbers are also of particular interest. Laffaye et al.[35] described 3 overall components: training, muscle, and anthropometric characteristics—which explain about 64% of the variance in climbing performance, with trainable variables alone accounting for 46%. Similarly, in the study done by Mermier et al.[27] training components explained 59% of climbing performance in male and female climbers, while the contributions of anthropometry and flexibility were only around 1%. These findings do not support a significant influence of specific anthropometric characteristics on climbing performance.[36] Regarding the best climbing performance in on-sight and redpoint style, maximal relative strength and isometric endurance of the fingers, ape index (i.e., the ratio of arm span relative to body height), oxygen uptake during arm work at the anaerobic threshold, mental endurance, climbing technique, and attention and reaction time were found to explain 77% of the overall performance variance of advanced male climbers.[37] These findings add mental and technical components to the core set of physical requirements. Furthermore, ascent strategy and movement repertoire relative to the specific demand of the route appear to positively influence climbing performance.[38]

Various studies have tried to improve tests for assessing and monitoring climbing-specific fitness, optimizing climbing-specific training, and developing new training methods based on physiological functions and requirements that most strongly determine climbing performance.[2–11,39] While some of them focused on physiological determinants of climbing performance,[3–5,11] others translated them into training recommendations for developing strength and endurance and enhancing sport climbing performance.[6,7]

Even though scientific knowledge is increasing, current evidence on performance-determining factors in climbing is limited due to the lack of standardization of testing protocols and study populations.[9,10] Also, validity and reliability measures are rarely reported, further limiting an evidence-based approach.[10] A recent attempt to establish a test battery was made by Draper et al.,[40] who proposed the finger hang and "power slap" tests as valid and reliable sport-specific performance measures. The authors emphasize that future research is required to identify evaluation methods of flexibility, strength, and core stability capable of differentiating between climbing ability levels. Nonetheless, there is still no consensus on an evidence-based sport-specific performance assessment tool for the evaluation of functional determinants that would enable researchers to better predict performance, monitor training progress, and differentiate between climbers of different levels.[10]

Therefore, the present systematic review aimed to summarize the validity and reliability of climbing-specific tests for assessing performance determinants in climbers of different contiguous performance levels. The focus will be on tests that assess cardiorespiratory endurance; muscular strength, endurance, and power; flexibility; and balance (either in general or in a climbing-specific setting). Furthermore, this review aimed to provide an evidence-based and practical performance test battery to facilitate standardized monitoring and planning of training programs for these athletes.

2. Methods

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines.[41]

2.1. Search strategy

The literature search and article screening were performed up to December 20, 2022 in 3 electronic databases (PubMed, Web of Science, and Scopus). Limiting results to English articles, the research strategy included the following terms: ("sport climbing" OR "rock climbing" OR "climbing performance" OR "climbers") AND ("test" OR "evaluat*" OR "measur*" OR "assess*" OR "determinants") AND ("anthropometr*" OR "cardiopulmonary" OR "cardiorespiratory" OR "strength" OR "force" OR "finger" OR "flexibility" OR "power" OR "resistance" OR "endurance" OR "balance" OR "lactate"). In addition, reference lists from the included studies and relevant reviews were scanned to identify further articles for inclusion.

2.2. Study selection, inclusion, and exclusion criteria

The PICO (Population, Intervention, Comparison, Outcome)-style approach was adopted for deciding study eligibility. Articles were eligible if the "participants" were male and/or female human climbers of different self-reported climbing abilities, which had to be clearly specified. Regarding "intervention", a study was includible if it comprised climbing-specific or general functional evaluations. Moreover, the "comparative" factor as the main inclusion criteria identified studies that either perform a correlation analysis of outcomes measured with the self-reported climbing ability or where differences between groups of contiguous level of performance have been determined (i.e., lower grade *vs*. intermediate *vs*. advanced *vs*. elite *vs*. higher elite climbing level). “Outcomes” of interest were the validity and reliability of anthropometric characteristics and physiological determinants: cardiorespiratory endurance, muscular strength, muscular endurance, muscular power, flexibility, and balance assessed within or outside a specific climbing context. Cross-sectional, observational, and comparative studies have been included. Some intervention trials were also included, wherein the baseline assessment of climbers before the intervention was considered. Case control studies and reviews have been excluded. Further exclusion criteria were applied for those trials that assessed athletes from disciplines other than sport climbing (e.g., ice climbing) and for those that focused on cognitive and psychological aspects or diet.

Abstracts, full texts, and reference lists from included articles were scanned and assessed for eligibility by 2 authors (SF and NB). Conflicts were resolved by discussion among the authors.

2.3. Data extraction and synthesis

Data extraction was performed by 2 authors (SF and NB) to standardize outcome reporting. Characteristics of each included article were categorized by: reference, population, climbing ability group, age, height, body mass, climbing ability according to the International Rock Climbing Research Association (IRCRA) Reporting Scale, discipline, and outcome category. Functional outcomes extracted from included articles were classified into the following categories according to the American College of Sports Medicine:[42] cardiorespiratory endurance, muscular strength, muscular endurance, muscular power, flexibility, anthropometry, and balance. Apart from anthropometric and balance components, each of the other functional requirements was divided into general and climbing-specific characteristics according to the measurement methodology. For each outcome category, results are presented as follows: reference, population, climbing ability group (from lower grade to higher elite), test procedure, specific outcome, and association with climbing ability. The latter is presented by reporting either the correlation coefficient for the degree of linear association between the measured outcome and the self-reported climbing ability or the difference in the outcome between climbing levels. For missing data, authors were contacted. Significance levels of both the correlation index and the differences between groups were set as $p < 0.05$. The strength of the absolute numerical size of the correlation coefficient was considered weak ($r \leq 0.35$), moderate ($0.36 \leq r \leq 0.67$), strong ($0.68 \leq r < 0.90$), or very strong ($r \geq 0.90$).[43] In addition, analyzing reliability, the intraclass correlation (ICC) and coefficient of variation (CV) have been interpreted to have excellent reliability when, respectively, ICC > 0.9 and CV < 10%.[44–46]

In evaluating testing procedures, the correlation analysis may help to evaluate the validity of the measurements by comparing tests of unknown validity with tests of known validity.[47] The reference standard considered for the test of known validity has been identified in the self-reported ability (either redpoint (RP) or on-sight (OS)), which stands for the current (within the last 12 months) best on-sight ascent grade.[48] Redpoint is defined as a successful climb without falling after having made previous unsuccessful attempts,[6] whereas on-sight is defined as a successful climb at first attempt without prior knowledge of the route.[6] In this systematic review, both grading methods were considered valid and are reported when available. Moreover, the stratification of climbers based on their self-reported climbing ability was done according to the universal IRCRA scale developed by Draper et al.[49] It classifies climbers according to their highest self-reported RP ascent and provides breakpoints between lower grade, intermediate, advanced, elite, and higher elite male and female climbers. This numerical scale allows for the conversion of a variety of climbing scales to a specific score. In the present systematic review, the IRCRA Reporting Scale enabled the comparison of climbing performances between different studies.

2.4. Validity and reliability analyses

Results are presented as interclass correlation coefficients or differences between climbing levels to assess concurrent and construct validity, respectively. Concurrent validity refers to the performance test outcome and its correlation with the criterion measure—for example, the correlation between time to failure and self-reported climbing ability. Construct validity refers to the degree to which a test outcome measures a hypothetical construct—for example, the difference of time to failure between advanced and elite climbers.

Once strong or very strong correlations or significant differences were found, the ICC and CV analyses were done to produce reliability coefficients for the methodologies used to assess the respective outcomes.

3. Results

The systematic review PRISMA flow-diagram is presented in Fig. 1. The search through 3 electronic databases provided 1789 results. After removing duplicates, 986 articles were screened based on titles and abstracts, of which 243 full-text articles were further screened, resulting in 65 articles matching the selection criteria. Subsequently, 9 eligible articles were identified by scanning reference lists of the included articles. Therefore, a total of 74 articles were analyzed in this systematic review.

3.1. Study and participant characteristics

Included articles were published between 1993 and 2022. Characteristics of included studies are reported in Supplementary Table 1. Thirty-eight studies analyzed only male climbers,[17,25,35,46,51-56,60,66,69,70,74,76,78,79,81,83–88,90–93,96,98–100,103–105,108,115] 32 studies analyzed both male and female climbers,[16,26,40,57–59,61–65,67,68,71–73,75,77,80,89,94,95,97,101,102,116,117,118–122] while 2 studies included females

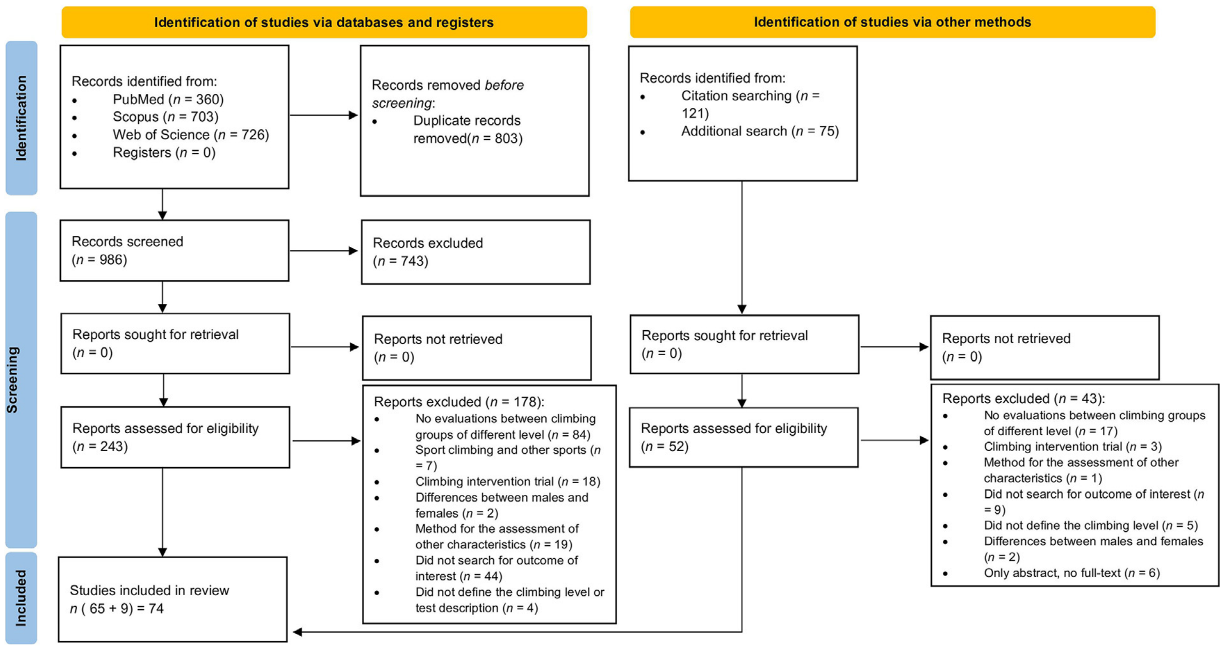

Fig. 1. PRISMA flow-diagram of articles selected and included in the systematic review.

only.[36,82] Sex was not specified by Ozimek et al.[28] nor by van Bergen et al.[50]

Fig. 2 represents the number of studies that evaluated specific outcome categories in climbers of contiguous climbing ability levels.

A total of 2691 climbers were included (25% females; the sex of 42 climbers was not specified), with ages ranging from 16 to 60 years. Climbers were classified into lead, boulder, both lead and boulder, as well as speed climbing categories in 52,[17,25,35,36,40,46,50−56−58,60−62,65,67,68−70,72,73,75,76,80,83−95,97,100,103−105,108,117,119,121] 4,[28,63,64,74] 16,[16,26,59,67,71,77−79,81,82,98,101,102,116,118,120] and 2[96,99] studies, respectively. When not specified, climbers were considered to be lead discipline. The ability level ranged from lower to higher elite grade for both males and females. An overview of available functional testing methods organized by category of performance is provided in Fig. 3. Analyses of validity and reliability for each performance outcome are reported in Supplementary Tables 2A−2D, 3A−3D, 4A−4D, 5A−5D, 6A−6D, 7A−7B, and 8A−8B.

3.2. Cardiorespiratory endurance

3.2.1. General cardiorespiratory endurance

Four[25,51,52, 68] of 7 studies found either significant correlations or differences between climbers of different climbing levels (Supplementary Tables 2A and 2B). Only peak oxygen uptake (VO_2) relative to body mass and peak power output relative to body mass assessed by an incremental maximal upper-body ergometer test displayed a strong correlation with climbing performance (r: 0.72 − 0.85) in elite male lead climbers.[51] Furthermore, time to failure as well as peak and mean power output during upper limb maximal incremental tests were significantly different between intermediate and advanced-elite male lead climbers.[25,52]

3.2.2. Climbing-specific cardiorespiratory endurance

Twelve studies[52−60,105,108−109] out of 13 found a significant relationship between climbing-specific cardiorespiratory endurance and climbing ability (Supplementary Tables 2C and 2D). Only in elite male athletes was a strong correlation reported between the self-reported redpoint climbing ability and the time to failure (assessed by traversing a near-ground standardized climbing route with a move every 5 s) ($r = 0.94$),[53] and blood lactate clearance rate following the climb ($r = 0.75$ RP, 0.82 OS). Furthermore, strong correlations were found in a group of male climbers from lower grade to elite level for mean heart rate and mean VO_2 while performing a set of climbing circuits on a 3-m high and wide bouldering wall (r: −0.77 to −0.84),[54] as well as for blood lactate recovery after climbing a route gradable as 7a (French Scale) ($r = 0.69$).[55] Without standardizing the climbing speed on a route of 25 movements, significant differences were reported between intermediate and advanced-elite male climbers for peak heart rate, highest post-climbing blood lactate concentration, and total metabolic work.[52] Performing the same ascent but going up and down as fast as possible over a 3-min period, intermediate male climbers showed a lower number of movements and a higher VO_2 time integral per number of movements than advanced-elite athletes;[56] this test showed an excellent reliability (ICC = 0.97). When standardizing the difficulty (IRCRA 7) and climbing speed of the route on a wall, the intensity—measured as Rating of Perceived Exertion (RPE) and Respiratory Exchange Ratio (RER)—appeared to be higher for lower-level compared to intermediate-level climbers.[57]

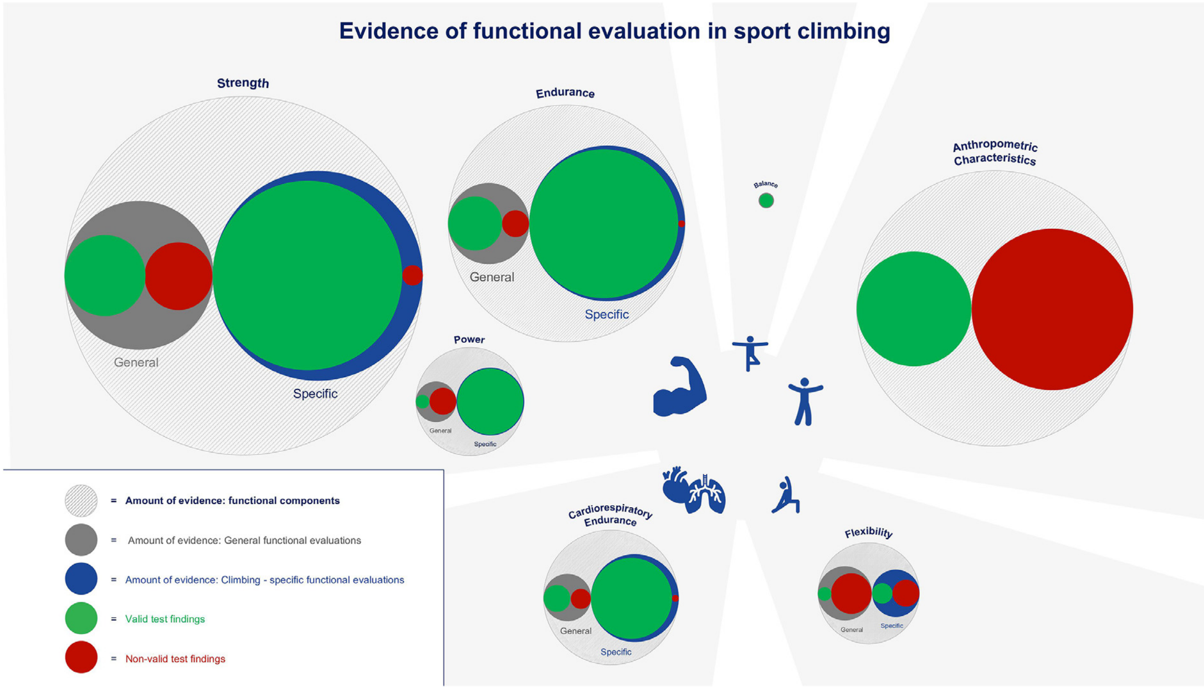

Fig. 2. Qualitative representation of current evidence regarding functional evaluation in sport climbing. Evidence regarding categories of sport climbing determinants is represented by a hierarchy circle chart; each circle's radius is proportional to the relative valid and non-valid evidence for different functional components and evaluation methods (see legend in figure). 3.8% and 7.1% of studies assessed general and climbing-specific cardiorespiratory endurance, respectively. 12.1% and 17.0% of articles evaluated general and climbing-specific muscular strength, respectively. Regarding muscular endurance, 6.6% and 12.6% of studies included general and climbing-specific muscular endurance assessment. General muscular power was analyzed by 3.3% of studies, while 5.5% assessed the climbing-specific muscular power. General flexibility was analyzed in 4.4% of studies only, and climbing-specific flexibility in 3.8% of articles. 1.1% of studies evaluated balance, while 22.5% analyzed anthropometric characteristics. Valid evidence means that studies found at least 1 statistically significant finding either as concurrent validity, by assessing the interclass correlation between outcome and climbing ability, or construct validity, by assessing differences between contiguous groups of climbers from lower grade to higher elite level; non-valid means that studies did not find any statistically significant results.

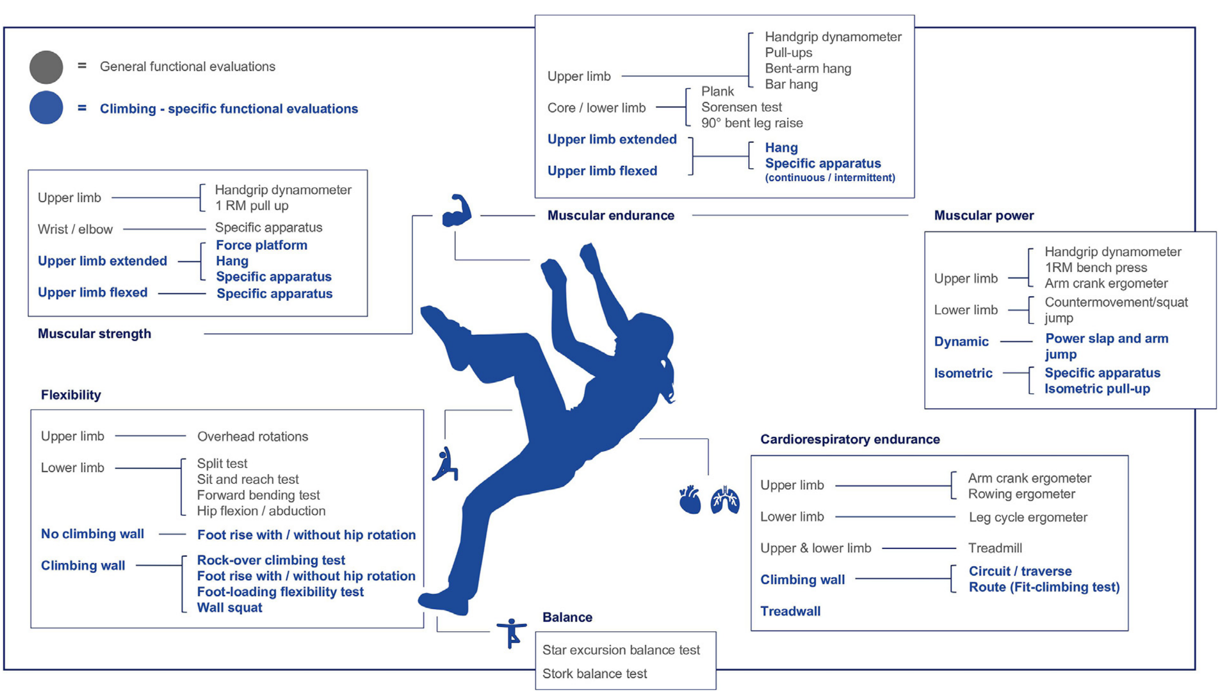

Fig. 3. Overview of available functional testing methods categorized by component of performance.

The same standardized ascent on a climbing ergometer (i.e., treadwall) at a 0° vertical angle confirmed higher RPE for lower-level compared to intermediate-level climbers, while RER and respiratory frequency discriminated between intermediate and advanced climbers.[57] Furthermore, climbing-specific cardiorespiratory endurance assessed on a treadwall showed strong correlations with and significant differences for time to failure in male climbers from advanced to elite level ($r = 0.76$).[58] Peak climbing velocity resulted in significant differences between advanced and elite male athletes, while correlation analysis with climbing ability was not performed. Across the spectrum of intermediate to advanced climbers, a strong correlation with bouldering ability ($r = 0.70$) was found for male and female climbers in the capacity to climb overhang, as assessed by an incremental climbing ergometer test at a constant speed of 9 m/min and increasing overhang.[59] Using a similar protocol, a strong correlation was found in intermediate to advanced male climbers for the peak angle (i.e., the maximum vertical inclination achieved by the athlete during the incremental treadwall test) ($r = 0.84$).[60] This peak angle also revealed significant differences between intermediate and advanced male climbers associated with corresponding physiological changes in heart rate, VO_2, minute ventilation, and flexor digitorum profundus (FDP) oxygen saturation at different wall angles. In more experimental evaluations, the FDP muscle oxygenation breakpoint has been assessed by the inflection point of the test-related deoxyhaemoglobin curve.[60] No reliability analysis was conducted during treadwall climbing tests.

3.3. Muscular strength

3.3.1. General muscular strength

Twelve studies[36,55,56,61–64,66–68,80,103] reported at least 1 statistically significant difference within or between climbing levels in muscular strength assessed in a non-climbing-specific setting, whereas 10 studies[17,35,53,58,69,70,74,88,114,123] did not (Supplementary Tables 2A and 2B). Strong correlations were found only for female climbers from lower grade to elite level regarding the maximum handgrip force relative to body mass (r: 0.72−0.76).[61,62] Conflicting results are corroborated by Watts et al.,[36] who measured a higher absolute (but not relative) handgrip force in advanced female climbers than in elite athletes. Boulder athletes only showed moderate correlations for this evaluation.[63,64] Excellent reliability values (ICC: 0.89−0.97) were reported for the handgrip test.[63,80] In a climbing-specific fatigue state, 1 study described a higher relative handgrip strength in advanced-elite compared to intermediate male athletes, and also a lower force reduction (%) between pre- and post-climbing.[56] Furthermore, significant moderate correlations were found for the maximum wrist flexion and elbow strength relative to body mass measured with an isokinetic device and climbing ability in advanced to elite male climbers[66] and in intermediate to advanced boulder athletes, respectively.[67] Also, the maximal bicep and pincer strength assessed with a functional isokinetic dynamometer showed only moderate correlations with climbing ability of intermediate to advanced male climbers.[68] The upper-limb strength assessment using the 1 repetition maximum (1RM) weighted pull-up did not show any significant correlation or differences between climbing levels.[69,70]

3.3.2. Climbing-specific muscular strength

Results are reported differentiating between testing protocols with upper limbs extended above the head and upper limbs flexed (Fig. 4). Of the 31 studies evaluating muscular strength in a climbing-specific manner, and therefore miming the climbing grip, 28[16,17,35,40,46,50,60,65,66,69–87] reported a statistically significant correlation/difference with the climbing ability (Fig. 2, Supplementary Tables 3C and 3D). Finger flexor muscle force with 1 or both upper limbs extended above the head has been tested using either a force transducer under the fingers, force platforms or electronic scales under the feet, or a system to add/remove weight, with strength expressed either as an absolute value or relative to body mass. Five studies found significant correlations/differences between climbing ability and finger flexor muscle force determined by adding or removing weight to the body while hanging from a rung with 1 or both upper limbs extended above the head.[69–73] Four studies assessed the outcomes of finger strength by hanging from a rung while standing on a force plate,[40,65,74,75] and 9 used a climbing-specific apparatus with a force transducer system under the rung.[50,60,76–82]

By adding or removing weight, a strong correlation ($r = 0.70$) was reported in advanced male climbers between climbing ability and maximal additional weight maintained for 3 s while gripping a 25 mm-deep ledge with both hands using a half crimp grip.[70] Similarly, in male and female elite climbers, the maximum added weight relative to body mass and edge depth (the minimum possible according to a previous test) maintained for 5 s with a bilateral hang correlated with climbing performance ($r = 0.84$) and was also significantly higher compared to advanced climbers.[73]

Using the force plate or electronic scale and measuring the decrease in body weight obtained by hanging on different edges with different hand and finger grips revealed strong correlations and significant differences between climbing levels, particularly for male athletes from lower grade-intermediate to elite levels (r: 0.71−0.81).[40,65,75] Regarding bouldering, only a moderate correlation was recorded when holding a 10 mm-deep edge with the middle and ring fingers ($r = 0.63$).[74] Reliability analysis displayed almost excellent ICC (>0.88) and good CV values (18.4%) by adding/removing weight and using force plates.[65,69–71,73,74]

With regard to climbing-specific devices for measuring the maximal finger flexor muscles strength with a slope grip and the upper limb extended above the head, a strong correlation was reported with climbing ability in intermediate to higher elite male lead and boulder climbers (r: 0.69−0.82; relative to body mass).[78,79,81] In addition, increased finger flexor muscle force was reported in higher elite *vs.* elite-advanced climbers,[76] as well as in advanced compared to intermediate climbers.[60] Moderate correlation coefficients were found in advanced to elite climbers with both redpoint and on-sight

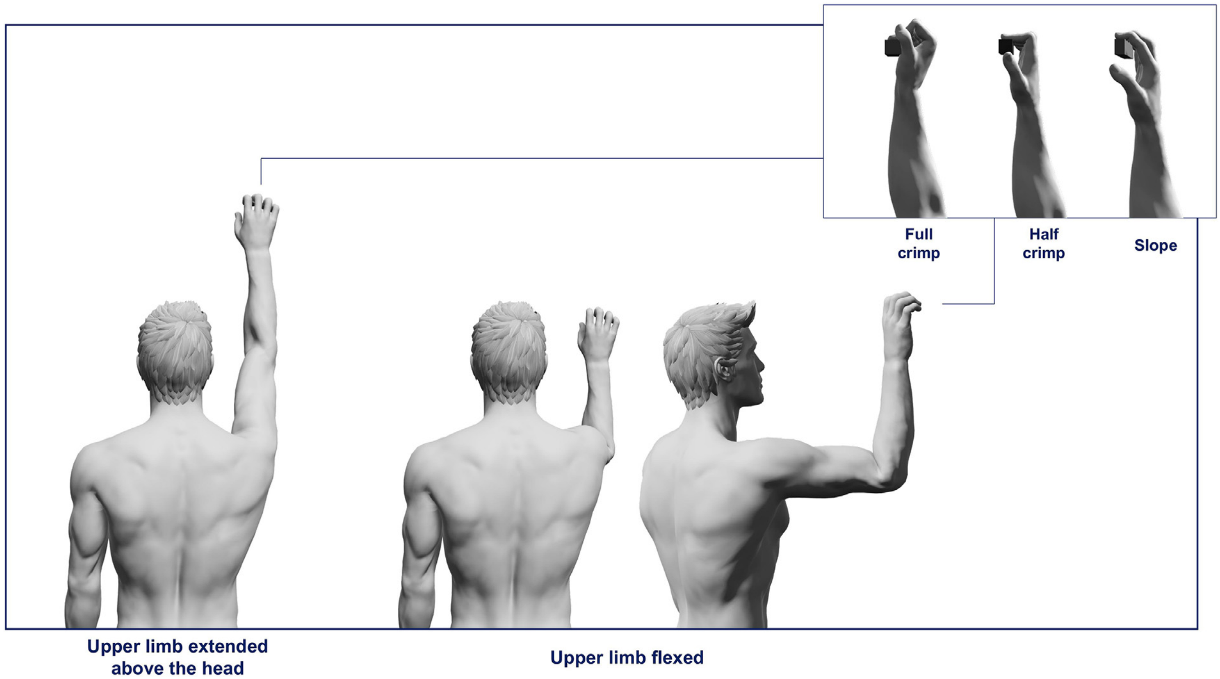

Fig. 4. Upper limb position during climbing-specific muscular strength and endurance tests. “Full crimp” also known as “closed crimp” grip, and “slope” also known as “open” grip.

climbing ability ($r = 0.59$ RP, 0.67 OS).[50] Moreover, the absolute maximal finger flexor muscles force appeared to be higher in intermediate-advanced climbers in comparison to lower grade athletes.[80] Similar moderate correlations have been found with both lead and boulder ability ($r = 0.46-0.64$ relative to body mass, r: $0.39-0.48$ absolute value),[77,82] with an increasing trend from intermediate to lower elite female climbers. These protocols reached excellent reliability with ICC values between 0.88 - 0.99.[50,79,80]

Thirteen studies assessed the muscular strength of the fingers using a testing protocol with the upper limb flexed at different angles, in most cases measuring the force by using a force transducer under the fingers.[16,17,35,46,50,79,80,83,84]. Some studies used a modified protocol by anchoring a static rope between a force cell on the ground or the ceiling and the climber.[77,85–87] A strong correlation was found between climbing ability and the absolute maximal finger flexor muscle force ($r = 0.72$)[35] in lower grade to elite male climbers, and the same such relationship was found in the intermediate to advanced male climbers ($r = 0.71$).[83] Relative to body mass, the maximal finger force showed moderate to strong correlations with intermediate to elite climbing ability using a slope grip (r: 0.67 RP, 0.72 OS)[50] or half (r: 0.60, 0.65)[17,79] or full crimp grip (r: 0.47 RP, 0.58 OS).[50] This testing method was able to discriminate elite from advanced athletes,[46] advanced from intermediate,[84] and intermediate-advanced from lower grade climbers.[35,80] Such strong correlations have also been confirmed for advanced-elite lead and boulder female climbers ($r = 0.92-0.97$).[16] Reliability analysis results were excellent (ICC = $0.93-0.99$, CV < 6%).[35,46,50,65,79,84]

According to the other methods described above, performing an isometric pull-up with a half crimp grip as quickly and forcefully as possible with the elbow flexed at 90°, elite male climbers developed an absolute peak force higher than advanced climbers (CV = 9%),[85,87] and the same was true for advanced as compared to intermediate climbers.[87] The correlation coefficients appeared strong from intermediate to elite (r: $0.73-0.79$)[87] and from intermediate to advanced climbing ability ($r = 0.73$) (ICC: $0.79-0.85$).[86] Furthermore, the relative maximal arm lock-off force (i.e., force exerted by pulling downward on a steel rung with the upper arm extended frontally, the elbow flexed at 90°, and the forearm perpendicular to the floor) showed a moderate correlation coefficient (r: $0.54-0.63$) and a significant difference between intermediate and advanced female climbers.[77]

3.4. *Muscular endurance*

3.4.1. *General muscular endurance*

General muscular endurance has been assessed by 12 studies, with 8[40,62,64,68–70,88,113] of them reporting statistically significant correlation coefficients/differences when climbing ability and group level are compared (Supplementary Tables 4A and 4B).

The outcome typically determined in these testing protocols was either the number of repetitions or the time to failure for different exercises. The number of pull-ups performed was able to discriminate male and female elite climbers from advanced, as well as male intermediate from lower grade climbers (ICC = 0.97).[40,69] Moreover, in intermediate to advanced climbers, the number of pull-ups significantly and strongly correlated with climbing ability (male: $r = 0.77$, female: $r = 0.73$).[68] The time to failure of a 2-arm bent-arm hang test also enabled differentiation between climbers of

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distinct performance levels, except for the intermediate-advanced level (ICC = 0.89).[40,88] This test displayed a strong correlation with climbing ability from lower grade to higher elite (male: $r = 0.70$, female: $r = 0.80$)[62] and from intermediate to advanced climbers (male: $r = 0.73$, female: $r = 0.74$).[68] In these 2 tests, the CV was significantly higher in lower levels and females than in higher levels and male climbers. Furthermore, in intermediate female boulderers, the number of pull-ups done hanging from 2 jug holds revealed a moderate correlation with climbing ability ($r = 0.57$).[64] Regarding core muscular endurance, time to failure performing the plank position was able to discriminate only intermediate male and female climbers from lower grade climbers; the 90° bent leg raise test showed no differences in males of different levels, but differences between advanced and intermediate levels were reported in females.[40] Average force and force-time integral assessed with a handgrip dynamometer via multiple repetitions or until failure did not display significant results.[58,89]

3.4.2. Climbing-specific muscular endurance

Climbing-specific muscular endurance was analyzed by 23 studies[17,35,40,60,62,69,70,72,73,76,78,79,81,84,89–95,113], and only 1[111] did not find significant performance related results (Supplementary Tables 4C and 4D). Testing modalities were divided into hanging on a ledge or using a climbing-specific apparatus, performing either a continuous or an intermittent contraction with upper limbs extended above the head or flexed (Fig. 4). Tests performed by hanging on a ledge were mostly done in a continuous manner and with upper limbs extended above the head. A bilateral continuous finger-hang on a 30 mm-deep rung showed differences between each climbing level category,[40] revealing strong correlations from lower grade to higher elite climbers (male: $r = 0.87$, female: $r = 0.81$).[62] Other strong correlations with climbing ability were found in elite male and female climbers for both time to failure and the minimum edge depth hold for 40 s, respectively (r: 0.77 to −0.73) also proving differences between elite and advanced climbing levels.[69,73] Moderate correlations were found in 4 other studies in advanced to elite climbers for time to failure and relative occlusion threshold of finger flexors (i.e., relative force limiting blood flow).[69,70,72,89] Time to failure while hanging continuously on a rung with upper limbs extended above the head showed almost excellent reliability ($0.88 \leq \text{ICC} \leq 1.00$), but the CV ranged between 32% and 11%, with higher values in lower grade/intermediate climbers and females.[40,70,73,90] Only 1 study evaluated the suspension time in intermediate to elite climbers performing a half crimp grip hang on a 40 mm-deep wooden rung with elbows flexed at 90°, and it reported a strong correlation with climbing ability ($r = 0.69$) and significant differences between these climbing levels.[17] Núñez et al.[90] reported differences between intermediate and higher advanced-elite male climbers performing an intermittent progressive effort of multiple steps with suspensions on 5 different ledges of a multi-hold panel; outcomes of interest were time to failure, step reached, and maximum number of repetitions.

When using more advanced methods involving specific devices or a dynamometer to assess the finger flexor muscle force over time, 10 studies[17,35,60,76,78,79,81,91,93,94] found significant correlations/differences within and between climbing groups, respectively. In continuous tests with upper limb extended above the head and maximal effort maintained for 30 s, the average maximal finger muscles force relative to body mass was strongly and directly correlated with redpoint climbing ability (r: 0.80−0.82)[76,81] of intermediate-advanced to higher elite male climbers ($r = 0.72$ force-time integral relative to body mass),[81] with higher elite athletes performing better than advanced-elite climbers. A strong correlation was also found for both time to failure and the sustained contraction impulse during continuous 60% maximal voluntary contraction (MVC) on a 23 mm-deep rung in advanced to higher elite male and female climbers ($r = 0.69$)[91] as well as in intermediate to advanced male climbers ($r = 0.75$).[60] Concerning boulderers' muscular endurance, a strong correlation was found within the intermediate to advanced performance level by assessing continuously for 30 s the all-out force with upper limb extended above the head and flexed at 90° ($r = 0.76$ and 0.72, respectively; ICC = 0.92).[79] Flexing the upper limb and adjusting the elbow on a plate, trying to maintain 40% of the MVC as long as possible, the tissue oxygenation and respective recovery of the FDP showed better performance in advanced male climbers as compared to intermediate.[92,93]

The climbing-specific apparatus used to assess muscular endurance of finger flexor muscles was also applied in intermittent tests by alternating contraction to rest phases with different work:rest ratios (e.g., 4:1, 3:1, 2:1, 1:1). The critical force of finger flexor muscles relative to body mass, which was determined by extending the arm above the head to develop as much intermittent force as possible (work:rest ratio = ∼2:1), was strongly and positively correlated with the self-reported climbing ability of intermediate to higher elite male and female climbers ($r = 0.79$, sex adjusted).[94] Performing until failure while maintaining 60% of MVC with 4:1 work to rest ratio discriminated advanced from intermediate male climbers.[60]

Similarly, while maintaining 40% of MVC until failure with upper limb flexed and work to rest duration of 10s work:3s rest, the force-time integral displayed higher values in advanced than in intermediate male climbers.[84] Differences in muscular endurance when performing repeated MVC were also highlighted in males from elite to lower grade climbing levels.[17,35] In addition, strong correlations with climbing ability were found for finger flexor muscular endurance while performing repetitive MVC in fatigue conditions for intermediate to elite male climbers ($r = 0.74$).[17]

The arm jump fatigue index (i.e., performing 10 explosive pull-ups with 10 s of rest after each repetition) was provided by Laffaye et al.[35] as a different method of assessing climbing-specific muscular endurance; it showed moderate correlations with climbing ability in lower grade to elite male climbers ($r = -0.64$). A force platform was used by Augste et al.[95] to assess the maximum number of repetitions while maintaining 60% of MVC with a half crimp grip, revealing strong and positive correlations with the self-reported climbing ability of lower grade to elite male climbers.

3.5. Muscular power

3.5.1. General muscular power

General muscular power has been assessed by 6 studies[35,58,64,68,70,96] (Supplementary Tables 5A and 5B). MacKenzie et al.[68] used a specific arm crank ergometer with submaximal resistance to report statistically significant correlations between the maximal/average power of shoulder muscles and the climbing ability of intermediate to advanced male climbers (r: 0.56−0.60). Interestingly, Krawczyk et al.[96] found strong correlations of countermovement jump height, power, and velocity with climbing performance in elite male speed climbers (r: −0.78 to −0.90, CV: 6.67%−16.28%). None of the other test procedures assessing the rate of force development (RFD), maximal power, and force (e.g., handgrip dynamometer, the 1RM bench press, the countermovement or squat jump) in lead and boulder athletes displayed significant results.

3.5.2. Climbing-specific muscular power

All 10 studies[35,40,46,82,85,87,96−99] assessing muscular power in a climbing-specific manner found significant associations within and between climbing ability levels (Supplementary Tables 4C−D). Functional evaluations are described based on their dynamic or isometric test modality. The main outcome evaluated with a dynamic power test was the slap height, which is the magnesia mark left by the hand after performing an explosive pull-up. This slap height tended to be highest in elite male and female climbers and was reduced with decreasing climbing level. Modifying test procedures by starting from a narrow position of the hands or releasing both hands improved the correlation (r: 0.69−0.79). Measurements of reliability were excellent in all males and higher-level females (0.95 ≤ ICC ≤ 0.98 and CV = ∼5%).[35,40,97,98] This test revealed only a moderate correlation with climbing ability in advanced-elite female boulder athletes.[82]

Two studies evaluated video-based power estimations during speed climbing relative to body mass in elite and higher elite male speed climbers and reported very strong correlations with the best individual climbing time (r: 0.90−0.98, CV: 3.46%−21.17%).[96,99]

Only 3 studies found significant differences between elite and advanced male climbers when assessing RFD by isometric muscular power tests.[46,85,87] Two tests[85,87] consisted in performing an isometric pull-up as quickly and forcefully as possible with a taut rope anchored to the ground and climbing harness, while 1 test[46] was performed with elbow and shoulder flexed at 90° to develop maximal power using either a slope or a half crimp grip. Significant differences between elite and advanced male climbers were detected for the RFD of the maximal finger flexor muscle force using both grips.[46,85,87] However, the time period considered for the RFD assessment might be a critical factor leading to conflicting study results and affecting correlations with self-reported climbing ability.[46,85,87]

3.6. Flexibility

3.6.1. General flexibility

General flexibility was analyzed by 8 studies,[58,64,68,77,82,100,101,123] and only 2[68,100] of them found moderate correlations in male climbers (Supplementary Tables 6A and 6B). Draga et al.[100] reported moderate correlations for the maximal straddle stand and sit score with climbing ability of advanced to higher elite climbers. Mackenzie et al.[68] evaluated the leg span as well as the sit and reach score, showing moderate correlations with climbing ability in intermediate to advanced male climbers.

3.6.2. Climbing-specific flexibility

Climbing-specific flexibility was mainly assessed using functional evaluations, which were performed on a climbing wall trying to simulate the climbing gesture. Three studies[40,101,102] out of 7[40,68,77,82,100−102] found a significant relationship between the measured outcomes and climbing ability (Supplementary Tables S5C−D). Generally, the flexibility of the lower limbs was assessed through a "foot rise test" starting with hands and feet on holds at the respective participant's height and raising the foot as high as possible, with or without the possibility to rotate the hip. When rotation of the hip was allowed, elite male athletes performed better than advanced, while intermediate performed better than lower grade climbers.[40] Positive moderate correlations were found with climbing ability from lower grade to higher elite climbers.[101] The test can be adapted by loading the risen foot and transferring the weight over the hip. Outcomes should always be related to the subject's height.[101] A further development of the latter test consists in reaching the highest possible wooden rung with the hand. Climbers' height-adjusted "rock-over climbing test" (ROCT) scores were positively correlated with climbing ability from lower grade to higher elite athletes (r = 0.67), with a continuous decrease in the score between advanced, intermediate, and lower grade climbers (ICC = 0.90).[102]

3.7. Balance

Regarding balance analyses, only 2 studies[64,68] were eligible for inclusion (Supplementary Tables 7A and 7B). Moderate correlations between balance and climbing level were found in a group of 14 male boulderers performing the "Star Excursion Balance" test (r: 0.47−0.59, left-right),[64] which consists in standing on 1 leg and reaching as far as possible along a taped line on the floor with the contralateral leg in anterior, posterior, medial, and lateral directions, and recording the farthest point reached. A further moderate correlation was found in intermediate to advanced female climbers with standing time on the unilateral forefoot (r = 0.58).[68]

3.8. Anthropometric characteristics

Forty-one studies analyzed anthropometric variables, of which 17[25,26,28,36,51,52,58,62,64,66,87,92,98,103−105,108] found significant differences between and within climbing levels (Supplementary Tables 8A and 8B).

Of the 4 studies[26,36,66,98] analyzing the effect of body height, conflicting negative and positive correlations with climbing ability were seen in intermediate to higher elite male climbers (r: −0.38, 0.69).[26,66] Indeed, a lower height was observed in elite female climbers when compared with advanced athletes;[36] similarly, intermediate and lower grade male climbers differed significantly in body height.[98] Regarding body mass and body mass index, again, conflicting correlations with climbing ability in intermediate to higher elite male climbers have been reported (r: −0.47, 0.71).[26,51,66] Similarly, results are contradictory in female athletes as both positive and negative correlations have been found between body mass and body mass index and climbing levels in intermediate to elite athletes (r: 0.87, −0.70).[58,64] Nonetheless, lower body mass in elite as compared to advanced female climbers has been described.[36] The body height/body mass ratio was positively correlated with the climbing level of lower grade to elite male climbers ($r = 0.80$),[103] while the Roherer's index (body mass/height^3) was inversely correlated in intermediate female boulderers ($r = -0.70$).[64] Moreover, positive correlations with climbing levels were found in advanced to elite boulder and lead climbers for arm length ($r = 0.77$), arm length index (arm length/body height) ($r = 0.80$),[28] hand length ($r = 0.72$), and forearm width ($r = 0.80$).[58] Shoulder width ($r = 0.68$)[64] also showed strong correlations with intermediate climbing ability in females. The ape index revealed only moderate positive correlations with climbing ability from lower grade to elite male and female climbers.[35,68,98,104] Regarding body composition analyses, 13 studies[25,28,36,51,52,58,62,64,87,92,104–105,108] found significant correlations/differences in climbers of different performance levels, particularly related to body fat mass in male and female athletes ($r = -0.61$ and -0.47 respectively).[62,104] When the group is limited to elite male boulder and lead climbers, stronger negative correlations with performance were found (r: −0.78, −0.82),[28,51] showing lower values of fat mass as climbing level is increases.[25,36,52,87,105,108] Lean body mass was positively correlated with climbing ability in advanced to elite female climbers ($r = 0.80$),[58] although another study reported opposite results for the fat-free mass of elite females, showing lower values than in advanced climbers.[36] Only 1 study found a strong negative correlation between the endomorphic profile and elite boulder level ($r = -0.74$)[28] and between forearm lean mass and advanced to elite climbing level in males.[58] Moreover, higher skinfold thickness was found in intermediate climbers when compared to higher advanced-elite male athletes.[52] Finally, a higher bone mineral density has also been described in elite climbers.[58]

4. Discussion

The present systematic review was designed to summarize the validity and reliability of climbing-specific tests that assess performance determinants in climbers of different contiguous performance levels. After analyzing the available general and climbing-specific functional tests, it appears that no consensus exists regarding preferred sport climbing performance evaluation; this was previously stated by Stien et al.[10] and Langer et al.[11]

4.1. Cardiorespiratory endurance

4.1.1. General cardiorespiratory endurance

With regard to cardiorespiratory endurance, upper limb ergometer tests highlighted a closer relationship with climbing performance from intermediate to elite levels when compared to treadmill or cycling tests. Moreover, the only strong and positive correlation was found with relative VO_{2peak} and peak power output for a test specifically created to simulate climbing activity with a vertically mounted isokinetic rowing ergometer. Michailov et al.[51] concluded that aerobic capacity is a major determinant of elite rock-climbing performance, and they advise not abandoning its evaluation, even if reliability data are still missing, since this testing modality is standardized, feasible, and repeatable. Sport-specific upper-body ergometer tests should be preferred because they aim to replicate the pulling movement to fatigue during climbing. Indeed, Billat et al.[115] described an involvement of ∼40% of the "running" VO_{2peak} and ∼100% of the "pulling" VO_{2peak} during route climbing. Despite this, cycle ergometers adapted to the upper body also deserve further investigation since some promising construct validity (see Methods Section 2.4. Validity and reliability analyses for concurrent and construct validity) has been reported when analyzing time to failure as well as peak and mean power output.[25,52]

4.1.2. Climbing-specific cardiorespiratory endurance

Climbing-specific cardiorespiratory endurance has been tested via climbing traverses, circuits, or routes. The lack of standardized protocols between included studies is likely to represent a feasibility and reproducibility issue for coaches and athletes during their daily practice. For instance, the independent variables used to test cardiorespiratory endurance could be consistently manipulated by the difficulty of the path (the technical difficulty is usually set to a minimum level to eliminate the impact of climbing skills[53]), the number of movements, the wall climbing slope, and the pace (movements per min). In this regard, the total number of movements during the Fit-climbing test seems to be a reliable and valid marker for discriminating intermediate from advanced-elite male climbers.[56] Even without specific reliability data, time to failure and mean heart rate during a traverse or bouldering circuit seem to play important roles for elite climbers, especially when handholds are more difficult to grip, and for lower grade to elite climbers, especially when the wall inclination increases.[53,54] When using treadwall climbing tests, dependent variables such as the capacity to climb over the critical angle, peak climbing velocity, time to failure, and peak angle reached reveal strong associations with the climbing ability of intermediate to elite male climbers.[58–60,105] Submaximal (e.g., at different wall angles) compared to maximal (e.g., VO_{2peak}, peak heart rate) physiological parameters seem to better predict climbing

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performance, indicating better climbing economy to be a critical factor.[52,56] No reliability analysis was conducted for treadwall climbing tests. In incremental climbing tests, where the size and type of holds influence performance, a gradual advance in wall angle or speed has been shown to increase vertical forces on the holds, heart rate, VO_2, and lung ventilation and to decrease FDP oxygen saturation.[60,116,117] Moreover, submaximal VO_2 at different wall angles was higher in intermediate compared to advanced climbers, suggesting improved climbing economy at higher performance levels.[60] Also, FDP oxygen saturation decreased with increasing climbing speed in intermediate but not advanced climbers.[118] Thus, changes in wall angle or speed represent valid means of increasing intensity during climbing. Instead of assessing standard physiological parameters such as VO_{2peak} and peak heart rate, assessing climbing specific parameters such as peak angle, peak velocity, or time to failure may improve the validity of differentiating between different climbing levels.

If the aim is to assess the metabolic response across different climbing levels, it has been suggested to use a technically easy route to eliminate the impact of climbing skills on test duration.[53] In this way, a learning effect should not affect successive assessments.[59] Moreover, a minimum overhang acts as a constraint for the technique.[116] Whether it is better to manipulate the angle or speed when assessing climbing effort and performance remains an open question. However, when increasing the angle at a constant speed, the correlations of mean heart rate and VO_2, with climbing ability seem stronger ($r = -0.66/-0.82$ at 0° *vs.* $-0.77/-0.84$ at $-15°$ wall angle, respectively).[54] While there is limited evidence for peak climbing velocity,[58,105] there is construct and concurrent validity for peak angle for both boulder and lead climbers. Interestingly, the ability to climb over the critical angle (a climbing-equivalent of critical power) seems to be an even better performance discriminator for boulderers compared to lead climbers, and this might be due to the technical requirements.[59] However, determination of the critical angle requires repeated exhaustive ascents over several days which could lead to an important test feasibility issue. Regardless of angle or speed manipulation, time to failure is an easy outcome to evaluate, demonstrating both concurrent and construct validity. It has to be mentioned that the impact of climbing holds during these climbing-specific cardiorespiratory endurance tests has only rarely been evaluated; the test validity evaluating time to failure seems to significantly improve with increasing hold difficulty ($r = 0.60$ *vs.* 0.94).[53]

To conclude, submaximal and maximal wall climbing tests as well as treadwall testing analyzing time to failure, mean value of heart rate and VO_2, and peak angle yielded reasonably valid results, even if reliability data are insufficient and limitations could arise with regard to standardized test procedures.

4.2. Muscular strength

4.2.1. General muscular strength

The available literature concerning general muscular strength mainly adopted the handgrip test both with the whole hand and the ring finger only to investigate potential relationships with climbing performance. This type of handgrip test has been considered a non-climbing-specific measure since it reflects a comprehensive strength of the flexor muscles against that of the palmar, thenar, and hypothenar areas of the hand.[119] In line with this lack of test specificity of handgrip in sport climbing, Watts et al.[120] described a significantly higher forearm electromyography response in full crimp and slope grip position when compared to what has been revealed during maximal handgrip force measures. Indeed, the full crimp, half crimp, and slope grip position of the fingers strongly depend on the activity of the FDP and flexor digitorum superficialis (FDS) muscles, without opposition of the thumb against the palm and/or the fingers.[120,121] Although handgrip strength values relative to body mass showed better associations with climbing ability compared to absolute values, current literature confirms the overall limited specificity regarding climbing performance.[122] However, this easy to perform and highly reliable strength test might still be considered in daily routine, particularly in female climbers when other tests are not available.[61,62]

4.2.2. Climbing-specific muscular strength

To compensate for the lack of validity of handgrip tests in discriminating between climbers of different levels, various testing protocols for the evaluation of the finger flexor muscle force using pulleys, force platforms, and other specific devices have been proposed (see Results section 3.3.2. Climbing-specific muscular strength).

Test systems that allow for the addition and removal of weight through a pulley while the climber hangs from a rung with 1 or both arms[69–73] are affordable and reliable, enabling discrimination between advanced and elite climbers, even though concurrent validity does not seem to be strong. To increase validity and maintain good reliability, the maximal finger flexor force can be measured by transferring body mass from a force platform to the rung.[65,69–71,73,74] Concurrent validity is high in climbers from lower grade to elite levels, whereas construct validity was higher in male than in female climbers. Homogeneous results between different studies confirm the predictive value of maximal finger flexors strength and the use of an electronic scale as a simple tool for the assessment. Specific devices with a force transducer under the fingers were utilized to increase the complexity of the testing method used to evaluate the climbing-specific strength of finger muscles. With the upper limb extended at ∼170°–180° shoulder flexion, and using slope, half crimp, or even full crimp grip on a rung of 23 mm on average, the relative finger strength measures reached excellent reliability; still, conflicting results regarding validity limit current evidence. In lower grade to lower elite female boulder and lead climbers, the concurrent validity is moderate, even while the construct validity indicates possible differentiability between intermediate and advanced climbers. In males, high concurrent validity has been shown for intermediate to higher elite climbers and also when considering different disciplines; concurrent validity appeared to be higher for bouldering,[77,79] which confirms the results of previous studies specifically focused on differences between boulder and lead climbers.[19,20,33,34] Construct validity in males was reported for intermediate-advanced and elite-higher elite athletes, although these analyses were rarely reported. When a bar was positioned over the feet to keep participants from lifting themselves off the ground, only moderate correlations were found with both the redpoint and the on-sight level of advanced to elite climbers.[50] It is possible that the biomechanics behind this test could be a limiting factor due to the weak link represented by dorsal muscles of the feet rather than the forearm muscles. In fact, as an alternative approach, van Bergen's team suggested fixing a hold below the dynamometer positioned at the arm span distance to generate an opposing stopping force.[50] When testing the MVC by flexing the upper limb, correlations with climbing ability were moderate in lower grade to advanced female climbers and up to very strong in advanced to elite athletes, suggesting that this parameter might be less important for females of lower performance levels. In males, the concurrent validity was also moderate to strong, but values were different between all climbing categories (higher elite climbers were not tested). In most protocols, the climber was in a sitting position with the elbow flexed at 90˚ and fixed on a plate to standardize the test; a slope, half crimp, or full crimp grip was used to measure MVC, with the former showing stronger correlations. In general, reliability was excellent for these tests.

Currently, no consensus exists on climbing-specific muscular strength testing, but a standardization of available test methods may lead to more scientific evidence. It is noteworthy that by not fixing the elbow on a support, the shoulder girdle muscles would inevitably contribute to the recorded force,[79] excluding the assessment of the mere finger flexor muscle strength, and this should be taken into consideration before performing a test. Only 3 studies compared the 2 testing positions with arm extended or flexed at 90˚.[50,79,80] Generally, reliability was excellent for both testing conditions, but Michailov's[79] and Balas'[80] teams proposed that scores of MVC assessed with the arm extended above the head had higher validity. The possibility of using body mass to load the hold allows the test to be more sport-specific since the force on the hold is generated by the effect of body mass along the line of gravity.[120] Therefore, it might be recommended to test maximal finger flexor strength with arms above the shoulder since it more closely resembles the sport-specific gesture. Furthermore, novel procedures have been implemented by measuring the isometric peak force either pulling backward in the sagittal plane holding a hold affixed to a wooden board or performing an isometric pull-up with a taut rope anchored to the ground. Validity appears strong from intermediate to elite male climbers and reliability was almost excellent. Although these are promising results, the supporting evidence is still limited by the small number of studies.[85–87]

4.3. Muscular endurance

4.3.1. General muscular endurance

Both the bent-arm hang test and the number of pull-ups were able to discriminate between different climbing levels, and strong concurrent validity was found in males and females for both tests. Additionally, both tests displayed almost excellent reliability, although CV was worse in lower levels and females than in higher levels and male climbers. Reported results also suggest that in lower to intermediate level climbers, the reliability of the 2-arm bent-arm hang test cannot be considered sufficiently good; alternatively, either the number of pull-ups or the plank time may be assessed. Indeed, the plank position demonstrated discriminatory ability only between lower grade and intermediate climbers, and a general excellent reliability was reported in non-climbing-specific literature for young adult athletes (ICC: 0.91−0.99, CV = 2%[124,125]). However, there are no data for higher elite athletes, and the available general muscle endurance tests have not detected any differences between intermediate and advanced climbers, except for the 90˚ bent leg raise in female climbers.[40]

4.3.2. Climbing-specific muscular endurance

Climbing-specific evaluation of muscular endurance typically assessed the following outcomes: time to failure, number of repetitions, average force, force-time integral of the finger flexor muscles while performing continuous or repetitive intermittent maximal or submaximal MVCs, and oxygenation analysis of FDP (Supplementary Table S3C). However, many variables may affect these tests and interact with each other. Testing protocols may include performing a continuous or repeated MVC to failure, or evaluating repetitions/time, with the upper limb extended or flexed and using different holds and grip positions. For intermittent testing, another variable to consider is the work to rest ratio. Further possible determinants that may affect climbing-specific muscular endurance are the use of magnesium, available equipment, and verbal encouragement.

The time to failure hanging continuously on a rung with upper limb extended above the head showed moderate- to -strong concurrent validity from lower grade to higher elite climbers and was able to differentiate between most climbing levels. Reliability was shown to be almost excellent. It needs to be mentioned here that advanced/intermediate and elite/higher elite male climbers were poorly studied. Furthermore, the lowest CV values were found in lower grade/intermediate climbers and females; therefore, the continuous finger hang test should be interpreted with caution in these subjects. Using a specific device to assess the average maximal finger flexor muscle force or force-time integral relative to body mass, similar results were obtained for concurrent validity. Complementary data are available for the construct validity; advanced and higher elite athletes performed better than intermediate and elite male climbers, respectively, with excellent reliability.[79] To sum up, evidence supports the muscular endurance of finger flexor muscles in discriminating all levels of male climbers, while this is less clear for female athletes.

Only a few studies applied the above tests with both the shoulder and the elbow bent at 90˚. Even if the results of average force and time to failure in intermediate to elite climbers seemed similar, the available evidence is limited.

Nevertheless, as discussed above, the position with arms extended above the shoulders is more similar to the sport-specific gesture.

Some studies performed assessments with intermittent contractions, where the work to rest ratio varies considerably. These intermittent protocols are often preferred to a sustained isometric contraction since rock climbing is characterized by repeated isometric contractions of the finger flexors.[7,109] Regarding intermittent testing with upper limb extended above the head, data seem to indicate that critical force of finger flexor muscles, number of repetitions, and step reached during an intermittent-incremental protocol with suspension on different ledges are better performance markers compared to force-time integrals, time to failure, and oxygen saturation of FDP. Interestingly, the criteria for test termination seem to significantly affect the test outcome (i.e., number of repetitions) and its relationship with climbing ability in intermediate to elite climbers.[95] Furthermore, the critical force representing the mean end-test force measured during an all-out test[94,126] revealed strong correlations with climbing ability in intermediate to higher elite climbers. This highlights the importance of the fatigue resistance of the finger flexors in rock climbing and has been recommended as a test for evaluating fatigue resistance and as a subsequent training prescription.[94] Similarly, for intermittent tests with the upper limb flexed, concurrent validity demonstrated moderate correlations with climbing ability in lower grade to elite male climbers performing the "arm-jump"/"power slap" and MVC repeatedly over time and calculating the corresponding fatigue index. It is important to mention that data on reliability is not available.

Another approach to evaluate climbing-specific muscular endurance is related to testing protocols in fatigued conditions. Interestingly, MVC in a state of fatigue was strongly correlated with climbing ability in intermediate to elite male climbers, and both fatigue and climbing level were determining factors.[17] In terms of muscle groups, the fatigue of elbow flexors (i.e., brachioradialis) and finger flexors (i.e., FDS) were found to have a greater influence on climbing performance compared to the fatigue of shoulder adductors and lumbar flexor muscles in advanced male climbers.[127] Moreover, Feldamann et al.[91] found a decrease in MVC and force-time integral of finger flexors, evaluated per body weight during sustained and intermittent contraction testing, before and after a climbing-specific high-intensity session; correlation analyses with climbing ability were only performed using pre-fatigue strength and endurance values. Fatigue-related test findings may be important to (a) assist coaches in selecting strengthening and conditioning strategies that can improve muscular endurance of those muscles, and (b) improve the validity of general and climbing-specific testing procedures for muscular strength and endurance given that fatigue-induced performance deterioration may differ between climbers of different levels. It is worth noting that validity analyses assessing finger flexor muscle force in a state of fatigue among climbers of different levels are still extremely limited, which seems to be quite a relevant research gap since this might better allow for discriminating climbing ability.[17] Thus, further studies should provide validity and reliability measures of finger muscular strength and endurance assessed following standardized and prolonged fatigue protocols.

4.4. Muscular power

4.4.1. General muscular power

General muscular power assessed by a handgrip dynamometer, 1RM bench press, and squat jump did not display significant correlations or differences between climbing levels. The average shoulder power determined by a specific arm crank ergometer showed an association with the ability level of intermediate to advanced male climbers.[68] Considering the principal component analysis performed by Mackenzie et al.,[68] this last outcome explained 14% of the total variation in climbing ability, whereas 59% was explained by maximum number of pull-ups; in females this power assessment was not found to be a sport climbing performance determinant. Moreover, despite the limited evidence for speed climbing, the countermovement jump appeared strongly associated with the best climbing time of elite male speed climbers, even though reliability data are not excellent.[96] This valid, feasible, and low-cost evaluation method seems a valuable resource for performance diagnosis in speed climbing, and it deserves attention from coaches and researchers.

4.4.2. Climbing-specific muscular power

When climbing-specific tests were applied, the slap height derived from the "power slap"/"arm-jump" test was able to discriminate between all climbing levels in men; for females there is little evidence, and low reliability was reported for lower climbing levels.[35,40,97,98] The "power slap"/"arm-jump" test appears to be a quick, easily accessible, valid, and reliable test to discriminate between lower grade and elite male climbers, and between intermediate and elite female climbers. Its validity was also confirmed by comparing the slap height distance obtained from data on an accelerometer.[98] Minimal power is therefore required to rise to a skilled climbing level, but no data are available for higher elite climbers.

The only data on power generation in speed climbing are derived from video analyses during the race, which correlated very strongly with the best individual climbing time in a rather small sample of elite and higher elite climbers.[96,99] This anaerobic power parameter seems to represent a key factor for performance in speed climbers, but the level of evidence is limited. It must be mentioned here that the reliability appears excellent for higher elite climbers while it is less clear for elite speed climbers, and no data is available for lower climbing levels.

When muscular power was measured isometrically via climbing-specific assessment, the relative RFD (e.g., 50% of time to peak force) proved to be more suitable than the absolute RFD for discriminating advanced from elite but not intermediate male climbers. The reliability is questionable, especially in less advanced climbers and considering the shortest durations from the onset of contraction. Therefore, the relative RFD with longer durations could be a useful assessment in more skilled climbers.[46,85]

4.5. Flexibility

4.5.1. General flexibility

General flexibility (i.e., the forward bending test) showed neither meaningful correlations nor differences between climbers of different performance levels; only the maximal straddle score, the leg span, and the sit and reach score revealed moderate correlations with climbing ability in male athletes. Therefore, hamstrings as well as lower-limb and lower-back flexibility, assessed by common non-climbing-specific tests, do not appear to play a key role in climbing performance of different levels, particularly for female athletes. This interpretation is also corroborated by studies that performed principal component analysis. Mermier et al.[27] described that the range of motion of the hip and shoulder explained only 1.8% of the total variance in climbing performance,and Mackenzie et al.[68] concluded that flexibility was not a main determinant of climbing ability.

4.5.2. Climbing-specific flexibility

Compared to tests for general flexibility, concurrent and construct validity slightly improved when tests specifically designed for climbers were applied. In fact, the ROCT, which expressed the score relative to height, showed high reliability and moderate (almost strong) concurrent validity from lower to higher elite climbing levels, even though discrimination was detected only from the lower grade to the advanced level. This flexibility assessment is likely to stand out from other general and climbing-specific flexibility assessments because the test not only considers a climber's anthropometric characteristics but also includes a combination of flexibility and strength evaluation. This combination is especially required for pulling and pushing the starting handhold to achieve the highest upper rung. Accordingly, a gradual increase in concurrent validity was achieved when comparing the climbing-foot rise test with the foot-loading flexibility test and the ROCT. Draper et al.[40] suggested a threshold above which flexibility becomes less important as a performance determinant; but note that this was the only study that performed a sex specific analysis and reported construct test validity in males but not in females. Since females are generally more flexible than males,[128] climbing-specific assessment of flexibility should consider this basal difference in the general population. Indeed, flexibility might not be a critical component for female climbers, but it may be for certain levels in men. Obviously, future research is required to identify tests of flexibility that are specific to climbing and that can differentiate between ability groups.[40] It is noteworthy that, as with climbing-specific muscular strength and endurance, values gain importance when normalizing to body mass; similarly, flexibility data should be related to the subject's body height.

4.6. Balance

To the best of our knowledge, very few studies have investigated the influence of balance on performance in sport climbing.[64,68,129,120] These results found only moderate concurrent validity of non-climbing-specific balance tests in intermediate to advanced climbers and in 11 female participants of the Youth World Championship. Clearly, too little data is available and further analyses on this topic are required.

4.7. Anthropometric characteristics

Almost all performance studies provided basic standardized measures of body height, body mass, and circumferences (e.g., waist, hip, forearm). It is important to mention that body mass and height should be considered to normalize outcomes of functional tests (e.g., force as strength-to-body mass ratio, flexibility as specific score-to-body height ratio), which was clearly shown to increase the association between evaluated variables and performance levels. However, by looking specifically at anthropometric characteristics, conflicting evidence is depicted, since many studies were not able to find an impact of these parameters on climbing performance. Recently, Ginszt et al.[39] reported a lower body fat content and body mass in elite sport climbers compared with less advanced or non-climbers, concluding that these parameters may be associated with sport climbing performance. Overall, the data are contradictory. Some studies show a relationship between climbing levels and body mass[26,58,66] or body fat[28,36,51,52,62,104–105,108] while others do not.[16,17,26,35,52,58,69,71,73,74,76,82,85,87,90,96,98,105,108,110–112] However, our findings are in line with multiple regression and principal component analyses, which found anthropometric variables to explain around 0.3%–4.0% of variance in climbing performance.[27,35] Therefore, meta-analyses of the different anthropometric components are needed in order to improve evidence regarding their impact on climbing performance.

5. Proposal of an evidence-based Functional Sport Climbing (FSC) test battery

Based on this systematic assessment of the current knowledge, a feasible test protocol can be proposed to exercise professionals and coaches; however, it will need to be validated by future studies (Fig. 5). The test battery considers and is, therefore, presented and discussed based on (a) the available validity and (b) reliability for the broadest range of climbing performance levels, (c) the feasibility of testing procedures (i.e., simplicity of standardization, minimal financial and equipment constraints), as well as (d) the quantity of evidence per discipline, climbing ability level, and sex (Fig. 5 and 6). Some potentially interesting innovative tests were not considered for this test battery as the current evidence is still limited, but they may improve the FSC test battery in future updates.

5.1. FSC_a test battery(advanced-equipment version)

The following test battery has been designed for top-level climbing centers with access to all types of equipment, and specifically for advanced-high level climbers

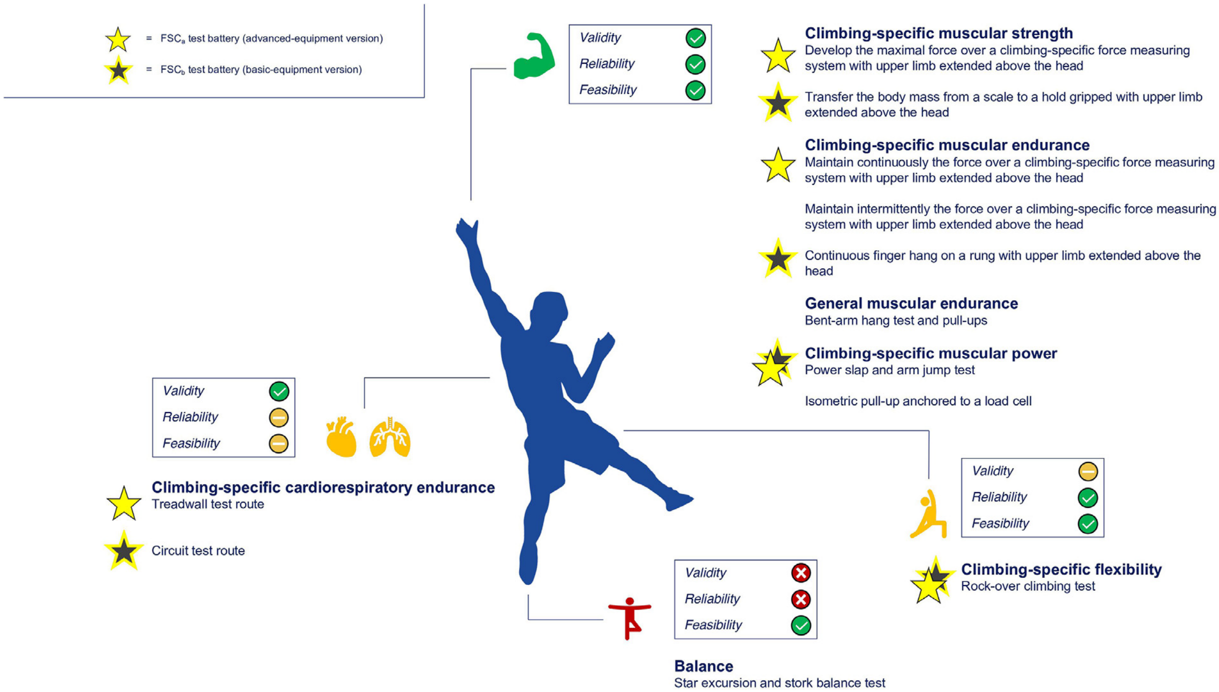

Fig. 5. Evidence-based functional sport climbing (FSC) test battery. Proposal of a functional testing protocol based on qualitative analysis of current literature. It considers (a) the available validity and (b) reliability for the broadest range of climbing performance levels, (c) the feasibility of testing procedures intended as simplicity of standardization as well as minimal financial and equipment constraints, and (d) the quantity of evidence per discipline, climbing ability level, and sex. **Green**, **yellow**, and **red** flags are indicative of high, moderate, and low quality of considered criteria (validity, reliability, and feasibility), respectively. Red flags (low quality) could indicate either an absence of evidence or low values of validity and reliability.

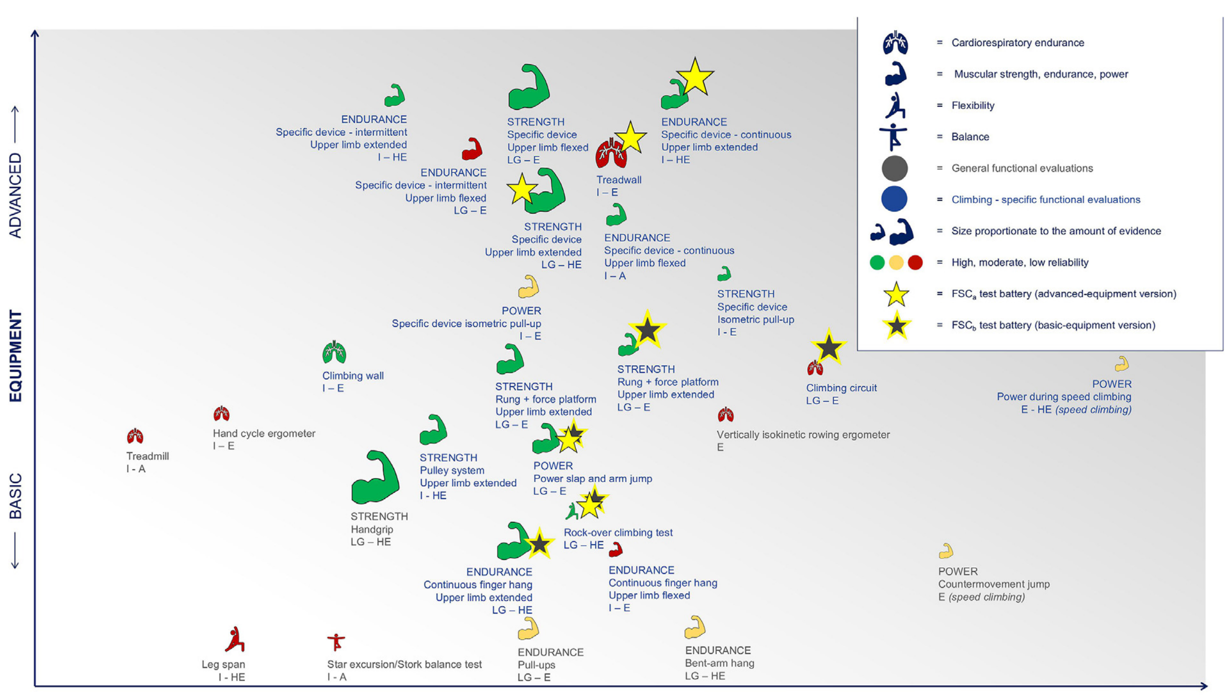

Fig. 6. Evidence-based classification of functional evaluation in sport climbing. Qualitative classification of current evidence regarding functional evaluation per degree of validity (concurrent validity reported on the x-axis and construct validity reported as range of climbing ability levels), required equipment, amount of evidence, and reliability.: A = advanced; E = elite; HE = higher elite; I = intermediate; LG = lower grade.

5.1.1. Cardiorespiratory endurance

Test: Incremental testing by climbing a treadwall route. The speed or the wall angle of the test protocols should be adapted in order to obtain comparable and meaningful test results. The requirement/instruction is to climb until failure.

Outcome: peak climbing velocity, peak angle, time to failure, critical angle and capacity to climb over the critical angle, submaximal VO_2, and heart rate at the respective angle or speed (iso-time).

Alternative test: Climbing a technically easy circuit test route on a slightly overhanging climbing wall, performing movements at a constant pace. The requirement/instruction is to climb until the end of the predefined time or until failure.

Outcome: mean VO_2, mean heart rate, and time to failure.

5.1.2. Muscular strength

Test: Standing and facing a climbing-specific force measuring system with dominant arm extended above the head, shoulder engaged, and fingers on the rung. The requirement/instruction is to develop as much force as possible for 3−5 seconds.

Outcome: maximal finger flexor muscle force relative to body mass.

5.1.3. Muscular endurance

Continuous test: Standing and facing a climbing-specific force measuring system with dominant arm extended above the head, shoulder engaged, and fingers on the rung. The requirement/instruction is to develop as much force as possible and maintain maximal effort for 30 s.

Alternative intermittent test: Standing and facing a climbing-specific force measuring system with dominant arm extended above the head, shoulder engaged, and fingers on the rung. The requirement/instruction is to develop and maintain intermittently as much force as possible with a work:rest ratio = 7 s:3 s for 24 repetitions (4-min all-out).

Outcome: force-time integral relative to body mass, and critical force of finger flexor muscles relative to body mass.

5.1.4. Muscular power

Power slap test: Hanging from a rung with arms fully extended above the head. The requirement/instruction is to perform an explosive pull-up without momentum and release the dominant hand to slap as high as possible.

Outcome: slap height.

Alternative test: Standing with elbow and shoulder flexed at 90° and gripping a rung. The requirement/instruction is to perform an isometric pull-up as quickly and forcefully as possible and hold for 3−5 s while anchored to a force cell at the ground with a static rope.

Outcome: rate of force development.

Speed climbing-specific muscular power test:

Countermovement jump: Standing with both hands on hips, the requirement/instruction is to perform an explosive jump as high as possible with a counter movement.

Outcome: countermovement jump height, power, and velocity.

5.1.5. Flexibility

ROCT: From a starting position with both hands and feet on holds positioned at the participant's height, with breadth corresponding to the acromion distance, perform the 2 parts of the rock-over move: the requirement/instruction is to raise the foot on a wooden rung and in a controlled way reach the highest upper handhold that can be grasped through extension of the upper leg.

Outcome: ROCT score (distance between the hand on the starting hold and the hand on the highest rung reached) relative to body height. ROCT evaluates flexibility but is also affected by muscular strength.

5.2. FSC_b test battery (basic-equipment version)

The following test battery has been designed for climbing centers with access to basic equipment (rung, bar, force platform/electronic scale, and free weights) and might thus be more useful for basic-intermediate climbers.

5.2.1. Cardiorespiratory endurance

Test: Climbing a technically easy circuit test route on a slightly overhanging climbing wall, performing movements at a constant pace. The requirement/instruction is to climb until the end of the predefined time or until failure.

Outcome: mean VO_2, mean heart rate, and time to failure.

5.2.2. Muscular strength

Test: The dominant arm fully extended above the head while standing on a force platform with the body center directly below the edge to be gripped. The requirement/instruction is to pull down (by flexing knees) with the maximum effort to transfer the body mass from the scale to the hold.

Outcome: maximal finger flexor muscle force relative to body mass (body mass + additional weight − the lowest value recorded on the scale for at least 3 s).

Alternative (valid only for females): handgrip test in a sitting position with extended elbow and shoulder at 0° flexion. The requirement/instruction is to develop as much force as possible with dominant and non-dominant hand.

Outcome: maximal mean left and right handgrip force relative to body mass.

5.2.3. Muscular endurance

Test: continuous finger hang on a rung with upper limbs extended above the head. The requirement/instruction is to hang until failure.

Alternative test: Bent-arm hang test. Hanging from a bar with bent arms and chin above the bar, the requirement/instruction is to hold the position until failure.

Outcome: time to failure.

5.2.4. Muscular power

Power slap test: Hanging from a rung with arms fully extended above the head. The requirement/instruction is to perform an explosive pull-up without momentum and release the dominant hand to slap as high as possible.

Alternative test: Arm-jump test releasing both hands.

Outcome: slap height.

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5.2.5. Flexibility

ROCT: From a starting position with both hands and feet on holds positioned at the participant's height, with breadth corresponding to the acromion distance, perform the 2 parts of the rock-over move: the requirement/instruction is to raise the foot on a wooden rung and in a controlled way reach the highest upper handhold that can be grasped through extension of the upper leg.

Outcome: ROCT score (distance between the hand on the starting hold and the hand on the highest rung reached) relative to body height. ROCT evaluates flexibility but is also affected by muscular strength.

To sum-up: regarding cardiorespiratory endurance, climbing tests using circuits or treadwall routes are promising in validity, but feasibility and standardization are more difficult to achieve. Muscular strength of finger flexor muscles assessed specifically with a force transducer and upper limb extended above the head demonstrated excellent reliability and differentiability from lower grade to higher elite male and female climbers. If a handgrip dynamometer is available, it could provide additional useful information for lower grade to higher elite females regarding muscular strength. Finger muscular endurance assessed continuously with a force transducer under the fingers and with the upper limb extended above the head displayed good reliability and discriminatory capacity over a wide performance range. If this evaluation method is not available, the continuous hang on a ledge can be considered with similar test characteristics. Also, the 2- and 1-arm bent-arm hang test might be feasible as an easily accessible field test for male climbers of all levels and advanced to higher elite female climbers, while pull-ups could be used to assess muscular endurance in lower grade to elite male climbers. Regarding the assessment of dynamic muscular power, the power slap or the arm jump test could be considered. The ROCT might be suggested for discriminating the climbing-specific flexibility of lower grade to higher elite climbers with excellent reliability, though this evaluation method is also affected by an athlete's muscular strength. Balance evaluation is currently not included in this evidence-based test battery due to a lack of validity measures.

6. Limitations and future perspectives

Data extraction was somewhat challenging due to the heterogeneity and lack of fundamental information in reporting data (e.g., specifications about sex, climbing ability, preferred discipline, climbing groups not referable to the IRCRA scale, lack of reliability/validity data). Also, non-standardized testing protocols challenged data analyses and test-clustering for the different functional components. Thus, future studies should aim to (a) validate the standardized $FSC_{a/b}$ test battery developed according to the currently available literature, (b) provide more evidence for promising new functional evaluation methods including validity and reliability analyses, and (c) evaluate/report baseline characteristics of the sample in more detail. Indeed, climber characteristics should be reported according to the IRCRA recommendations;[49] these include sex, predominant discipline, time spent climbing indoors or outdoors, mean training time, and climbing level according to the respective reporting scale. When differences between climbers and performance levels are evaluated, data on test validity and reliability should be provided. The further development of valid and reliable climbing-specific functional tests would also enable the evaluation and monitoring of the effectiveness of training methods and interventions. Furthermore, multi-center research projects[40] and meta-analyses should be encouraged and planned in order to consolidate existing knowledge and explore new research questions with a strong link to applied sport science.

7. Conclusion

This is the first systematic review leading to an evidence-based FSC test battery based on a qualitative synthesis of encompassing functional properties (i.e., cardiorespiratory endurance, muscular strength, muscular endurance, and muscular power, as well as flexibility, balance, and anthropometric characteristics) and capable of discriminating performance of climbers of various ability levels. The main findings are that current data are to some extent heterogeneous and functional testing methods lack standardization. As a result, firm conclusions about the influence of functional test determinants on climbing performance cannot yet be drawn. Nonetheless, some evidence suggests that cardiorespiratory endurance, muscular strength, muscular endurance, and muscular power may influence climbing performance, while flexibility, balance, and anthropometric characteristics seem to be less important. Climbing-specific testing protocols seem better suited to discriminate climbers of different levels when compared to general fitness assessments. To improve the applicability of functional testing in predicting performance as well as programming and monitoring training interventions, structured large-scale studies that incorporate standardized, valid, and reliable testing procedures are needed. Accordingly, the attempt to introduce the standardized FSC test battery for an advanced (FSC_a) and basic (FSC_b) level (Section 5, Fig. 5A and 5B) should be scientifically validated by targeted investigations.

Authors' contributions

DN conceived, designed, and supervised the study and publication process; SF conceived, designed, supervised the study and publication process, performed the main literature search, and revised it, conducted the analysis, interpreted the data, and wrote the first draft of the manuscript; NB revised the literature search, conducted the analysis, and interpreted the data; MV, FB, GQ, FD, and AE also collaborated in data presentation/interpretation as well as in an internal revision process; HB engaged in a climbing-specific revision from the athlete/coach perspective; while HG and MB provided an external scientific supervision and revision of the manuscript. All authors contributed to the paper draft and provided critical revision of the report. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

Q3 **Uncited references**

[106,107]

Declaration of competing interest

The authors declare that they have no competing interests.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jshs.2024.100974.

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