RESEARCH IN SPORT CLIMBING

EDITED BY: Stefan Künzell, David Giles, Vanesa España-Romero, Pierre Legreneur
and Jiri Balas

PUBLISHED IN: Frontiers in Psychology, Frontiers in Sports and Active Living and
Frontiers in Nutrition

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88971-609-8
DOI 10.3389/978-2-88971-609-8

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RESEARCH IN SPORT CLIMBING

Topic Editors:
Stefan Künzell, University of Augsburg, Germany
David Giles, Independent researcher, United Kingdom
Vanesa España-Romero, University of Cádiz, Spain
Pierre Legreneur, Université Claude Bernard Lyon 1, France
Jiri Balas, Charles University, Czechia

Citation: Künzell, S., Giles, D., España-Romero, V., Legreneur, P., Balas, J., eds. (2021). Research in Sport Climbing. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-88971-609-8

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frontiers in Psychology

EDITORIAL
published: 22 September 2021
doi: 10.3389/fpsyg.2021.752617

Editorial: Research in Sport Climbing

Stefan Künzell[1]*, Jiri Balas[2], Vanesa España-Romero[3], David Giles[4] and Pierre Legreneur[5]

[1] Institute for Sports Science, University of Augsburg, Augsburg, Germany, [2] Faculty of Physical Education and Sport, Charles University, Prague, Czechia, [3] Department of Teaching Physical Education, Fine Arts and Music, University of Cádiz, Cádiz, Spain, [4] Lattice Training Ltd, Chesterfield, United Kingdom, [5] Université de Lyon, LIBM, Lyon, France

Keywords: sport climbing, research, competitive sport, sport psychology, applied research

Editorial on the Research Topic

Research in Sport Climbing

Sport climbing is enjoying growing popularity—on rock in the great outdoors and especially indoors on artificial climbing walls in inner-city gyms. Increased enthusiasm and participation in the sport has led also to greater interest in competitive climbing—ultimately leading to sport climbing being included as an Olympic discipline in Tokyo 2020 and beyond. It is hoped that the sport being showcased on the international stage will result in increased participation around the world.

Along with participation in climbing, interest in and research on the science of the sport has increased considerably. In 2011, the International Rock Climbing Research Association (IRCRA) was founded, which holds an international congress on research in climbing every 2 years. This Research Topic is the outgrowth of the last meeting of IRCRA in Chamonix in the summer of 2018, organized by its current president Pierre Legreneur.

Two strands with different objectives are emerging in climbing research. The first strand focuses on understanding and improving climbing performance. Performance-determining factors are sought and found, and a wide variety of training procedures are examined for their effectiveness. Conversely, the second strand focuses on climbers as a special population to be studied in terms of their perceptions, stress processing, and other personality traits. Such characteristics are examined to determine whether the practice of climbing promotes outcomes that are educationally or therapeutically desirable or just scientifically interesting. This Research Topic is predominately focused on the first strand.

Related to both the health and performance of climbing athletes, Gibson-Smith et al. assessed the dietary intake, body composition, and iron status. While the authors did not find significant differences between climbing ability groups (intermediate-advanced/elite-higher elite) for any of the parameters analyzed the results suggest experienced climbers are at risk of energy restriction and iron deficiency and monitoring of nutritional intake in training experienced athletes would be of benefit. Similarly, Joubert et al. surveyed a larger number of climbers using a web-based questionnaire and found that climbers are not immune to disordered eating, especially elite female climbers.

Concerning the technical movement performance, Reveret et al. analyzed the body motion of speed climbers (a sub discipline of climbing, involving the fastest possible ascent of a standardized 15 m route) in 3D. The ability to observe and quantify the velocity profile of speed climbers may help to highlight potential deviations from an optimal climbing path and shows the points where the upward movement stalls, providing coaches and climbers with actionable feedback on climbers speed performance.

Many athletes have to deal with stress and climbing is no different in this respect. For instance in bouldering competitions, a problem must be mastered in as few attempts as possible within a 4 or 5 min window, and the movements required often involve a high risk of failure. In their paper, Hill et al. presented a procedure to develop individual load-response profiles comparing difficulty with

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Edited and reviewed by:
Yair Galily,
Interdisciplinary Center Herzliya, Israel

***Correspondence:**
Stefan Künzell
stefan.kuenzell@uni-a.de

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: 03 August 2021
Accepted: 25 August 2021
Published: 22 September 2021

Citation:
Künzell S, Balas J, España-Romero V, Giles D and Legreneur P (2021) Editorial: Research in Sport Climbing. Front. Psychol. 12:752617. doi: 10.3389/fpsyg.2021.752617

the number of attempts required, creating a system which may help coaches to find the optimal stress level in training for their athletes.

Considering the cognitive demands of the sport, Limonta et al. were interested in climber's route preview capacities and their ability to recall movement sequences. Analyzing both parameters in on-sight (without prior knowledge and practice of a route) and red-point (following practice) climbing the authors reported that, even for advanced climbers, the on-sight style is more physiological and psychological demanding than red-point climbing. The results highlight the interaction between perceptual, physiological, and psychological factors and the importance of psychological performance in on-sight climbing. Developing on the theme of the cognitive demand of on-sight climbing, Garrido-Palomino et al.'s study investigated the relationship between attention and self-reported climbing ability. The authors found that attention is positively related to on-sight but not red-point climbing ability, suggesting that higher level on-sight climbers are better able to attend to the task of climbing and not to external factors (e.g., risk of a fall) which may affect performance.

Research of the second strand is reported by Gajdošík et al. They studied climbers with different expertise as they climbed through an identical climbing route, one close to the ground and one at height. They were able to show that the perceived exertion for advanced climbers was in good agreement with the objective measurements. However, less proficient climbers overestimated their actual exercise intensity when climbing at height.

Fuss, Weizman et al. investigated the climbers abilities to perceive the roughness and grippiness of climbing holds. The construed holds from different materials that differed in these properties. They found that climbers mainly use grippiness for the evaluation of the holds. They use the estimated grippiness in planning the force they use to achieve the necessary friction efficiency and not slip off the hold.

In addition to the eight original research articles, the Research Topic is supplemented by three short reports. Sas-Nowosielski and Kandzia report the positive effect of post-activation potentiation on upper-body climbing-specific power exercise, Fuss, Tan et al. examine the behavior of heart rate during speed climbing, and Mitchell et al. examine the visual search strategies of experienced climbing coaches.

In anticipation of the approaching Olympic Games and climbing's debut, in this Research Topic, we have brought together research articles that predominately focus on improvements in the athletic performance of climbers. While developments in this area continue to be important and relevant the "second strand" of educationally and/or therapeutically relevant outcomes should be given more weight at future meetings and may become dominant content in a later Research Topic.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

Conflict of Interest: DG was employed by company Lattice Training Ltd.

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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ORIGINAL RESEARCH
published: 11 March 2020
doi: 10.3389/fpsyg.2020.00272

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Antifragility in Climbing: Determining Optimal Stress Loads for Athletic Performance Training

Yannick Hill[1]*, Adam W. Kiefer[2], Paula L. Silva[3], Nico W. Van Yperen[1], Rob R. Meijer[1], Nina Fischer[1] and Ruud J. R. Den Hartigh[1]

[1] Department of Psychology, University of Groningen, Groningen, Netherlands, [2] Department of Exercise and Sport Science, The University of North Carolina at Chapel Hill, Chapel Hill, NC, United States, [3] Center for Cognition, Action & Perception, Department of Psychology, University of Cincinnati, Cincinnati, OH, United States

In the past decades, much research has examined the negative effects of stressors on the performance of athletes. However, according to evolutionary biology, organisms may exhibit growth under stress, a phenomenon called antifragility. For both coaches and their athletes, a key question is how to design training conditions to help athletes develop the kinds of physical, physiological, and behavioral adaptations underlying antifragility. An answer to this important question requires a better understanding of how individual athletes respond to stress or loads in the context of relevant sports tasks. In order to contribute to such understanding, the present study leverages a theoretical and methodological approach to generate individualized load–response profiles in the context of a climbing task. Climbers (n = 37) were asked to complete different bouldering (climbing) routes with increasing loading (i.e. difficulty). We quantified the behavioral responses of each individual athlete by mathematically combining two measures obtained for each route: (a) maximal performance (i.e. the percentage of the route that was completed) and (b) number of attempts required to achieve maximal performance. We mapped this composite response variable as a function of route difficulty. This procedure resulted in load–response curves that captured each athlete's adaptability to stress, termed phenotypic plasticity (PP), specifically operationalized as the area under the generated curves. The results indicate individual load–response profiles (and by extension PP) for athletes who perform at similar maximum levels. We discuss how these profiles might be used by coaches to systematically select stress loads that may be ideally featured in performance training.

Keywords: complex systems, hormesis, metastability, phenotypic plasticity, resilience

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Edited by:
Jiri Balas,
Charles University, Czechia

Reviewed by:
Juan González Hernández,
Universidad de Granada, Spain
Bettina E. Bläsing,
Technical University Dortmund, Germany

***Correspondence:**
Yannick Hill
y.hill@rug.nl

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *16 October 2019*
Accepted: *05 February 2020*
Published: *11 March 2020*

Citation:
Hill Y, Kiefer AW, Silva PL, Van Yperen NW, Meijer RR, Fischer N and Den Hartigh RJR (2020) Antifragility in Climbing: Determining Optimal Stress Loads for Athletic Performance Training. Front. Psychol. 11:272. doi: 10.3389/fpsyg.2020.00272

INTRODUCTION

In competitive sports, athletes constantly interact with stressors, which represent events that athletes need to adapt to. Sport scientific research on stressors typically focuses on understanding and identifying strategies to promote athletes' ability to return to their previous level of functioning following exposure to a stressor (Hill et al., 2018a,b). This ability, termed resilience, often presupposes a *negative* effect of stressors

(Sarkar and Fletcher, 2013; Galli and Gonzalez, 2015). There is no question that stressors can disrupt the state of the athlete both on short timescales (e.g., losing a point) and long timescales (e.g., suffering an injury). However, previous research has shown that biological systems, under certain conditions, are capable of changing their structure and behavioral patterns when exposed to stress leading to growth rather than disruption in function (e.g., Cowin and Hegedus, 1976; Calabrese, 2005a). Growth from stress, termed antifragility (Taleb, 2012), is nicely illustrated when athletes implement novel and creative task solutions "on the fly" in response to challenges created by opponents in the field of play (Kiefer et al., 2018). Antifragility is ubiquitous in complex biological systems (Costantini et al., 2010; Calabrese and Mattson, 2011; Kiefer et al., 2018) and should therefore be a central target of sports training.

For both coaches and their athletes, a key question is how to design training conditions to help athletes develop the kinds of physical, physiological, psychological, and behavioral adaptations underlying resilience and antifragility. Research on psychological resilience shows that optimal adaptive responses to stressors are more common in individuals who have been exposed to intermediate loading in terms of lifetime adversity (Seery et al., 2010; Seery, 2011). Individuals who experienced either high or low amounts of stressors demonstrated lower levels of adaptability. Interestingly, such findings extend beyond psychological development and are in accordance with various stress–response processes studied in the field of evolutionary biology, medicine, toxicology, and sports (see for a review Costantini et al., 2010; Agathokleous et al., 2018). For example, human immune systems exhibit a response profile that is dependent on the toxicity (stress) that infectious agents impose to it: if the stress is too low, there is no response; if the stress is too high, it is harmful (Calabrese, 2005a). Vaccination is an effective treatment in that it imposes an optimal *level* of toxicity to "train" the immune system to respond to infectious agents. Similarly, following a (not too severe) bone fracture, the remodeling process of the bone produces tissue that is prepared to bear greater loads than before (Cowin and Hegedus, 1976). Also, following strength training with appropriate levels and types of load, muscle tissue grows (Jones et al., 1989) and is able to better respond to stress (Ocarino et al., 2008; Aquino et al., 2010). In the domain of sport psychology, clues for facilitative responses under specific loading can be derived from arousal–performance relationship theories (e.g., Kerr, 1985). Specifically, when athletes are somatically and cognitively under-aroused, increasing their level of arousal also increases their athletic performance until a threshold is exceeded and performance declines with increasing somatic and cognitive arousal (Hardy, 1990).

These examples capture a phenomenon, which can be observed across a broad range of biological systems, called *hormesis* (Southam and Ehrlich, 1943; Calabrese, 2005b; Costantini et al., 2010; Mattson and Calabrese, 2010; Agathokleous et al., 2018). Hormesis describes the biphasic relationship between the dosage of a potential harmful stressor and the response it triggers in an organism. Specifically, if the dosage is too small, it may yield a smaller beneficial effect in the immediate term; if the dosage is too large, it may trigger the opposite effect relative to baseline (**Figure 1**). Therefore, in order to elicit a desirable response, an optimal level of a stressor (or load) must be defined (Jaspers et al., 2018, 2019; Van der Sluis et al., 2019).

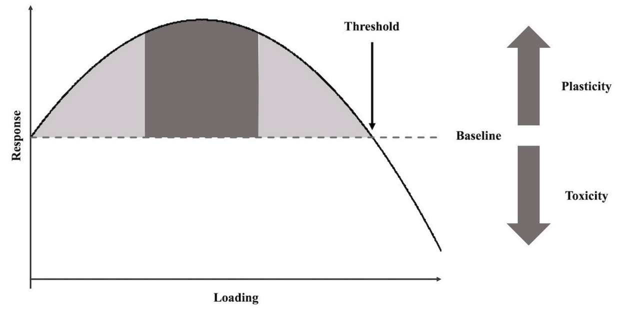

FIGURE 1 | Hypothetical hormetic (i.e. biphasic) response curve for athletic performance training. The solid black line represents the system's response to the increasing stress load relative to the system's baseline (dashed line). The gray areas represent a system's plasticity (or antifragility), while the dark gray area represents the maximum response of a system.

While useful for understanding dose–response dynamics in complex biological systems, the symmetrical shape and biphasic characteristics of the hormetic response curve illustrated in **Figure 1** is not representative of all biological systems or organisms. For example, during strength training, the optimal load is known to differ between individuals (Jones et al., 1989). Just as biological organisms with similar genotypes express vastly different phenotypic responses to environmental extremes (Ghalambor et al., 2007; Costantini et al., 2010), athletes adapt and ultimately perform differently in the face of adversity. This means that two athletes, who perform at a similar level, may differ substantially in terms of how they adapt to different loading. For example, two athletes who can run a given distance in the same amount of time under low stress training conditions may perform very differently when environmental circumstances become more challenging due, for instance, to a temperature change. One athlete may need substantially more time with increasing heat, whereas another athlete may not differ very much from his or her personal best or even improve with increasing temperature (i.e. loading). Thus, it is necessary to individualize stress loads to trigger facilitative responses in the training context (Kiefer et al., 2018). To identify the optimal (training) load for each athlete, the hormetic curve can be used to quantify each athlete's *phenotypic plasticity* (PP)—i.e. the athlete's readiness to adapt to stress. PP can be quantified as the area under an athlete's hormetic curve (Calabrese and Mattson, 2011; Kiefer et al., 2018). The resulting profile provides a systematic way to identify loads that can be expected to trigger optimal behavioral responses, those that might be too small to trigger beneficial responses, and those that might be too large for the system to maintain proper functioning. In the previous example of the runners, the time needed to cover the specified distance would be plotted as a function of increasing temperature to pinpoint under what temperature loading the optimal response of each athlete is triggered.

Therefore, the response pattern that emerges from exposure to different levels of loading not only provides insight into the maximum performance level athletes can reach but also provide more nuanced yet relevant information about their adaptability to stress (or fitness).

The concepts of hormetic responses and PP have been successfully employed in the field of evolutionary biology for optimizing stress levels in a variety of biological systems (Costantini et al., 2010; Kiefer et al., 2018). However, they have yet to be applied to an athletic context (for a comprehensive review outlining the theoretical underpinnings of hormesis/PP in the context of athletic performance, see Kiefer et al., 2018). One barrier to application of this promising conceptual framework is the lack of objective measures to determine optimal loads for athletes in order to optimize performance development, enhance resilience, and promote antifragility. These objective measures are necessary to accurately map the changes in the response variables (e.g., running speed) as a function of loading (e.g., temperature). Equipping coaches and athletes with the necessary objective measures can help them design scientifically grounded training routines that facilitate athletes' self-improvement in a safe training environment.

The Current Study

The aims of the current study are (1) to provide a first empirical step toward the application of hormesis and PP to athletic performance training and (2) to determine whether the pattern of the hormetic response profile could be utilized to develop specific training recommendations. To achieve these aims, we designed a study involving a bouldering (climbing) task. In bouldering, loading can objectively be operationalized on the basis of the different difficulty degrees of particular routes (Draper, 2016). Although performance consists of many constituent variables, which could potentially be utilized for building load–response profiles, we assessed each athlete's climbing performance in terms of the degree to which a route was completed as it provides an objective performance indicator inherent to each motor task (i.e. the route). Additionally, we recorded the number of attempts the athletes required to reach the maximum performance per route. These values were combined into a response variable. We mapped this composite response variable as a function of route difficulty. This procedure resulted in load–response curves that captured each athlete's adaptability to stress, or PP, specifically operationalized as the area under the generated curves. Because similar genotypes demonstrate vastly different phenotypic expressions at loading extremes (Ghalambor et al., 2007; Costantini et al., 2010; Kiefer et al., 2018), Hypothesis 1 states that a group of climbers who reach similar maximum performance levels will exhibit a large range of PP scores (i.e. area under the load–response curve). Furthermore, across individuals, we expected to observe the typical characteristics of hormetic response curves, with evidence of antifragility. Specifically, Hypothesis 2 was that loading levels yield functional responses that intensify with increasing loading before reaching a peak amplitude. Following the peak amplitude, the response pattern begins to reverse until the athlete's performance begins to degrade and they are ultimately unable to perform (Cowin and Hegedus, 1976; Calabrese, 2005a,b; Calabrese and Mattson, 2011).

Finally, we will discuss how the load–response profile can be utilized to develop specific training programs. Specifically, the anticipated profiles indicate under what loading athletes are not sufficiently challenged (i.e. easy routes, which are completed in a single attempt), under what loading the athlete's capabilities are exceeded (i.e. unsuccessful completion regardless of the number of attempts), and when loadings trigger adaptive responses (i.e. completion of the routes in several attempts) (Kiefer et al., 2018). The identification of a systematic and objective strategy to assess how athletes respond to loading is a necessary step toward the development of training programs based on athlete- and task-specific PP (i.e. environmentally triggered, adaptive change).

MATERIALS AND METHODS

Participants

We recruited 37 intermediate-level climbers (26 male, 11 female) who voluntarily signed up to participate in the study by distributing flyers at a bouldering gym and advertising the study on social media. Eligibility for participation required a climber to be able to, at minimum, successfully complete bouldering routes equivalent to the difficulty of 5A according to the French bouldering grade system (Draper, 2016), which is the classification of the easiest route in the current study. The mean age of the participants was 26.1 years (SD = 4.8), with one individual not disclosing his or her age, and a group average bouldering experience of 3.1 (SD = 2.7) years.

Experimental Design and Setup

The current study was conducted in a local bouldering gym. Eleven different bouldering routes were used in the current study and were designed by professional route setters to provide a proportional increase in difficulty from one route to the next, ranging from 5A (easy) to 7B (very difficult) according to the French grading system (Draper, 2016). The routes were designed to optimally support data collection. The wall was largely vertical with little overhang to ensure that athletes do not fail a route due to limited strength alone and to allow us to obtain clear video images with a straight angle. Furthermore, the holds and intended climbing technique were not systematically varied between routes by setters (in general, easier routes involved easier holds and leader-type climbing, which changes to increased finger strength and technical abilities with more difficult holds). The different routes were assigned specific color codes used in the gym to indicate the expected level of difficulty for the athletes. Therefore, we relied on the experts' assessments of increasing difficulty in the rank order of the routes. Each route contained at least one zone hold, while three routes (i.e. route numbers 5, 10, and 11) contained two zone holds. A zone hold represents a marked hold on the route, which indicates partial route completion. Because the athletes' performances were videotaped (using a GoProHero3+©, GoPro, Inc., United States) during both trials, all routes were placed at the same wall in order to (a) optimize the transitions between routes without requiring major changes

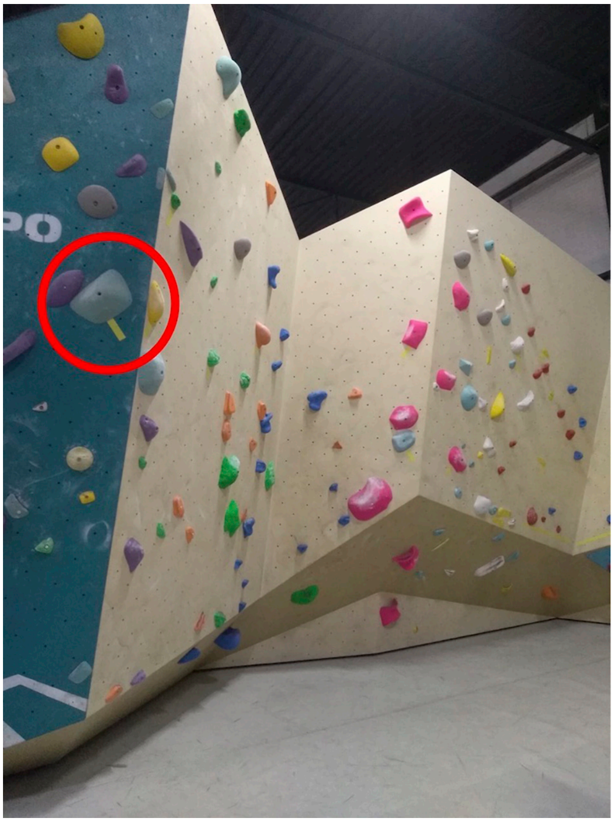

FIGURE 2 | Photograph of the experimental setup with most of the included routes. The zone holds were marked with yellow stripes for the athletes' clarity (an example is marked with the red circle). Consecutive holds of the same coloration yield one route.

to the setup and (b) minimize disruption to the flow of the athletic performance (see **Figure 2**).

Procedure

The study procedure was approved by the Ethical Committee Psychology, University of Groningen (research code "18237-O"). Upon arrival at the bouldering facility, participants received information about the study and filled in the informed consent form. During the study, participants used their own equipment (e.g., climbing shoes and outfits). The warm-up program lasted approximately 20 min, and consisted of several body weight and stretching exercises as well as short bouldering on easy routes (grade 3, French grading system) in a different part of the facility. After the warm-up session, the actual data collection began. First, the participants climbed a maximum of 11 routes in a fixed order of increasing difficulty. The participants were instructed to complete as many routes as they could within the allotted time of 10 min. They were only allowed to move to the next more difficult route once a route had been completed. The number of attempts per route was not limited, and the athletes were encouraged to approach the routes as they would in regular training. For example, if they required more time to visualize a route before attempting it, they were allowed to do so. However, in order to avoid injuries by exposing athletes to overwhelming stress, the trial was terminated when a participant was unable to complete a given route (i.e. the participant could not reach the final hold and decided to stop or the 10 min had passed).

After the first trial, the participants sat at a desk with their backs facing the climbing routes and filled out a questionnaire assessing their demographics, physical fitness, and bouldering and climbing experience. During this 10–15-min break, the participants were also provided with refreshments and time to rest. However, during the break, the participants did not talk to other athletes in the facility and could only ask the experimenter questions related to the study. Furthermore, the participants were prohibited from seeing the routes and other athletes climbing these routes in order to avoid visualization effects (e.g., Sanchez et al., 2012; Orth et al., 2016). Following the break, the athletes conducted the second trial with the exact same routes in the same order. Afterward, the participants had the opportunity to receive a copy of the video files for both trials alongside a full debriefing of the study.

Measures

Performance

For each route, the participants received a score that varied between 0 (i.e. not reaching a zone hold or the final hold) and 1 (i.e. successful completion of the route) for every attempt they conducted. We considered that an athlete successfully completed a route when the final hold was reached and held for 2 s, which was signaled by the experimenter. Reaching a zone hold yielded a proportional completion score depending on the number of zone holds per route (see **Table 1** for possible scores). In line with the rules of the International Federation of Sport Climbing (International Federation of Sports Climbing [IFSC], 2019), we considered that an athlete reached a zone hold if he or she used the hold to produce a stable or controlled position or to progress along the route. Specifically, to gain the score for reaching a zone hold, the athlete had to: (a) make contact with the zone hold with one foot or hand while remaining in a stable position for at least 2 s, (b) use the zone hold to stabilize before progressing, or (c) use the zone hold to quickly progress with no interruption. Thus, shortly tapping the hold before falling onto the safety mats did not count as reaching the zone hold. Once an athlete was unable to successfully complete a route, the subsequent routes were also scored with 0.

TABLE 1 | Possible scoring outcomes for performance for a given attempt.

Coding result	Completion rate	Performance
0 holds	0%	0
1 out of 2 zone holds	33.33%	1/3
1 out of 1 zone hold	50%	1/2
2 out of 2 zone holds	66.67%	2/3
Reaching final hold	100%	1

Attempts

The video footage was coded for the amount of attempts a participant required for each route. An attempt was counted if the athlete had both hands and feet on the starting holds and was thus off the ground. Any contact with the ground without successfully completing the route granted the opportunity to make a new attempt. There were no restrictions in the total number of attempts: the athletes were free to decide how many times they wished to attempt a given route.

Data Analysis

The first step of the data analysis was to determine the maximum performance that each athlete achieved per route in each trial. For example, if a participant required more than one attempt but managed to complete the route, the maximum performance score reflected successful completion (i.e. a score of 1; **Table 1**). To assess systematic differences among trials, we computed the mean scores and the standard deviations of the number of attempts, the accumulated maximum performance scores for each route, and the number of routes completed for each trial. In order to account for potential learning effects and random variation, we averaged the maximum performance and the number of attempts per route of the trial before the break and the trial following the break. In order to assess each climber's responses to loading (determined by a given route), we computed a "response" variable normalizing the average maximum performance by the average number of attempts:

$$\text{Response} = \frac{M_{\text{Perf}}}{M_{\text{Att}}} \tag{1}$$

M_{Perf} equals the average maximum performance, whereas M_{Att} equals the average number of attempts. This equation yields values between a score of 1, reflecting route completion in a single attempt across both trials [i.e. M_{Perf} (= 1) divided by M_{Att} (= 1)], and 0 (i.e. no zone hold reached regardless of number of attempts across both trials). To illustrate, if a participant reached on average the second zone hold for a route in three attempts, they would earn a final response score of 0.222 (2/3 divided by 3, see **Table 2** for an elaborate example and https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/FJZ9AX for the full dataset). The resulting "response" scores were then plotted as a function of increasing loading (i.e. by increasing route difficulty) to create a load–response curve.

To quantify the range of PP among athletes, the analysis followed three steps. First, the area under the load–response curve was determined for each athlete. Because the loading on the *x*-axis represents discrete values with a constant loading interval (i.e. is an ordinal variable), the area under the curve can be approximated accurately by a cumulation of the response values on the *y*-axis:

$$AUC = \sum_{i=1}^{n} R_i \tag{2}$$

AUC represents the area under the curve, *n* the maximum number of routes in the study (i.e. 11), and R_i the "Response" value at a given route. Hence, the example outlined in **Table 2** would yield a PP (i.e. area under the curve) of 4.46 (given by $1 + 1 + 0.5 + 0.667 + 0.222 + 0.667 + 0.333 + 0.071$).

Having determined the PP per individual (Step 1), we tested whether climbers who had reached similar maximum performance levels exhibit different PP scores (Hypothesis 1). Specifically, as a second step, the resulting PP scores were sorted according to the maximum performance the athlete reached (i.e. the most difficult route for which a response value larger than 0 on the *y*-axis was determined. In the example of **Table 2**, this would correspond to route number 8). Third, the maximum range of PP scores was then calculated for each group, with each group defined as two or more climbers who reached the same maximum performance. The maximum range scores were then averaged across all groups that contained at least two individuals. Because all athletes within each group reached the same maximum performance level, the mathematically maximum possible range is limited by the value of the maximum performance level of a given group. For example, for a group reaching a maximum performance of 7, the maximum range can be any value below 7, but not equal to 7. A range approximating a value of 1 is interpreted as large and represents the maximum response score an athlete can reach on a given route. In other words, a range equal to 1 within a group demonstrates that there is a difference of at least one optimal performance route despite reaching the same maximum performance.

To test for antifragile (i.e. growth from loading) properties of hormetic response curves (Hypothesis 2), we calculated whether positive deviations from the baseline value (i.e. the response score on the first route) precede negative deviations as a function of increasing loading. The hypothesis is supported if positive deviations from the baseline score precede negative deviations across participants.

RESULTS

Before conducting the main analyses, we assessed the differences between the trial before the break and the trial following the break. Athletes used on average 15.4 (*SD* = 4.5) attempts for the first trial and 13.8 (*SD* = 3.7) for the second trial. The maximum performance reached was, on average, 4.5 (*SD* = 2.2) on the first trial and 4.8 (*SD* = 2.5) on the second trial, while the average number of completed routes was 4.4 (*SD* = 2.3) for the first trial and 4.6 (*SD* = 2.5) for the second trial (see **Figure 3** for a graphic illustration of the distributions). Thus, there seems to be a slight increase in maximum performance and number of routes completed, while the number of attempts between the two trials slightly decreases.

Hypothesis 1 was that athletes who reach similar maximum performance levels display a large range of PP. To test this hypothesis, we assessed the maximum range of PP within a group of athletes who reach the same maximum performance in terms of route completion. Grouping the athletes according to their maximum performance scores yielded eight different routes, where at least two individuals reached their maximum performance level (see **Table 3** and supplementary material) with

TABLE 2 | Full response calculation example.

Route	Trial 1		Trial 2		Average		Calculation	Response
	Comp	Att	Comp	Att	Comp	Att	M_{Perf}/M_{Att}	
1	1	1	1	1	1	1	1/1	1
2	1	1	1	1	1	1	1/1	1
3	1	3	1	1	1	2	1/2	0.5
4	1	2	1	1	1	1.5	1/1.5	0.667
5	1	8	1	1	1	4.5	1/4.5	0.222
6	1	1	1	2	1	1.5	1/1.5	0.667
7	1	1	1	5	1	3	1/3	0.333
8	0.5	2	0	5	0.25	3.5	0.25/3.5	0.071
9	0	–	0	–				0
10	0	–	0	–				0
11	0	–	0	–				0

Comp represents completion rate of the route for the trial, Att represents the number of attempts per route for the trial. The athlete does not manage to complete route 8 in each of the trials, which ended a given trial. The subsequent performance scores are set to 0.

a mean average range of 0.951 ($SD = 0.377$). Because the average range approximates 1 (i.e. maximum response score for a given route), this provides an indication that athletes reaching the same maximum performance level indeed show considerably different adaptability under different loading extremes (Hypothesis 1). For example, **Figure 4** represents four different athletes who complete the same number of routes but display unique load–response curves each and accordingly a large range of PP scores.

Hypothesis 2 was that the resulting profiles show typical properties of the hormetic response curve. That is, functional responses increase with increasing loading until a peak amplitude is reached, after which the pattern is reversed. Results obtained from the analysis of response profiles did not show the expected increase in performance from baseline with low levels of load before showing a decrease in performance with higher levels of lead. Thirty-six out of the 37 participants reached the maximum performance score (i.e. a score of 1) for the first route and therefore did not allow for any positive deviation from the baseline score for the subsequent routes (see **Figure 3** for examples). Therefore, Hypothesis 2 is not supported.

DISCUSSION

The aim of the current study was to provide a first empirical step toward the application of hormesis and PP to human performance (Kiefer et al., 2018). This approach has the potential to provide researchers, coaches, and athletes alike with specific methods to objectively determine the optimal loading for athletic performance training. In order to test its feasibility in the context of sports performance, behavioral responses need to be initially examined as a function of increased loading (Costantini et al., 2010; Agathokleous et al., 2018; Kiefer et al., 2018). The resulting profiles can be analyzed to quantify an athlete's PP by calculating the area under the load–response curve to determine the optimal training load for the athlete (cf. Calabrese and Mattson, 2011; Kiefer et al., 2018).

Our results suggest that load–response profiles provide novel information that can be used to generate specific recommendations for athletic performance training. That is, we found that athletes who reach similar maximum performance levels can demonstrate a rather large range of potential PP scores indicating their adaptability under various loadings. Due to this variability of load–response profiles (and by extension PP), any given profile is likely difficult to generalize to a broad range of athletes. Thus, the strategy must be personalized and starts with objective assessment of loading responses of each individual (Ghalambor et al., 2007; Costantini et al., 2010; Kiefer et al., 2018).

In line with the typical hormetic response curve, we expected the response curves of the athletes to first show an increase with intensifying loading before a critical point is reached after which the pattern reverses (e.g., Cowin and Hegedus, 1976; Calabrese, 2005a,b; Calabrese and Mattson, 2011). However, because all but one athlete reached the maximum response score on the first route, which served as the baseline for the fitness assessment, we did not observe enhancement in the behavioral response as a function of initial increases in loading. Thus, we cannot make inferences about antifragility in the observed athletes. The failure to find the expected pattern may be due to the fact that our baseline score does not represent the state of the athlete in the absence of any loading, as a true baseline score should (Costantini et al., 2010; Calabrese and Mattson, 2011). Since our response variable was a composite score of task-relevant behavior, it may not be possible to measure it in the absence of any loading. Future research should explore different measures, such as neuromuscular activity during performance, which allows measurements in the absence of loading.

Despite the absence of true antifragility evidence, the current load–response profiles of the athletes may still be utilized for training. Specifically, these profiles allow objective determination of routes that do not challenge the athlete, routes that exceed the capacity of the athlete, and routes that challenge the athletes. Routes that do not challenge the athlete are fully completed

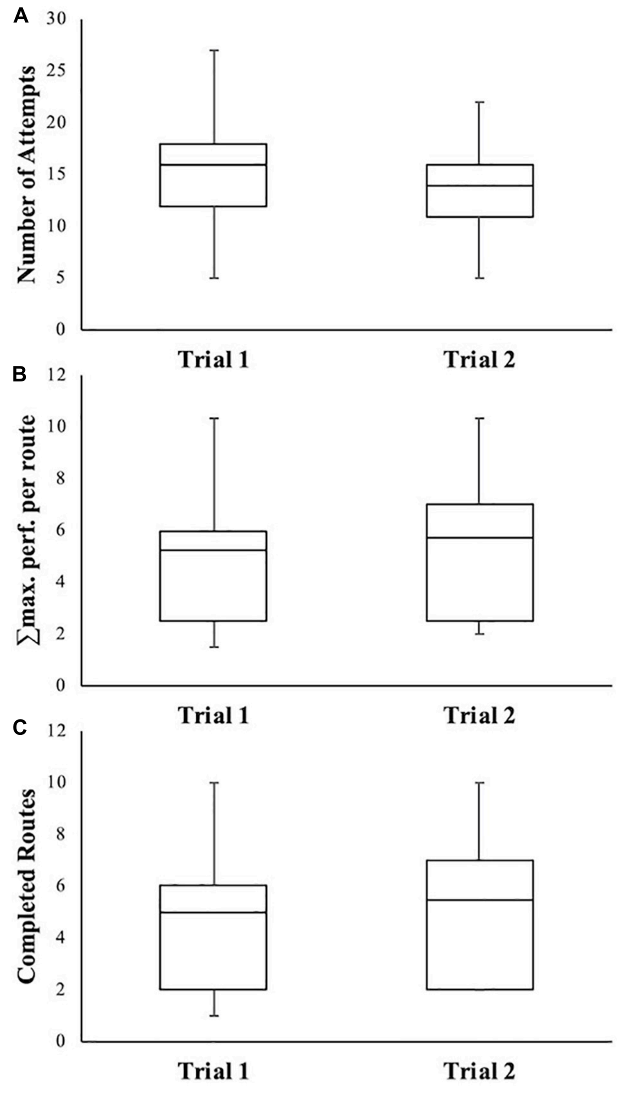

FIGURE 3 | Boxplots depicting the medians, quartiles, minimum, and maximum of the number of attempts **(A)**, accumulated maximum performance **(B)**, and number of routes completed **(C)** for each trial.

with a single attempt as they do not foster adaptations in the motor solutions employed to progress. When routes exceed the capacities of the athletes, they cannot make any progress (in terms of zone holds) independent of the number of attempts an athlete conducts. We classified routes situated in between these extremes as challenging because athletes can complete them but after more than one attempt. According to our scoring system, a response value of 1 would represent an easy route, a response score of 0 represents routes that exceed the capacity, and values ranging between 0 and 1 represent challenging routes: lower values indicate greater challenges. Challenging routes force the athlete to actively explore new motor solutions to adapt to his or her environment (Latash, 2012), which improves overall performance on routes of various difficulty levels (Seifert et al., 2014; Orth et al., 2016).

TABLE 3 | Maximum range values of phenotypic plasticity for different maximum performance (Max. Perf.) by route.

Max. Perf. by route	*n*	Maximum range
2	6	1.083
3	7	1.258
4	6	0.833
5	5	0.967
6	3	0.929
7	4	1.583
8	1	0
9	2	0.583
10	2	0.373
11	1	0

The size of each group is given by n.

In line with the variability of the response profiles (and therefore, PP) of the athletes, the range of challenging routes can differ between athletes, who reach a similar level of maximum performance (**Figure 3**; Kiefer et al., 2018). For example, most routes for the athlete displayed in **Figure 4A** may be considered too easy before the capacities are exceeded. This results in a rather small training window (**Figure 5A**). In contrast, the athlete displayed in **Figure 4D** encounters many challenging routes residing between too easy levels and exceedingly difficult levels, thus resulting in a relatively large recommended training window (**Figure 5B**). Creating load–response profiles can yield important insights into the stress–response of an athlete, which should be considered for his or her training regimes. In the current study, there was only one athlete who either easily completed a route or failed, leaving no “challenging” routes in the profile (**Figure 5C**).

The recommendations derived from the response profiles are also in line with research beyond the stress–response literature. For example, research on goal setting has shown that goals which are challenging but attainable yield optimal results in terms of performance and development (Locke and Latham, 2013; Van Yperen, 2020). Individuals setting easily attainable goals do not sufficiently challenge themselves, whereas individuals setting unattainable goals predispose themselves to failure, which can later be excused with the difficulty of the goals. In terms of hormesis, individuals who pursue challenging goals may expose themselves to loading that triggers positive behavioral responses but, due to the attainability of these goals, do not overload themselves.

Limitations

In order to validate the specific recommendations for performance training derived from the load–response profiles, longitudinal studies need to be implemented. Specifically, studies identifying optimal loading for athletes should be coupled with designing training schedules leveraging this information. Athletes training under optimal loading should develop more motor solutions to behavioral task as well as improve their overall performance more than athletes training at suboptimal levels or who train based solely on information about maximal

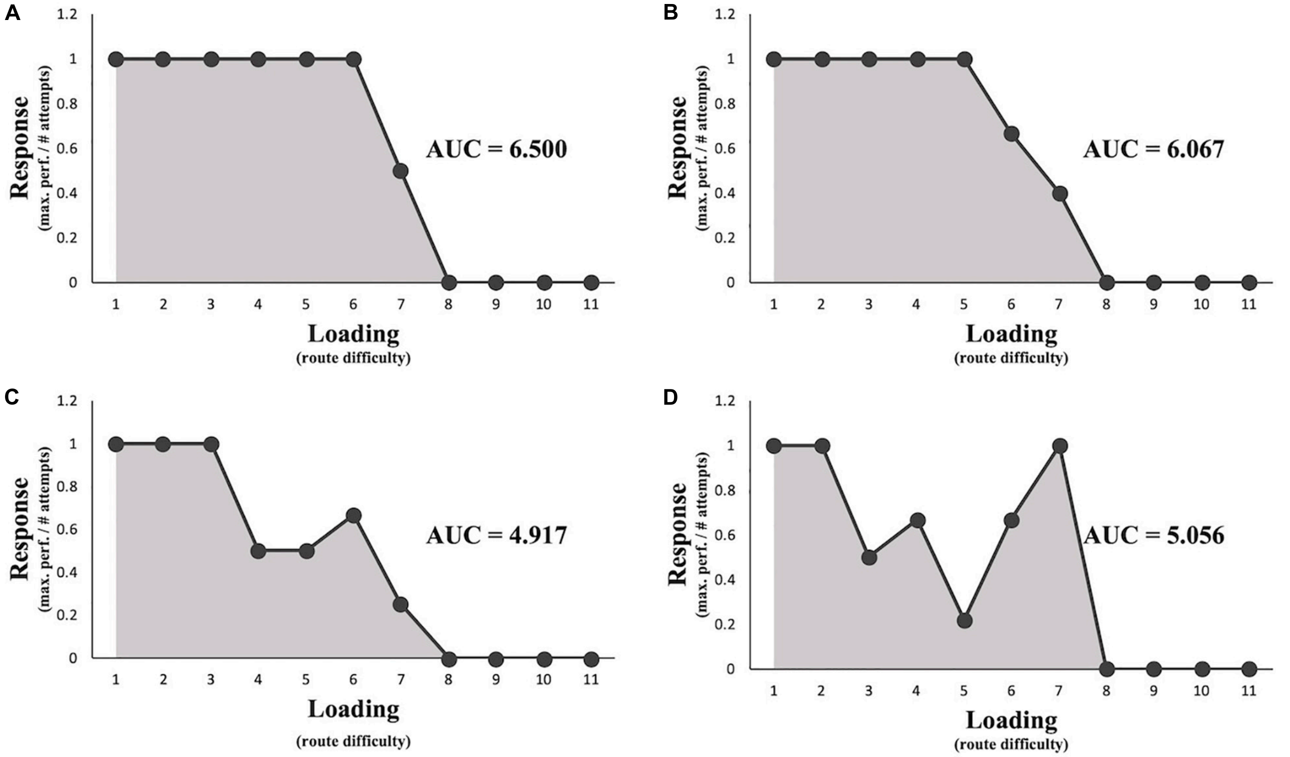

FIGURE 4 | Four examples of different athletes' load–response curves reaching the same maximum performance level **(A–D)**. The curves are created by mapping the response scores (see Eq. 1) as a function of loading determined by routes ordered from easiest (1) to most difficult (11). The gray area under the curve (AUC) score (i.e. the sum of an individual's response scores, see Eq. 2) represents an athlete's phenotypic plasticity (PP).

performance (i.e. conditioning hormesis; Calabrese et al., 2007). However, it should be noted that once the training routine begins, the optimal loading for athletes may change over time (as a function of changes in internal and/or external factors), thus requiring frequent monitoring of the plasticity profiles to ensure the exposure to optimal loading throughout such studies.

Although the current study provides an important first step toward the possible application of hormesis and PP to the domain of sports, our assessed response variables do not provide extensive information regarding the sport-specific behavior of the athletes. In order to fully translate the assessment of biological responses (i.e. response variables) to the domain of sport, in-depth measurements of the behavioral responses need to be obtained (Kiefer et al., 2018). For example, previous research has shown that non-linear complexity measures of athletic performance can provide insight into the dynamics of sport-specific movements (Den Hartigh et al., 2015; Kiefer and Myer, 2015; Araújo and Davids, 2016). Mapping such biological sport-specific variables as a function of loading may yield more sensitive and thorough profiles than overt behavioral measures. Such variables may also yield higher resolution for behavioral responses to variations in loading. In the current study, the maximum amount of data points that can be mapped as a function of loading may not be ideal for specific training recommendations as the patterns in the response profiles are based on discrete changes between two points rather than a trend of behavioral change of an athlete with successively increasing loading. Optimizing this resolution may increase the precision and effectiveness of specific recommendations derived from the response profiles (Calabrese et al., 2019).

Finally, in order to avoid injuries due to the exposure to loads that are too high, the athletes in the current study were asked to stop performing once they could no longer successfully complete a route. This also implies that the order of the routes had to be sorted by increasing difficulty and could not be completed in a randomized order. Fixing the order may have caused the athletes to become systematically more fatigued with increasingly difficult routes. Future studies may consider exposing athletes safely to increased levels of stress without risking harmful consequences by utilizing mixed reality [e.g., virtual reality (VR) or augmented reality] devices (Kiefer et al., 2017). Mixed reality environments may enable the safe exposure to highly standardized stressors while obtaining a multitude of sport-specific response variables in lab settings. Furthermore, securing safe exposure to varying stressors allows for a randomized presentation of different loadings. This, in turn, decreases the chance of finding lower response levels at higher levels of loading caused by fatigue. Ideally, virtual environments should be designed to capture the environmental information to which the athlete has to adjust during performance as closely as possible. This aspect of design is critical to optimize the chances that athletes will display responses to stressors in VR

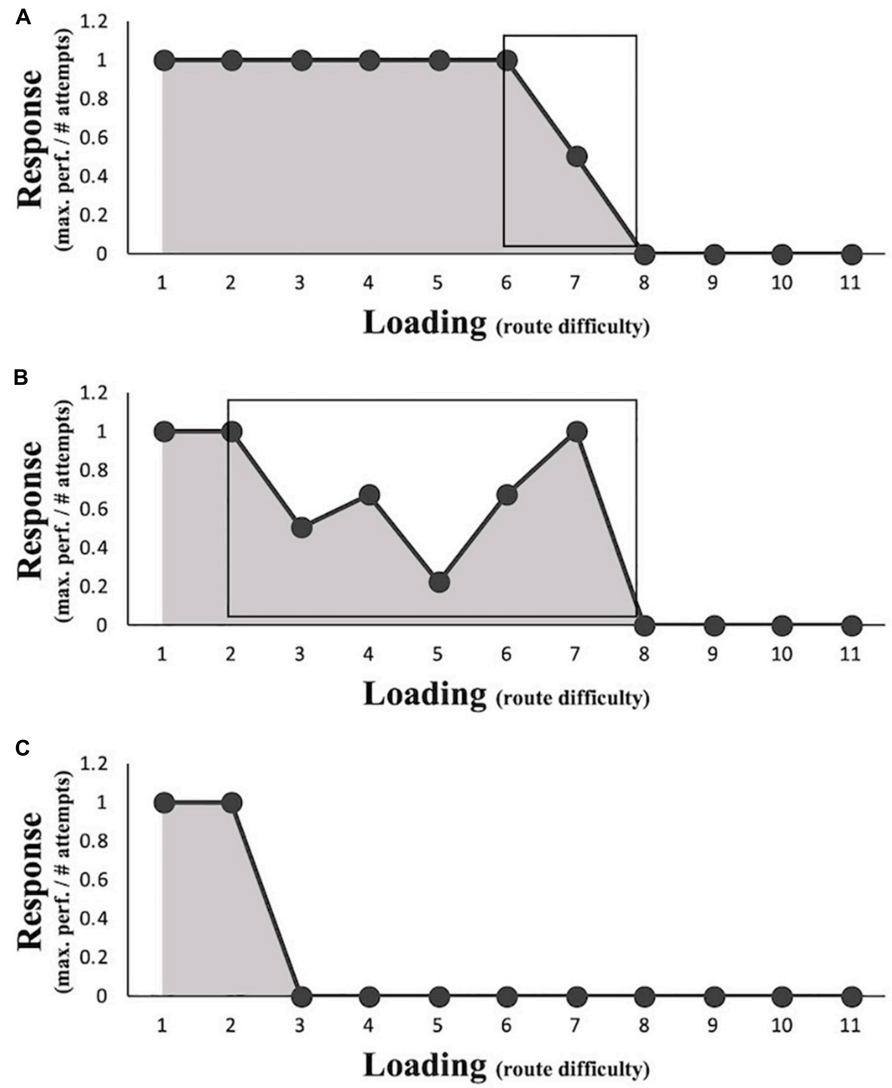

FIGURE 5 | Three examples of load–response profiles for training recommendations. The black rectangles **(A,B)** represent the recommended training area residing between easy and too difficult routes. The athlete represented in **(C)** only demonstrates easy and difficult routes with no pattern in between.

sports scenarios that are representative of those displayed in the real-world setting (Araújo et al., 2006).

Implications

Establishing load–response profiles to optimize athletic performance training is not restricted to individual sports, such as climbing. It can be extended to other domains. For example, when different athletes perform together, they form a dynamical, biological system of constantly interacting individuals (e.g., Gorman et al., 2017). Thus, a sports team could be viewed as a system, which follows many of the same dynamic principles as individual athletes. Similarly, as evolutionary biology demonstrates, the notion of hormesis can be extended to a collection of organisms within the same species and colony (Mattson and Calabrese, 2010). Successfully adapting to small environmental hazards increases the biological fitness of a species, which increases the resistance to higher dosages of environmental hazards. This implies that load–response profiles can also be established for sports teams to pinpoint the optimal loading for performance training. In the case of crew rowing, for instance, there are several factors, such as coordination of the strokes of the individuals (e.g., Hill, 2002; Den Hartigh et al., 2014; De Poel et al., 2016), that contribute to the team's performance and could thus be used as a response variable. Loading could be varied systematically by asking the teams to row a certain distance at different amounts of time (i.e. speed). The resulting profiles would then map coordination (i.e. response) as a function of speed (i.e. loading) to pinpoint at which speeds the athletes coordinate well or struggle to coordinate. Therefore, to extend load–response profiles to different sports, it is essential to define one or multiple response variables, which can be measured as a function of systematically varied loading.

For more dynamic team sports, such as soccer, it is much more difficult to identify a single determinant of player performance. Instead, it is likely more useful to obtain information from different load–response profiles for individual skills and behaviors to determine optimal loading. For example, avoiding collisions on the field can be regarded an important skill for a soccer player because it increases the chance of passing an opponent while simultaneously decreasing the chance of acquiring injuries (Silva, 2017). Using mixed reality devices, an athlete could be asked to complete a short sprint while trying to avoid virtual obstacles. Loading could be manipulated by varying the amount and difficulty (e.g., size and movement) of the obstacles. Then, the time the athlete needs to complete the sprinting route and the number of obstacles avoided can be combined with the response, which is plotted as a function of loading. Similar profiles can then be established for passing accuracy given the distance to the teammate and opposing players similar to game-relevant behaviors (Silva, 2017; Kiefer et al., 2018).

In addition to a quantitative approach, qualitative accounts may help explain the idiosyncratic shape(s) of load–response profiles. More specifically, interviews following the experiment or asking participants to verbalize their thoughts during the performance may help to match the specific strategies applied by the athletes to their load–response. This could help coaches to facilitate effective strategies.

CONCLUSION

In conclusion, the current study provides a first empirical insight into the applicability of hormesis and PP to the assessment of athletic performance. We assessed climbers' performance as a function of increasing difficulty in bouldering routes (i.e. loading). Our results suggest that the application of PP to assessment of adaptability to loading is scalable to human performance. Therefore, training programs that enhance both athletic performance and athletes' adaptability to stressors (i.e. resilience, antifragility) should consider the load–response curves of individual athletes for a more precise and personalized intervention. These profiles enable researchers and coaches to objectively determine optimal loading and provide a basis for understanding the resulting dose–response dynamics throughout athletic performance training.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dataverse at doi: 10.7910/DVN/FJZ9AX.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical Committee of Psychology (ECP) RuG (University of Groningen). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

YH developed the theoretical framework, conceived the study, analyzed the data, and wrote the manuscript. AK and PS developed the theoretical framework, analyzed the data, and provided critical feedback on the drafts. NV conceived the study, guided the analyses, and provided critical feedback on the drafts. RM conceived the study and provided critical feedback on the drafts. NF conceived the study, collected the data, and aided the analysis process. RD developed the theoretical framework, conceived the study, guided the analyses, and provided critical feedback on the drafts.

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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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ORIGINAL RESEARCH
published: 13 March 2020
doi: 10.3389/fpsyg.2020.00252

Climbers' Perception of Hold Surface Properties: Roughness Versus Slip Resistance

Franz Konstantin Fuss[1], Yehuda Weizman[1], Günther Niegl[2] and Adin Ming Tan[1]***

[1] Smart Products Engineering Program, Swinburne University of Technology, Melbourne, VIC, Australia,
[2] Climb-on-Marswiese, Sportstättenverein Marswiese, Vienna, Austria

The more experienced a climber is, the more friction they can impart on a climbing hold surface. The aim of this research was to investigate how the properties of a hold's surface are perceived and how the perception relates to the amount of friction applied to the hold. The holds' surface properties are roughness/smoothness and grippiness/slippiness. Fourteen different surfaces with a wide range of property combinations were selected and placed on an instrumented climbing hold, mounted on a bouldering wall, and incorporated into a climbing route. Twenty-two climbers participated in the study. The ratio of friction to normal force (denoted friction coefficient or COF subsequently) was obtained from the sensor data, and the subjective ranking of the surface properties was provided by the participants. The average COF applied to the surfaces ranged from 0.53 (Teflon) to 0.84 (rubber). The surfaces with the lowest and highest grippiness and roughness ranking were Teflon and sandpaper, respectively. The correlation between roughness and COF was insignificant, whereas the correlation of grippiness and COF was significant. This applies to the 22 participants at the group level. At the individual level, 50% (11 climbers) of the participants did not show any correlations between surface properties and COF; eight climbers exhibited correlations between the combined grippiness and roughness (multiple regression) and COF, as well as grippiness and COF; only one climber out of the eight showed an additional correlation between roughness and COF. The results are interpreted in a way that climbers assess a hold's surface based on grippiness, and not on the roughness, and apply a COF to the hold that reflects the perception of grippiness.

Keywords: perception, climbing, handhold surfaces, roughness, slip resistance, grippiness, implicit surface assessment, conscious surface ranking

OPEN ACCESS

Edited by:
*Stefan Künzell,
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Reviewed by:
*Simon Fryer,
University of Gloucestershire,
United Kingdom
Michail Lubomirov Michailov,
National Sports Academy "Vasil
Levski", Bulgaria*

****Correspondence:***
*Franz Konstantin Fuss
fkfuss@swin.edu.au*

Specialty section:
*This article was submitted to
Movement Science and Sport
Psychology,
a section of the journal
Frontiers in Psychology*

Received: *04 November 2019*
Accepted: *03 February 2020*
Published: *13 March 2020*

Citation:
*Fuss FK, Weizman Y, Niegl G and
Tan AM (2020) Climbers' Perception
of Hold Surface Properties:
Roughness Versus Slip Resistance.
Front. Psychol. 11:252.
doi: 10.3389/fpsyg.2020.00252*

INTRODUCTION

Friction is one of the most important parameters in climbing, as it decides over failure or success when gripping a hold. There is extensive literature on friction in climbing, including a review article by Fuss and Niegl (2012). An additional publication by Fuss and Niegl (2008a) analyzed the friction produced by climbers on a hold instrumented with force transducers during the ladies' quarterfinal of the 2002 Climbing World Cup in Singapore. Among other parameters, the authors detected that more experienced climbers produce more friction (i.e., a higher friction coefficient) at the hold's surface. The reasons for this are the following. Firstly, experience is gained through a long-term training effect, which, over time, allows experienced climbers to reduce the margin of error and approach the point of impending slippage. Secondly, experienced climbers exert a smaller force to the handhold compared to less experienced climbers (Fuss and Niegl, 2008a). By shifting the load (normal force) from hands to feet, the coefficient of friction (COF) increases (Fuss and Niegl, 2012). Thirdly, experienced climbers do not fatigue that quickly and thereby maintain the normal force at a magnitude that keeps the COF in the substatic regime. Lastly, long-term climbing, specifically outdoors, leads to thicker and rougher skin, which also contributes to a greater COF. At this point, it has to be mentioned that climbers usually slip more often with their feet rather than with the hands.

In contrast to the extensive literature on climbing and friction, to the best knowledge of the authors, there is no literature source on the perception of surface properties of climbing holds.

Perception is a well-researched area within the discipline of Psychology. "Texture perception" is "the experience of any of a number of surface qualities, for example, roughness, smoothness, . . . stickiness, slipperiness,. . ." (Lederman, 1982). Several authors such as Stevens and Harris (1962); Ekman et al. (1965), and Verrillo et al. (1999) correlated the perceived roughness of sandpaper to their grit number and discovered that the regression function follows a power law. Ekman et al. (1965) confirmed this behavior also for the relationship between perceived roughness and the COF. Smith and Scott (1996) extended this research to the correlation between perceived slipperiness and the COF of smooth surfaces. Comparable perception research was applied to the perception of fabrics and textiles. Ramalho et al. (2013) measured the kinetic COF of five fabrics against the skin at loads between 0 and 1 N and a sliding speed 35 ± 10 mm/s and found a correlation with two texture properties, namely "rough/smooth" and "adhesive/slippery." Chen et al. (2015) and Ding et al. (2018) investigated the roughness ranking of fabrics and their relation to the COF.

When handling objects, test persons perceive slipperiness automatically and implicitly under static conditions by adjusting the grip force automatically such that the object does not slip out of their hands (Johansson and Westling, 1984; Cadoret and Smith, 1996). In contrast to this, Grierson and Carnahan (2006) found that for conscious and accurate perception of slipperiness, movement of the fingers over the surface is required. The latter principle is expected to apply to climbers too. When climbing, they assess the properties of a hold based on its size, shape, surface inclination, and surface properties. This is done by consciously moving the palm over the hold at low force during the "setup" phase of the hand contact (Fuss and Niegl, 2008a). Yet, when loading the hold with greater forces during the "crank phase" (Fuss and Niegl, 2008a), the hand and fingers remain statically on the hold, and the friction force exerted on it is expected to be adjusted implicitly. These expectations are intended to be verified in this paper, supported by appropriate hypotheses.

"Friction" is usually expressed as the ratio of the friction force to the normal force, i.e., the friction force normalized to the normal force and referred to as the COF. At the point of impending slippage, we encounter the static COF, whereas beyond the point of impending slippage, i.e., when sliding over a surface, we deal with the dynamic or kinetic COF. Both cases, even if not desired, occur in climbing when the climber slips off a hold. The ratio of the friction force to the normal force before the point of impending slippage, the common case in climbing, is usually not referred to as the COF; however, for simplicity reasons, the ratio will be denoted as the (*sub*static) COF throughout this paper. The hand or fingers will slip off the hold for two reasons:

(1) If the finger flexing muscles fatigue when clinging to a hold, and weight is shifted from hands to feet, then the normal force on the hands or fingers decreases, which in turn causes the COF to increase, approach the point of impending slippage, and finally exceed this point.
(2) In cases without fatigue, if the static COF is misjudged, the COF applied to the surface exceeds the point of impending slippage.

Performance parameters of climbers are mirrored by difficulty parameters related to a climbing route. This means that when a climber produces a low COF on a hold, then this can be interpreted as a low performance of the climber or as an increased difficulty of gripping the hold (Fuss and Niegl, 2008b; Fuss et al., 2013). The more difficult a hold becomes to deal with and the greater is the danger of slipping off, the more dynamic a move becomes (Fuss and Niegl, 2008b). Climbers use "chalk" (magnesium carbonate) for improving friction on the hold (Fuss et al., 2004). However, chalk can have a negative effect, namely reducing the friction, if a hold is already polluted with chalk or if the surface of a hold is smooth (Fuss et al., 2004; Fuss and Niegl, 2012).

That more experienced climbers exert a higher COF to a hold is an expression of long-term training (Fuss and Niegl, 2008a), i.e., extensive exposure to many different hold surfaces indoors and outdoors. However, it is unclear how climbers assess the surface of a hold and what parameter drives them to produce more friction or less friction on the surface. Potential parameters include the roughness of the surface profile and its slip resistance. Subsequently, these two parameters shall be denoted as roughness/smoothness (rough/smooth) and grippiness/slippiness (grippy/slippy). Based on these two parameters, two cardinal hypotheses can be formulated:

> Hypothesis 1: The rougher the surface, the smaller is the chance of slipping off the hold and the more friction the climbers apply to the hold.
>
> Hypothesis 2: The grippier (more slip-resistant) the surface, the smaller is the chance of slipping off the hold and the more friction the climbers apply to the hold.

As the surface properties of a hold are a combination of different degrees of roughness and grippiness, these two parameters must be separated, which can only be done by offering various combinations of high/low roughness and grippiness. As these extreme combinations are not represented by commercially available climbing holds, they can only be provided by using surface materials that are currently not common to sport climbing.

The aim of this paper is to investigate these two hypotheses, insofar as how climbers perceive the surface of a hold and which parameter (rough or grippy) they consciously or implicitly give preference to. This perception study was conducted by offering a range of different surfaces to climbers with a combination of different degrees of grippiness and roughness. We assessed the implicit perception by measuring the COF on the surface and the conscious but subjective perception by ranking the surfaces in terms of grippiness and roughness.

MATERIALS AND METHODS

Rationale of the Method

Perception is a subjective parameter. For experienced climbers, judging the surface of a hold is expected to be an implicit task, which has been trained and perfected over the years of climbing. Nevertheless, the outcome or effect of this task can be measured objectively by instrumenting a hold and calculating the ratio of friction to the normal force, i.e., the COF. Rating and ranking a surface not during climbing is equally a subjective task and reflects the conscious perception of a surface.

The terminologies of surface properties to be used in this paper are as follows:

> *Grippiness*: represents a *grippy* surface with high slip resistance;
> *Slippiness*: represents a slippery or *slippy* surface with low slip resistance;
> *Roughness*: represents a surface with a high amplitude of surface asperities;
> *Smoothness*: represents a surface with a very low amplitude of surface asperities or without asperities at all.
> COF: the ratio of the friction force to the normal force, which is usually *before* the point of impending slippage ("substatic" COF) in climbing, as *at* the point of impending slippage (static COF), the danger of slipping off (sliding off) a hold is imminent (kinetic COF when slipping).

To statistically separate the two parameters of grippiness and roughness, the climbers must deal with both range and the combination of different degrees of roughness and grippiness, and this is done during climbing for measuring the COF and after climbing for ranking the surfaces. The four combinations thus are:

(a) grippy and rough;
(b) grippy and smooth;
(c) slippy and rough;
(d) slippy and smooth.

It is evident that the two hypotheses formulated in the *Introduction* are inapplicable to combinations (b) and (c). Therefore, the two hypotheses are combined into one, for combinations (a) and (d):

> Hypothesis 3: The rougher and grippier (or smoother and slippier) the surface, the lower (or higher, respectively) is the chance of slipping off the hold and the more (or less, respectively) friction the climbers apply to the hold.

Furthermore, if opposing parameters are combined, i.e., combinations (b) (smoother and grippier) and (c) (rougher and slippier), then the options for climbers are putting more importance on either:

- Grippiness (such that the friction increases as grippiness does); or
- Roughness (such that the friction increases as roughness does); or on
- The average of grippiness and roughness, resulting in average friction.

To confirm Hypothesis 3 and assess the additional three options, the following investigations were carried out based on the processed data of the instrumented hold (with 14 different surfaces) and the subjective ranking of roughness and grippiness:

- Hold surfaces and their difference in the COF, roughness, and grippiness;
- Four combinations of roughness and grippiness in terms of which combination drives the climber to produce the highest and the lowest COF; and
- Difference between climbers in terms of the individual and the combined influence of roughness and grippiness on their COF produced on each hold.

These investigations come down to answering the following three questions.

- Does "the property" of the hold's surface influence the COF produced by a climber in a sense that perception of "the property" triggers the amount of friction applied "automatically" or implicitly to the hold?
- Which parameter are the climbers implicitly going for when assessing or gripping a hold's surface during climbing: roughness/smoothness or grippiness/slippiness or both?
- Are individual climbers really "implicitly aware" of what they are doing on a hold, e.g., because of a long-term training effect or intuitively?

Surface Materials for the Instrumented Hold

The rationale for the selection of materials was driven by the intention to have several surfaces for all the four combinations explained above. Naturally, combinations (b) and (c) are difficult to achieve.

The theoretical starting point for finding surfaces that fit into all four combinations would have been by using commercially available artificial climbing holds of different brands. This would have been unfeasible for various reasons.

- To minimize the variables of this study and for comparative reasons, the surfaces had to be of the same size and shape, preferably flat.
- Flat (plane) surfaces also reduce the complexity of the instrumentation, as for a curved surface, we need two transducers (surface curved only in one direction) instead of one. In a curved surface, the average COF is determined at (and tangent to) the COP (center of pressure), which

can only be calculated when measuring the moment from two transducers.
- It is extremely difficult to find holds that have an almost flat surface segment and this from several brands.
- Purchasing different holds and cutting them to size, i.e., to the flat segment only (for mounting them on the transducer), does not guarantee that we obtain the required combinations and ranges of grippiness and roughness for drawing convincing conclusions.

Consequently, some materials were selected from the stock we had at our Health and Sports Technologies Laboratory, and others were purchased at a hardware supermarket. The selection criteria were twofold, namely, (1) find the required range of roughness and grippiness combinations, and (2) introduce materials that are common (rocks, sand) and uncommon (e.g., rubber, carpet) in climbing.

The justification of the first selection criterion is provided by the range and combinations of grippiness and roughness, specifically by unusual combinations such as combinations (b: grippy and smooth) and (c: slippy and rough). These special combinations separate the two properties and allow for determining whether the climbers assess a surface based on grippiness or roughness.

The justification of the second selection criterion is provided by the fact that not all special and extreme combinations can be obtained from surfaces common in climbing. For example, the combination of grippy and smooth is typical for rubber but atypical in a rockface. To prevent climbers from associating one extreme surface property with a common material (e.g., rough with a rock surface) and another property with an uncommon material (e.g., smooth with a polymeric surface) and thereby recognize a pattern that could influence their decisions or reactions, we had to provide a variety of common and uncommon surfaces. We could have used smooth stone surfaces instead of polymeric ones, but they would not have been that grippy as rubber is.

During the selection process, different surface materials were assessed manually, and finally, 14 surfaces were selected (**Figure 1** and **Table 1**).

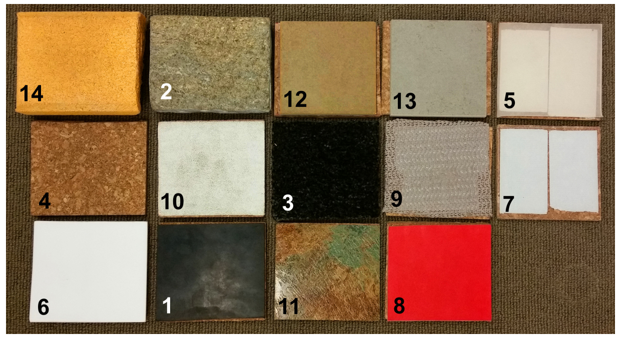

FIGURE 1 | Fourteen hold surfaces numbered **1**–**14** (according to **Table 1**)—(1) black rubber; (2) mica schist; (3) carpet; (4) cork; (5) silicone rubber; (6) Teflon; (7) translucent plastic; (8) leather; (9) magic stop; (10) sandpaper; (11) green tile; (12) ceramic tile brown; (13) ceramic tile gray; (14) sandstone; surfaces no. 5 and 7 are translucent and therefore the double-sided adhesive tape, used for attaching the surfaces to a cork carrier, is visible.

TABLE 1 | Description of the 14 different surfaces.

Surface ID number	Name	Description
1	Black rubber	A mixture of natural and synthetic rubber; smooth surface; color: black
2	Mica schist	Rock based on mica (phyllosilicates) and quartz arranged in layers; color: grayish/bluish/greenish
3	Carpet	Polypropylene carpet, 5-mm tuft length; color: gray
4	Cork	Cork tile, 6-mm thickness, color: brown
5	Silicone rubber	Smooth surface; color: whitish translucent
6	Teflon	PTFE (polytetrafluoroethylene); smooth surface; color: white
7	Translucent plastic	Clear Vinyl sheet, 0.75-mm thickness; smooth surface; color: translucent
8	Leather	Tanned cowhide used for producing Australian-Rules (AFL) footballs; color: red
9	Magic stop	Non-slip rubber used as slip protector underneath carpets, color: gray
10	Sandpaper	Sandpaper, 80 grit, color: white
11	Green tile	Vinyl floor tile "green slate"; color: brown/green
12	Ceramic tile brown	Ceramic tile, color: brown
13	Ceramic tile gray	Ceramic tile, color: gray
14	Sandstone	Brick, color: yellowish

Instrumented Hold

A hold was designed in Solidworks 2019 (Dassault Systèmes, Nashville, TN, United States) and manufactured of aluminum (**Figure 2**) that allows for inclining the surface at three different angles (0, 9, and 20°) and for quickly changing the surface materials. The size of the surfaces was 100 mm × 100 mm so that the skin surface distal of the fingers' MCP joints (metacarpophalangeal joints) fit entirely on the hold. The design of the hold eliminated the size, shape, and inclination factor and confined the variability to the surface properties. The hold was connected to a 3 DOF strain-gauged force transducer (5 kN in each direction; type F233, Novatech Measurements, Ltd., East Sussex, United Kingdom), which in turn was mounted on an aluminum plate (to be attached to a climbing wall). The force transducer was connected to a microcontroller (TEENSY 3.1, 32-bit ARM Cortex-M4 72 MHz CPU, PJRC, Sherwood, OR, United States), and the data were recorded at a sampling rate of 10 Hz. The accuracy of the force transducer was verified after assembly with various weights (10–200 N), introduced at different locations within the placement area of the 14 different surfaces.

Climbing Route

The climbing route was designed by one of the participants together with the authors of this paper on an indoor bouldering wall. It consisted of four moves (**Figure 3**): both hands on the

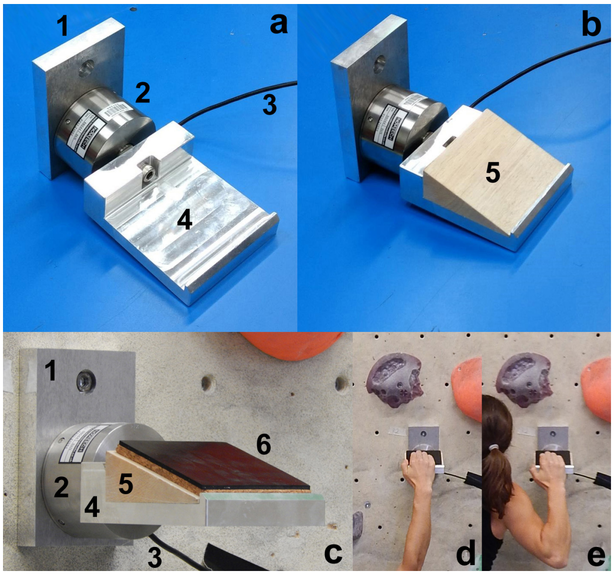

FIGURE 2 | Instrumented hold; **(a)** hold—transducer assembly; 1 = plate (for mounting the assembly on the climbing wall); 2 = force transducer; 3 = transducer cable; 4 = aluminum frame of the hold; **(b)** assembly with a 20° wooden wedge (5); **(c)** assembly mounted on the wall with black rubber surface (6); **(d,e)** position of the climber's hand on the hold.

FIGURE 3 | Climbing route and moves; **(a)** bouldering wall with mounted instrumented hold (2; cable to the right of the hold); the blue arrows indicate the movement sequence between the handholds (1, 2, 3, 4); some of the surfaces of the instrumented hold are visible in the lower right corner; **(b–f)** movement sequences; **(g)** enlarged handhold area; the distances indicated by the two blue arrows are 0.605 m each.

starting hold (hold no. 1, jug); right hand to the instrumented hold (hold no. 2); left hand to hold no. 3 (jug); right hand also to hold no. 3; and finally left hand to hold no. 4 (large hold) after which the climbers jumped off the wall. The vertical distances between hold nos. 1, 2, and 3 were 0.605 m each.

The inclination of the hold's surfaces was −20° (sloping downward) with respect to the coordinate system of the force transducer. The hold was mounted on a −9° inclined (overhanging) wall so that the inclination angle of the hold with respect to the horizontal axis of the global coordinate system was −29°. This total inclination angle of −29° requires a minimum COF of 0.5543 (tan 29°) for preventing slipping off the hold. The total inclination angle was selected such that there is a realistic chance of slipping off a surface, at least off the most slippery one (surface no. 6, Teflon).

Note that if the minimum COF is smaller than the actual static COF, then the minimum COF is substatic, and the climber will not slip off the hold. If the minimum COF (required for a specific inclination angle) is greater than the actual static COF, then the minimum COF is either dynamic on velocity-strengthening (the COF increases as the sliding velocity does; Fuss, 2012), resulting in slipping (if the increased dynamic COF does not exceed the minimum COF) or slip-stick (if the increased dynamic COF exceeds the minimum COF and subsequently oscillates between static and dynamic), or can never be reached on velocity-weakening (the COF decreases as the sliding velocity increases; Fuss, 2012), resulting in slipping off the hold. The slip-stick phenomenon will hardly happen as the surface of climbing holds is usually curved and therefore the minimum COF increases when slipping off a hold.

The participants had to grip the surface of the instrumented hold with the open hand grip (**Figures 2d,e**, **3c**).

Participants

Twenty-two climbers participated in this study: 8 female and 14 male climbers; 1 left-hander and 21 right-handers. Their age was 27.27 ± 8.47 years; climbing experience 11.34 ± 7.32 years; redpoint grading (lead climbing) 21.11 ± 4.17 (IRCRA Climbing Grades; Draper et al., 2015) corresponding to an average of 7c French grading; onsight grading (lead climbing) 17.84 ± 4.24 (IRCRA Climbing Grades; Draper et al., 2015) corresponding to an average of 7a+ French grading (for conversion to other grading systems, see Draper et al., 2015); body height 1.74 ± 0.073 m; body mass 67.5 ± 9.9 kg; BMI 22.12 ± 2.16 kg/m^2.

This study was granted ethics approval by the Swinburne University Human Ethics Committee (approval no. 20191290-1680) and adhered to the Declaration of Helsinki.

Experimental Procedure

The participants filled in an informed consent form before the start of the experimental procedure, which includes their anthropometric data and climbing performance. The consent form informed the climbers of the instrumented hold and that force data applied to the hold were recorded.

The purpose of the study was not revealed to the participants before climbing. Any information on surface properties (grippiness, roughness) could influence the participants by paying more attention to the surface than usual and thereby distract them from unbiased climbing.

The climbers were not allowed to use "chalk" while climbing. There are three reasons for this. First, using chalk on smooth polymeric surfaces considerably decreases the COF. In a study by Fuss et al. (2004), the average static COF between Perspex and a dry hand was 1.475, whereas between Perspex and the hand covered with powder chalk or dried liquid chalk, it reduced the average static COF to 0.722 and 0.634, respectively. Such a reduction by 50% explains that when using chalk, the effect of the grip-enhancing agent is assessed rather than the surface properties. We had three polymeric surfaces and three elastomeric surfaces among our surface samples. Secondly, the surfaces should not get polluted and thereby should not change their properties over time. This could have been prevented by cleaning, i.e., washing the surfaces after each climb. However, some surfaces change their properties when being in contact with water. This applies to the cork and carpet surfaces, which should have been dried completely after washing, and to the sandpaper that tends to disintegrate on contact with water. Alternatively, the surfaces could have been replaced throughout the experiments, which would have resulted in a too high workload. Thirdly, the participants had to rank the grippiness (and the roughness) of the surfaces after the climb, which again, when using chalk, would have resulted in assessing the effect of the grip-enhancing agent, which defied the purpose of the study.

A clean towel was provided for the participants for cleaning their hands before climbing in the case of having sweaty hands or hands covered with residues of chalk.

The climbers were informed that, depending on how difficult it is to have a firm grip on the surfaces, both static and dynamic moves are allowed.

Before starting the experiment, the climbers tested the route a couple of times with a specific hold to avoid a learning effect during climbing, which could influence the results. Before starting the experiment, the force transducer was switched on for recording of the data. Before each of the 14 climbs, a new surface was placed on the instrumented hold in a random order, and the surface ID no. was recorded on the consent form. The random order of the different surfaces was required such that the property of a preceding surface influencing the perception of the following one does not produce a systematic error. Any comments expressed by the participants during climbing were recorded by noting them down on the consent forms. After completing the 14 ascents, the data recording was stopped, and the participants were informed of the principles of roughness/smoothness and grippiness/slippiness (slip resistance). Subsequently, they were asked to rank the 14 surfaces with respect to grippiness first, followed by roughness. For this purpose, the 14 surfaces were placed on a wooden box at the bottom of the climbing route; the climbers slid their fingers over the 14 surfaces and lined up the surfaces from the lowest to greatest grippiness and the lowest to greatest roughness. The sequences of the surfaces were recorded on the consent form after each ranking exercise (grippiness from 1 to 14; roughness from 0 to 10, with 0 assigned to the perfectly smooth surfaces). Finally, the climbers were asked to indicate whether they assess a hold for roughness or grippiness (slip resistance) when climbing. Any further feedback arising from the last question was recorded too.

Data Processing

Our software provided the data as vertical and horizontal forces (in Newtons) applied to the force transducer. After offset correction (the surfaces placed on the hold had different masses), the forces were rotated by 20° (inclination of the hold's surface with respect to the coordinate system of the force transducer) and thereby converted to normal forces (perpendicular to the surface) and friction forces (parallel to the surface). For each loading period related to a specific surface, the following data were extracted: maximum friction and normal forces, the COF at the maximum normal force, and average friction and normal forces (F and N, respectively). The average COF was calculated as a weighted average COF (weighted with respect to the normal force N), as the resolution and measurement errors of the force transducer at small forces can produce an excessive COF and therefore an incorrect (unweighted) average COF. The weighted average COF results from

$$COF_{weighted} = \frac{\sum (COF \cdot N)}{\sum N} = \frac{\sum F}{\sum N} = \frac{\bar{F}}{\bar{N}} \tag{1}$$

considering that COF = F/N and that the loading periods of F and N were equal.

Statistical Analysis

For the surface analysis, the averages and standard deviations of the weighted average COF, grippiness ranking, and roughness ranking were calculated. The averages served for comparison and further ranking, whereas the standard deviations informed of the parameter consistency across the different surfaces.

For hypothesis testing, the combinations of grippy, slippy, rough, and smooth were compared with unpaired t-tests and ANOVA. The normal distribution of the data was verified with the Shapiro–Wilk test. For the t-tests, the variances were assessed with the F-test, and the significance of the combinations in the ANOVA test was assessed with the following *post hoc* tests: Tukey, Scheffe, Bonferroni, and Holm. For significance testing, α was set to 0.05.

For the climber analysis, multiple and single regressions were analyzed: grippiness + roughness vs. COF, grippiness vs. COF, and roughness vs. COF. This served for quantifying the influence of the surface ranking on the COF, e.g., if the R^2 value of grippiness vs. COF was 0.4, then 40% of the magnitude of the COF can be explained from the degree of grippiness. The conditions imposed on the regressions was that all trends had to be positive and significant ($\alpha = 0.1$), positive because the COF is expected to increase as grippiness and roughness do. From the three R^2 values of multiple and single regressions, the combined influence was calculated from the sum of the R^2 of the single regressions minus the R^2 of the multiple regression. The individual influences (semipartial correlations) of grippiness and roughness were calculated from the single regression R^2 minus the combined influence. The influences were expressed as a percentage, resulting from 100 * R^2. The condition imposed on the combined influence was that it had to be positive. Negative combined influence indicates that there is no combined influence.

RESULTS

Surface Analysis

The surface properties are listed in **Table 2**. The highest COF was produced on the black rubber surface (0.841 on average) followed by sandpaper (0.823); the lowest one was on Teflon (0.529 on average), followed by mica schist (0.634). Note that black rubber and Teflon surfaces were perfectly smooth. The surface that was ranked the highest for slip resistance was sandpaper followed by black rubber; the lowest was Teflon followed by translucent plastic. The surface that was ranked the highest for roughness was sandpaper followed by mica schist; the lowest was, evidently, the four perfectly smooth surfaces. Interestingly, although black rubber ranked higher than sandpaper while climbing, the climbers considered the rough sandpaper grippier than the smooth black rubber surface.

In terms of the standard deviations, for the weighted average COF, the least controversial surfaces (with the smallest standard deviation) were sandstone, Teflon, and mica schist (probably because climbers are more familiar with rocky surfaces and because Teflon was both smooth and most slippy); the most controversial were black rubber and the green tile (black rubber probably because it was smooth and the most grippy surface).

In terms of slip resistance ranking, Teflon and sandpaper were the least controversial ones (most consistent ranking); black rubber and silicone rubber were the most controversial ones (most inconsistent ranking).

Figure 4 shows the distribution of average ± 1 standard deviation of COF (**Figure 4a**), slip resistance ranking (**Figure 4b**), and roughness ranking (**Figure 4c**).

In terms of roughness ranking, the least controversial surfaces were leather and cork, and the most controversial were carpet and the brown ceramic tile.

Five out of 14 surfaces were held by all climbers (success rate of 100%). The two surfaces with the least success percentage were silicone rubber (surface no. 5) with 77.3% and Teflon (surface no. 6) with a 40.9% success rate.

It seems that the success rate can be explained from the average COF and the grippiness rather than from the roughness. Correlating the success rate (%) against the average COF, average grippiness rank, and the average roughness rank returns R-values of +0.6187 ($p = 0.0008$), +0.5292 ($p = 0.0032$), and +0.1564 ($p = 0.1620$), respectively. Correlating the ranked success rate against the ranked average COF, ranked average grippiness rank, and the ranked average roughness rank returns R-values of +0.3316 ($p = 0.0312$), +0.5024 ($p = 0.0045$), and +0.0661 ($p = 0.3747$), respectively. These data confirm that the positive regression trends of the success rate are significant only for an average COF and average grippiness. Whether this result suggests that the COF depends more on the grippiness rather than on the roughness will be examined subsequently.

Figure 4d shows the distribution of average ± 1 standard deviation of the individual climbers' COF. The weighted average COF ranges considerably over 0.292, from 0.562 to 0.855. The smallest average COF is just a little over the minimum COF required for holding the inclined surface of the instrumented hold.

The individual climber's COF (average across all 14 holds of the weighted average COF per hold) correlated significantly with the climbing experience (in years) through a positive trend ($R^2 = 0.2000$, i.e., 20% of the COF were explained from the climbing experience; $p = 0.0362$; $\alpha = 0.1$). The same trend was seen when correlating all weighted COF data of each hold and the climber with the climbing experience ($R^2 = 0.0684$; $p < 0.0001$, $\alpha = 0.1$). The correlations of the individual climber's COF or all weighted COF data with RP or OS were non-significant.

Hypotheses Testing

Figure 5 shows the distribution of the two parameters, average grippiness ranking and average roughness ranking. Dividing

TABLE 2 | Surface properties; highest rank = best performing, i.e., greatest COF, grippiest, roughest, 100% success (not slipping off any surface); note that the inclination angle of the hold's surface (−29°) requires a minimum COF of 0.5543, and that the average COF of Teflon was below this threshold; note that an average ± standard deviation of 0 ± 0 indicates a perfectly smooth surface.

Surface ID no.	Name	Weighted average COF avg ± std	Rank	Grippiness ranking avg ± std	Rank	Roughness ranking avg ± std	Rank	Success rate (%)	Rank
1	Black rubber	0.841 ± 0.125	14	10.545 ± 3.555	13	0 ± 0	0	100	7
2	Mica schist	0.634 ± 0.092	2	7.045 ± 3.000	5	8.318 ± 1.729	9	90.9	5
3	Carpet	0.706 ± 0.094	8	8.000 ± 3.309	6	5.318 ± 2.533	5	81.8	3
4	Cork	0.760 ± 0.093	10	8.045 ± 2.081	7	3.636 ± 1.293	3	100	7
5	Silicone rubber	0.687 ± 0.116	4	4.727 ± 3.355	4	0 ± 0	0	77.3	2
6	Teflon	0.529 ± 0.090	1	1.500 ± 0.913	1	0 ± 0	0	40.9	1
7	Translucent plastic	0.718 ± 0.107	9	3.136 ± 2.965	2	0 ± 0	0	86.4	4
8	Leather	0.766 ± 0.106	11	8.182 ± 2.702	8	2.091 ± 1.477	1	100	7
9	Magic stop	0.788 ± 0.121	12	9.500 ± 2.483	12	4.818 ± 2.062	4	95.5	6
10	Sandpaper	0.823 ± 0.119	13	13.409 ± 1.141	14	9.273 ± 1.486	10	100	7
11	Green tile	0.692 ± 0.121	5	4.545 ± 2.614	3	2.591 ± 1.894	2	90.9	5
12	Ceramic tile brown	0.706 ± 0.096	7	8.477 ± 2.872	9	6.477 ± 2.073	8	81.8	3
13	Ceramic tile gray	0.699 ± 0.110	6	8.977 ± 3.041	10	6.432 ± 1.978	7	95.5	6
14	Sandstone	0.680 ± 0.078	3	9.000 ± 2.911	11	6.318 ± 1.729	6	100	7

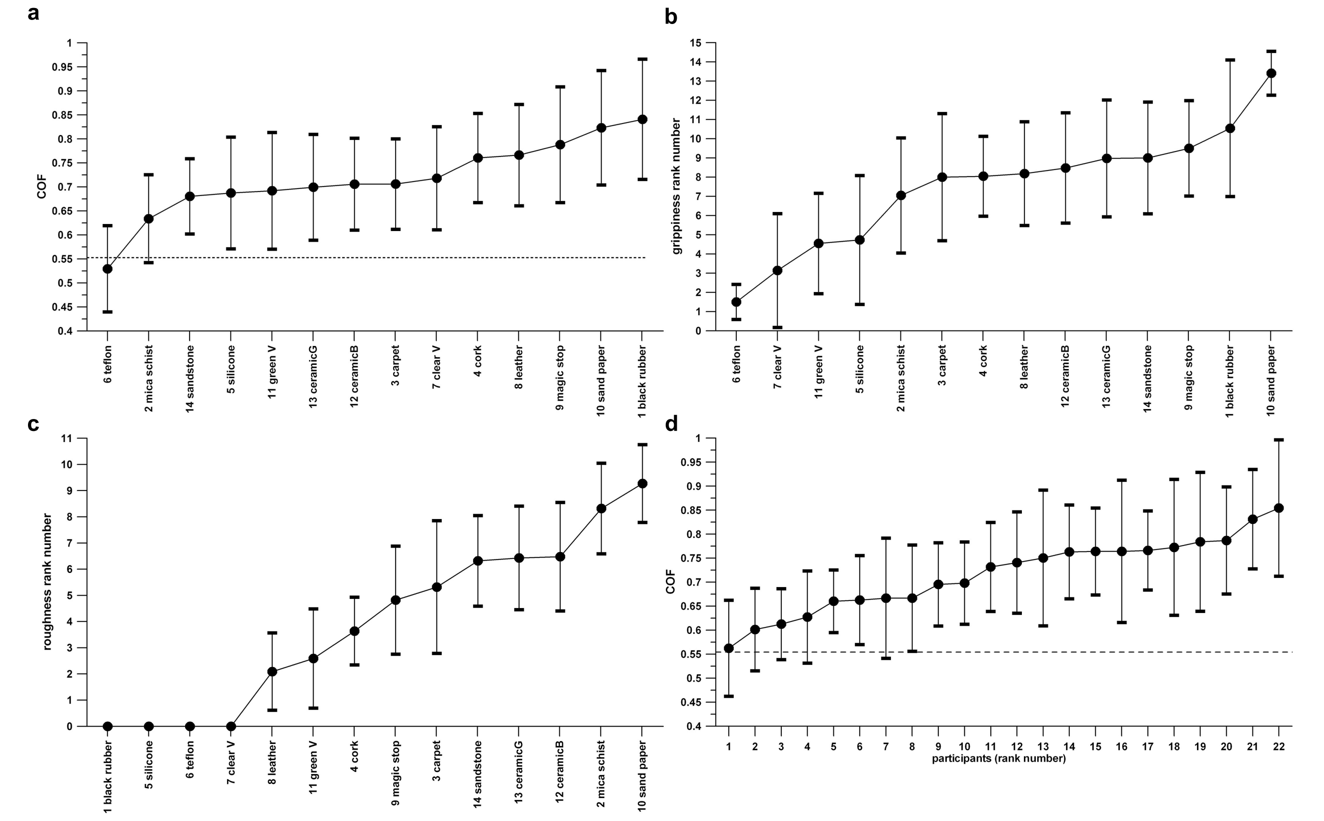

FIGURE 4 | Fourteen hold surfaces and their average (± standard deviation) coefficient of friction (**a**), grippiness ranking (**b**), and roughness ranking (**c**); and the climbers' COF (average ± standard deviation); (**d**); lowest to highest from left to right; the dashed line in subpanels (**a**,**d**) indicates the minimum COF of 0.5543 required for holding a surface of an inclination angle of –29°.

both parameters into two halves of equal number of data isolates the four combinations of grippiness/slippiness and roughness/smoothness and divides **Figure 4** into four quarters.

The extreme representatives of each quarter were:

- Quarter I (slippy and rough): mica schist;
- Quarter II (grippy and rough): sandpaper;
- Quarter III (grippy and smooth): black rubber;
- Quarter IV: (slippy and smooth): Teflon.

As already mentioned earlier, the two combinations of opposing properties—grippy and smooth, and slippy and rough—are difficult to achieve and therefore underrepresented in the graph. The number of surfaces in each quarter is 2, 5, 2, and 5 from Quarter I to Quarter IV (**Figure 5**). To obtain a more even number distribution (3, 4, 3, 4), one data point in each of the quarters with five data is moved to the quarters with two data. The two data points are ceramic tile brown (moved from Quarter II to I) and cork (moved from Quarter IV to III). This data inclusion is justified as both surfaces have equal grippiness ranking and weighted average COF ($p = 0.5710$ and $p = 0.0617$, respectively; two-tailed unpaired t-test for normally distributed data sets). The more even data point distribution across the four quarters avoids that a single high- or low-performing surface could dominate one quarter.

To test Hypothesis 3, Quarters II and IV are compared first (grippy + rough vs. slippy + smooth), as to the weighted average COF:

- Mean COF grippy + rough: 0.7477
- Mean COF slippy + smooth: 0.6567

p-value: 3.99×10^{-6} (two-tailed unpaired t-test, equal variances, normal data distribution); effect size $d = 0.7069$ (medium effect).

Hypothesis 3 is thereby confirmed, namely that the surface property combination "grippy + rough" has a significantly greater COF than the combination "slippy + smooth."

Which one of the two properties (grippy/slippy or rough/smooth) influences the most the difference between the two averages? This is tested by comparing two halves of the diagram in **Figure 5**, namely grippy vs. slippy; and rough vs. smooth:

(1) Grippy vs. slippy

- Mean COF grippy: 0.7655
- Mean COF slippy: 0.6674
- p-value: 4.21×10^{-12} (two-tailed unpaired t-test, equal variances, normal data distribution); effect size $d = 0.7616$ (medium effect).

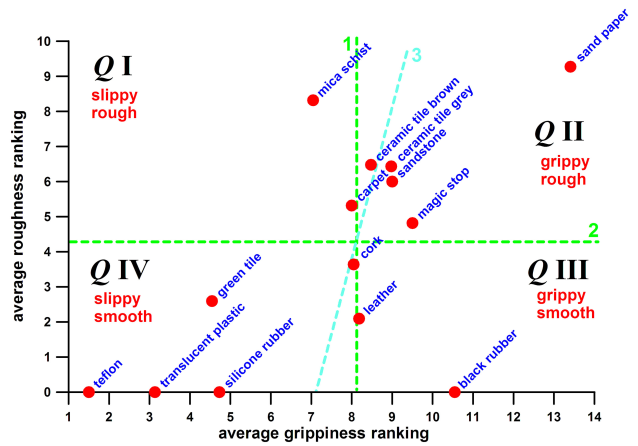

FIGURE 5 | Hold surface property map, average roughness ranking vs. grippiness ranking; (QI–QIV) Quarters I to IV; (1) dashed line dividing the surfaces into a slippy and grippy half; (2) dashed line dividing the surfaces into a rough and smooth half; (3) tilted line 1 required for a more even distribution of the surfaces across the four quarters.

(2) Rough vs. smooth

- Mean COF rough: 0.7194
- Mean COF smooth: 0.7135
- p-value: 0.6851 (two-tailed unpaired t-test, *un*equal variances, normal data distribution); effect size $d = 0.0463$ (very small effect).

Grippy surfaces have a significantly higher mean COF than slippy ones. Although the mean COF of smooth surfaces is slightly smaller than the one of rough surfaces (expectedly), the two mean COFs are not significantly different, with a very small effect size. These results indicate that climbers give preference entirely to grippiness (slip resistance) rather than to roughness.

To verify the group differences, the weighted average COF data of each quarter are compared to each other with an ANOVA test, with the following outcome:

- p-value of the ANOVA test: 1.05×10^{-11}

p-values of the *post hoc* tests plus their interpretations:

- Grippy + rough vs. slippy + rough: $p \leq 0.009$ (significant difference; grippy > slippy, rough = rough, difference comes from grippy/slippy); effect size: $d = 0.5122$ (moderate effect).
- Grippy + rough vs. grippy + smooth: $p \geq 0.064$ (equal averages; grippy = grippy, rough = smooth [because of $p > 0.05$]); effect size: $d = 0.3222$ (small effect).
- Grippy + rough vs. slippy + smooth: $p \leq 0.001$ (significant difference; grippy > slippy, rough = smooth, difference comes from grippy/slippy); effect size: $d = 0.7069$ (moderate effect).
- Slippy + rough vs. grippy + smooth: $p \leq 0.001$ (significant difference; grippy > slippy, rough = smooth, difference comes from grippy/slippy); effect size: $d = 0.8344$ (large effect).
- Slippy + rough vs. slippy + smooth: $p \geq 0.194$ (equal averages; slippy = slippy, rough = smooth); effect size: $d = 0.1947$ (very small effect).
- Grippy + smooth vs. slippy + smooth: $p \leq 0.001$ (significant difference; grippy > slippy, smooth = smooth, difference comes from grippy/slippy); effect size: $d = 1.0291$ (large effect).

These results confirm the outcome of the initial t-tests.

The difference between the mean COFs of grippy + rough and grippy + smooth is not significant (small effect size); the same applies to slippy + rough vs. slippy + smooth (very small effect size).

What these two combinations have in common are the properties of "grippy" and "slippy," respectively, which proves that the non-significant difference and the small effect size must come from "rough" and "smooth."

The opposite is true for the combinations grippy + rough vs. slippy + rough and grippy + smooth vs. slippy + smooth, with significant differences and moderate to large effect sizes. What these two combinations have in common are the properties of "rough" and "smooth," respectively, which proves that the significant difference and moderate to large effect sizes must come from the difference between "grippy" and "slippy."

The results of the ANOVA analysis, applicable to all combinations, are that there is a significant difference between the surface properties of "grippy" and "slippy" but not between rough and smooth.

Climber Analysis

The individual climbers are analyzed as to their surface property preference (grippiness/slippiness or roughness/smoothness) with individual and multiple regression analyses (both properties vs. weighted average COF and each property individually vs. COF). The results to be compared are the trends of the individual regression analysis (positive trends for both regressions), the coefficients of determination (R^2) of individual and multiple regressions, the individual (semipartial correlations) and combined influences of both properties on the COF, and the amount of the COF not explained from both properties (grippiness/slippiness and roughness/smoothness). **Table 3** shows the correlation data of each participant as well as their classification type (1–5).

Type 1, in 11 out of 22 participants (50%), is characterized by insignificant trends in all regressions (multiple and single individual ones). The unexplained influence was therefore set to 100%.

Type 2 (13.64%) shows a significant correlation between grippy/slippy and COF but an insignificant correlation between rough/smooth and COF, which is, moreover, negative. Therefore, the multiple regression was not calculated as the roughness-related coefficient of the multiple regression equation had a negative sign, which turns the originally negative correlation into a positive one. The unexplained influence was determined from the R^2 of the correlation between grippy/slippy and COF.

TABLE 3 | Influence of the holds' surface properties on the COF (coefficient of friction).

Participant no.	100 * R^2 of multiple regression	100 * R^2 of grippy/slippy vs. COF	100 * R^2 of rough/smooth vs. COF	Combined influence on COF (%)	Individual influence of grippy/slippy on COF (%)	Individual influence of rough/smooth on COF (%)	Unexplained influence (%)	Classification type
All participants, all data	**18.63**	**16.74**	n/a	n/a	n/a	n/a	**81.37**	**3**
All participants, average data of each hold	**80.11**	**56.96**	n/a	n/a	n/a	n/a	**19.89**	**3**
4	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
5	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
7	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
11	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
13	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
14	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
15	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
16	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
17	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
18	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
20	n/a	n/a	n/a	n/a	n/a	n/a	**100**	**1**
8	n/a	**58.35**	n/a	n/a	n/a	n/a	**41.65**	**2**
12	n/a	**30.16**	n/a	n/a	n/a	n/a	**69.84**	**2**
19	n/a	**20.97**	n/a	n/a	n/a	n/a	**79.03**	**2**
1	**47.48**	**40.99**	n/a	n/a	n/a	n/a	**52.52**	**3**
10	**51.51**	**45.18**	n/a	n/a	n/a	n/a	**48.49**	**3**
21	**59.69**	**57.57**	n/a	n/a	n/a	n/a	**40.31**	**3**
22	**67.35**	**56.34**	n/a	n/a	n/a	n/a	**32.65**	**3**
2	**36.82**	**36.81**	n/a	**7.96**	**28.85**	n/a	**63.18**	**4**
3	**46.85**	**44.13**	n/a	**7.2**	**36.93**	n/a	**53.15**	**4**
6	**43.98**	**43.86**	n/a	**18.92**	**24.94**	n/a	**56.02**	**4**
9	**54.96**	**43.12**	**42.83**	**30.98**	**12.13**	**11.84**	**45.04**	**5**
Type 1, all participants, all data	n/a	**7.66**	n/a	n/a	n/a	n/a	**92.34**	**2**
Types 2–5, all participants, all data	**29.45**	**29.00**	**2.60**	**2.15**	**26.85**	**0.45**	**70.55**	**5**
Type 1, all participants, average data of each hold	n/a	**33.44**	n/a	n/a	n/a	n/a	**66.56**	**2**
Types 2–5, all participants, average data of each hold	**72.31**	**66.95**	n/a	**1.58**	**65.37**	n/a	**27.69**	**4**

Bold values indicate percentages and classification types.

Type 3 (18.18%) shows a significant correlation between grippy/slippy and COF but an insignificant correlation between rough/smooth and the COF, which is positive. Therefore, multiple regression was calculated. The combined and individual influences were not determined because the combined influence was negative.

Type 3 was also found when using the data of all participants combined (with low R^2 values), as well as the average data of each hold across all participants (with high R^2 values; **Table 3**).

Type 4 (13.64%) is comparable to Type 3 with the difference that the combined influence was positive; this allowed identifying the individual influence of the grippiness/smoothness on the COF.

Type 5 (4.55%) was represented by only one participant, exhibiting significant multiple and single individual regressions and combined and individual influences on the COF. The multiple regression R^2 was 55% (i.e., 55% of the COF could be explained from combined grippiness and roughness), and the single individual regression R^2 was 43% each. This led to a 31% combined influence and 12% individual influences each of the two properties on the COF. This was the only participant that showed a significant influence of the roughness on the COF and this at the same level as the grippiness.

In types 2–5, 21–58% (43.40 ± 11.50%) of the magnitude of the COF could be explained from grippiness. Grouping the data of all participants of types 2–5 together, then 29% of the COF could be explained from grippiness; taking the average data of each hold across all participants, then 67% of the COF could be explained from grippiness.

In types 1–4, the roughness did not have any influence on the COF; neither did the grippiness in type 1, i.e., in 50% of the participants.

Surprisingly, grouping the data of all participants of types 2–5 together, the group performance corresponded to type 5. However, the percentage influences of roughness on the COF, the combined influence of grippiness and roughness, and the exclusive influence of roughness were very small (≤2.6%) but nevertheless significant. This stands in contrast to the average data of each hold across all participants, where the influence of roughness was insignificant, resulting in type 4. Three times the number of average data [i.e., 42 surfaces instead of 14 (at the same parameter distribution)] would have resulted in type 5 (at $\alpha = 0.1$).

At the group level, type 1 participants exhibited a significant influence of grippiness on the COF, resulting in type 2. This is applicable to all data and average data. The insignificance of the type 1 data ("n/a" in **Table 3**) at the individual level is therefore very much dependent on the small number of data per participant (14 holds) and is affected by a high level of group noise.

The classification type (1–5) correlated significantly with the climbing experience (in years) through a positive trend (R^2 = 0.1353, i.e., 13.5% of the classification type were explained from the climbing experience; p = 0.0921, α = 0.1). The correlations of the classification type with RP or OS were non-significant.

DISCUSSION

The main outcome of our research on climbing hold surfaces was that climbers judge the surface of a climbing hold from the perception of the grippiness rather than from the roughness profile. When designing the study, the authors heard different comments from climbers; some claimed that the roughness is the most dominant factor for assessing the surface of a hold, whereas others suggested the opposite. After climbing and after ranking, only 3 of the 22 participants indicated that the roughness is more important to them than the grippiness. From a perception point of view, the roughness profile can be easily felt simply from sliding the hand or the fingers over the surface. Conversely, the grippiness can also be felt easily by applying a slightly higher pressure and assessing the sliding resistance of the surface.

The individual perception of the holds' surfaces was very diverse, with 50% of the climbers (type 1) lacking any correlation between the COF on the hold and the ranking of the surfaces (grippiness and roughness). The reason for this is unclear: whether the inability to subjectively rank the surfaces (misunderstanding of concepts) or the implicit inability of assessing the properties of the surfaces is responsible for the low correlation. Yet, at the group level, type 1 participants behaved like type 2 by exhibiting at least a significant correlation between grippiness and the COF. The only striking yet seemingly unsurprising result was that the single climber representing type 5 was a route setter. Route setters, in addition to having a vast experience in outdoor climbing on different rock faces, are dealing with a wide variety of indoor climbing holds for designing routes of varying difficulty. It is therefore expected that they are also more experienced in judging the surface of a hold and have a better understanding of surface properties.

By comparing the results of our study to the results obtained from other surface types, on the one hand, earlier studies confirmed that there is a correlation between the COF and the perceived roughness (Ekman et al., 1965) or the perceived slipperiness (Smith and Scott, 1996). On the other hand, recent studies on fabric texture perception mostly suggest that the apparent correlation seen is due to chance. For the following three recent studies, however, we had to further analyze the literature data to verify or reject a correlation.

Ramalho et al. (2013) measured the kinetic COF of five fabrics (polyamide, polyester, silk, cotton, wool) against the skin at loads between 0 and 1 N and a sliding speed 35 ± 10 mm/s. The participants of this study had to rank the fabrics with respect to four properties, among which were "rough/smooth" and "adhesive/slippery," i.e., the same properties that were investigated in our climbing hold study. Ramalho et al. (2013) stated that "a positive correlation was obtained, especially concerning the slippery and the smoothness properties." As the authors did not provide any data or statistics to support their claim, the data were extracted from their graphs (figures 4, 5 of Ramalho et al., 2013). Correlating both smooth and slippery rankings to the COF (multiple regression) resulted in a high R^2 (0.7406); however, the regression was not significant (p = 0.2618), such that a correlation cannot be claimed to be established. The same result applied to the correlation of smooth ranking to the COF (R^2: 0.5412; p = 0.1561). Only the slippery ranking showed a significant correlation with the COF (R^2: 0.7401; p = 0.0616, α = 0.1).

Ding et al. (2018) investigated the roughness ranking of five fabrics (among other parameters) and their COF (measured at different speeds and loads with a steel ball probe). Roughness rankings and COF data were extracted from figures 2, 4 of Ding et al. (2018) and subsequently resulted in an insignificant correlation (R^2: 0.0225; p = 0.8085).

Only the data of Chen et al. (2015) showed a significant correlation after further data analysis. The authors investigated the roughness ranking of 10 fabrics (among other parameters) and their COF (measured at 10 mm/s and 1.5 N with a commercially available "artificial finger"). As the data were not correlated, the roughness data were taken from Table 2 of Chen et al. (2015), and the COF data were extracted from Figure 7 of Chen et al. (2015). Correlating the data delivered a significant and positive correlation (the rougher, the higher the COF; R^2: 0.7257; p = 0.0018).

The major difference between fabric perception studies and our climbing hold study is that for fabrics, the kinetic (sliding) COF is crucial (as fabrics slide along the skin), whereas climbing hinges on the "substatic" COF. Furthermore, the forces between skin and fabric are considerably smaller by several orders of magnitude compared to climbing. Finally, statistical evidence of correlations between subjective and objective parameters does not seem to be a priority in fabric perception.

To decide where this (statistical) inability comes from, the 14 different surfaces could have been investigated objectively as to grippiness and roughness (e.g., for comparing the objective results to the subjective ranking). This was not done for various reasons:

- The study deals with the climbers' perception in the first place. What influences climbing is how the climbers subjectively perceive the surfaces' properties and not how rough or grippy they objectively are.
- The grippiness or slip resistance can be assessed by determining the static COF at the point of impending slippage, which is pointless for various reasons. The static COF is load-dependent (force weakening and strengthening; Fuss, 2012). Applying the same average load (normal force) the climbers produced during climbing to the surface {i.e., average maximal force of 248 N [37.5% of the bodyweight (BW) on average] or average force of 150 N [22.8% BW]} and sliding the fingers or the palm over the surfaces up to the point of impending slippage would severely injure the skin on very rough surfaces (e.g., sandpaper). Furthermore, the kinetic COF does not necessarily decrease after the point of impending slippage but can increase such that climbers obtain an even better grip when sliding off a surface. This effect is known as velocity strengthening of the COF at lower sliding speeds followed by velocity weakening at higher sliding speeds (Fuss, 2012). Velocity strengthening was seen in surfaces of artificial climbing holds (Fuss and Niegl, 2012), as well as in the Teflon surface used in the present study (unpublished results). It is noteworthy to mention that these phenomena were found in fabrics as well (Ding et al., 2018).
- The roughness profile of a surface can be measured objectively but would be irrelevant if the COF cannot be determined objectively (owing to the reasons pointed out above), for comparative purposes.

Both grippiness and roughness influence the COF. Even if grippiness is directly related to the static COF, this does not explain the better correlation of grippiness and the COF found in this study. There are several reasons for this principle:

(1) The roughness of a surface profile also influences the COF as seen in the rough structures of antislip floor and tool surfaces and shoe sole profiles. In fact, Fuss and Troynikov (2012) found a significant positive power-law correlation between the *Ra* (arithmetic mean roughness) of pimpled rugby ball surfaces and their kinetic COF.
(2) Climbers apply to the hold a "substatic" COF rather than aiming for the static COF as known from Fuss and Niegl (2008a): the better the performance, the closer the climbers approach the static COF.
(3) The friction force is accentuated by the interlocking of a soft surface with a rough and harder surface. In climbing, this is achieved from the interaction of the fingers' skin and the hold's surface roughness for improving a firm grip. The formation of finger folds even improves the interlocking further.

As such, a "safe" grip on a flat and inclined surface can be judged by either, or both, surface property, i.e., grippiness and roughness.

The climbers reacted to the surfaces in different ways during or after climbing. Nine participants (40.9%) had no problems and succeeded with climbing all surfaces. Most of them did not make any comments. Climbers who slipped off one or more surfaces made comments related to the difficulty of getting a firm grip. It appeared that most of the climbers were surprised by the black rubber surface when climbing because of the high slip resistance despite the lack of roughness. Some climbers considered the surface variety as a new, different, and interesting way of experiencing climbing. Some stated that the reason they slipped is triggered by the thought that they could not hold on to a surface, resulting in eventual failure. A wider range of different surfaces is therefore also important for mental training of climbing.

To the best of the authors' knowledge based on an extensive literature search (including review papers such as Orth et al., 2016, 2017), it seems that the research presented in this paper has never been done before. The applicability of our research results, however, has important implications. Artificial climbing holds and their properties were designed to mimic rock surfaces and structures (sandstone in most cases as they are made mostly from sand and resin with comparable surface roughness and porosity), thereby bringing the natural training facilities to the gym for reasons of accessibility. Why not approach the problem the other way around, namely by introducing surfaces and structures into the gym that are not common to rockfaces? This would enhance the training experience considering that gyms are predominantly created to facilitate training. Such an enhanced training process would be more versatile, holistic, and better suited for preparing the climber to quickly respond to extreme surface properties. Although it was already stated that more experienced climbers get closer to, but do not exceed, the static COP (as "experts are better than non-experts in picking up perceptual cues, as revealed by measures of response accuracy and response time"; Mann et al., 2007), in more general terms, "research has shown that perceptual-cognitive skills form an integral component of elite performance" (Klostermann and Mann, 2019). As such, perceptual training should be introduced to sport climbing, starting with surface perception.

CONCLUSION

Perception is inherently a research area of psychology, specifically when it comes to conscious or implicit perceptions and how they are related to each other. We investigated the perception (both implicit and conscious) of the surface properties of climbing holds and identified that the perceived grippiness outweighs the perceived roughness in producing the amount of the COF applied to a surface. The grippiness is therefore implicitly more important than the roughness property.

The correlation between roughness and the COF was insignificant, whereas the correlation between grippiness and COF was significant at the group level. At the individual level, 50% of the participants did not show any correlations between surface properties and the COF; 36.4% exhibited correlations between the combined grippiness and roughness (multiple regression) and the COF, as well as grippiness and the COF; only 4.5% of the 36.4% showed an additional correlation between roughness and the COF. The results are interpreted in a way that climbers assess a hold's surface based on the grippiness and not on the roughness, and apply a COF to the hold that reflects the grippiness perception.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors to any qualified researcher, if they have obtained Ethics Approval for secondary use of existing data through a Consent Waiver.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Swinburne University Human Ethics Committee (approval no. 20191290-1680) and adhered to the Declaration of Helsinki (Swinburne University of Technology, Melbourne, VIC, Australia). The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

ACKNOWLEDGMENTS

We would like to thank all the climbers who participated in this study and the staff of the climbing gym. Furthermore, we would like to thank the two reviewers for their valuable comments and suggestions to improve the quality of the manuscript.

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Conflict of Interest: GN is employed by company Sportstättenverein Marswiese.

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.

frontiers in Psychology

BRIEF RESEARCH REPORT
published: 24 March 2020
doi: 10.3389/fpsyg.2020.00467

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Post-activation Potentiation Response of Climbers Performing the Upper Body Power Exercise

Krzysztof Sas-Nowosielski* and Klaudia Kandzia

Institute of Sports Sciences, The Jerzy Kukuczka Academy of Physical Education in Katowice, Katowice, Poland

The purpose of this study was to determine a performance-enhancing effect of post-activation potentiation (PAP) stimulus on climbing-specific upper body power exercises, measured by the IRCRA Power Slap test on a campus board. Two groups of climbers performed the test under one of two conditions: without initial pre-loading (control group) or after 5RM (repetition maximum) pull-ups (PAP group).The test was performed at four time points: at baseline (PRE) and after 4 (POST4), 6 (POST6), and 8 (POST8) minutes of a PAP stimulus (PAP group) or after the same rest period lengths (control group). The results showed that post-baseline slap distances were significantly greater in the experimental group while no change was seen in the control group [repeated measures ANOVA: $F_{(3,42)} = 6.26$, $p = 0.001$]. *Post hoc* analysis revealed no significant difference between any of the post-baseline trials in both groups. The mean improvement in the first POST4 test in the experimental (PAP) group was +6.5 cm (6.8%). The results of the present study suggest that PAP might be beneficial for acute improvement of upper body power performance in climbers. Therefore we conclude that such stimuli might be advisable for climbers as a part of the warm-up before bouldering competitions and training as well. They might also offer a stronger stimulus for climbers working on power development.

Keywords: sport climbing, bouldering, campus board, postactivation potentiation, rate of force development

OPEN ACCESS

Edited by:
Jiri Balas,
Charles University, Czechia

Reviewed by:
Petr Stastny,
Charles University, Czechia
Eloisa Limonta,
University of Milan, Italy

****Correspondence:***
Krzysztof Sas-Nowosielski
k.sas-nowosielski@awf.katowice.pl

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *30 November 2019*
Accepted: *27 February 2020*
Published: *24 March 2020*

Citation:
Sas-Nowosielski K and Kandzia K (2020) Post-activation Potentiation Response of Climbers Performing the Upper Body Power Exercise. Front. Psychol. 11:467. doi: 10.3389/fpsyg.2020.00467

INTRODUCTION

Rock- and sports-climbing continuously increase in popularity; following a recent decision of the International Olympic Committee, sports climbing will enter the program of the 2020 Summer Olympics. The popularity of climbing is also reflected by an increasing number of scientific studies on this activity. While physiological, kinematic, and biomechanical demands of climbing, anthropometric, and physiological characteristics of climbers as well as climbing-related medical problems were frequently studied (Quaine and Martin, 1999; Mermier et al., 2000; Vigouroux et al., 2006; Fuss and Niegl, 2010; Folkl, 2013). However, less is known about sports climbers' training, including the effects of various exercise protocols, the effectiveness of training modes and methods. Whenever undertaken, such studies have mainly concerned finger strength training on hangboards (Levernier and Laffaye, 2019; López-Rivera and González-Badillo, 2019) and, less often, other aspects of preparation (Philippe et al., 2019). It stands in contradiction to increasing demands of extreme rock-climbing and competition climbing. Climbing, including extreme rock climbing, has long been seen as an activity that requires a high level of muscular strength rather than a great rate of force development (RFD) or power. Nowadays, many top ranked routes demand moves in which a climber has to generate force in an explosive manner. This tendency is even more visible in competitive speed climbing and bouldering. Both disciplines include single movements or sequences of moves that require dynos and jumps, sometimes done in a series, i.e., one after another, bringing to mind rather *le parkour* than climbing that had been practiced a couple of decades ago. As a consequence, biomotor abilities that became of utmost importance for climbers are power and RFD. The former is an amount of force exerted in a unit of time (Zatsiorsky and Kraemer, 2006) while the latter is a measure of how fast an athlete can develop force and is considered a "mechanism behind the expression of power in sport" (Taber et al., 2016, p. 38). Although few researchers have addressed the problem in the context of climbing, the results obtained so far seem important in all climbing disciplines (Fanchini et al., 2013; Levernier and Laffaye, 2019). Not surprisingly, every climber is inclined to include power exercises into their practice regimen.

Among various methods of power development that could be employed into sports climbers' training is complex training. The term of complex training was introduced by Verkhoskanky, who defined it as "concurrent use of different training means in the same workout, microcycle or mesocycle" (Verkhoshansky and Siff, 1999, p. 365). Considering a single training session, this differentiation mainly refers to selection of exercises which are biomechanically similar, and which should be used in the following sequence: resistance exercise followed by a plyometric, ballistic or speed exercise. The most popular pairs of exercises include squats and jumps, squats and sprints, bench press and clap push-ups, and shoulder presses and overhead medicine ball throws (Seitz and Haff, 2016; Harrison et al., 2019). Such exercise sequences result in a temporal increase in power and force production, thus allowing greater training stimuli and/or enhancing acute performance effect (Docherty and Hodgson, 2007). The physiological rationale for complex training effectiveness is a phenomenon known as post-activation potentiation (PAP), defined as "acute enhancement of muscular performance characteristics as a result of their contractile history" (Tillin and Bishop, 2009, p. 148). Exact nature of PAP is still debatable, and several mechanisms are proposed to explain its effect on performance, e.g., as it act through increasing neural excitability (better motor-unit recruitment and synchronization, decreased presynaptic inhibition), increased amount of Ca^{2+} in the sarcoplasmic reticulum and greater sensitivity of the myofilaments to Ca^{2+}, reduction in the sensitivity of Golgi-tendon organs and Renshaw cells thus weakening their inhibitory actions, changes in muscle architecture, and especially a decrease in the pennation angle of muscle fibers with resultant increase of forces that are transferred onto the bones (Scott and Docherty, 2004; Docherty and Hodgson, 2007; Tillin and Bishop, 2009).

Regardless of the true nature of PAP, it seems to induce acute and long term effects on performance in various lower- and upper body activities such as jumps and sprints as well as selected upper-body exercises including bench press throws (Duthie et al., 2002; Docherty and Hodgson, 2007; Liossis et al., 2013; Loturco et al., 2014). To our knowledge only Gołaś et al. (2016) investigated PAP in the upper-body exercises that also involved "pulling" movements – namely Lat pull-downs and dumbbell rows. The main finding of this study was that such exercises might be effective in eliciting PAP in luge athletes. Implementation of these findings into climbing is limited by differences between muscle activity and kinematics characteristic of exercises used by Gołaś et al. (2016) and movements that predominate in climbing (displacement of the body's center of mass against gravity). One of the most popular forms of climbing-specific power training are campus board exercises (Michailov, 2014), a majority of which are variations of moving up the board from rung to rung (usually referred to as *laddering*), reaching explosively upwards as far as possible with one hand (usually called *reaches* or *touches*) or two hands (usually called *doubles* or *dynos*). Campus exercises are considered an "extraordinary tool for developing explosive strength, improving force gradient, intramuscular and intermuscular coordination" (Michailov, 2014, p. 103) and are executed with the repetitive and/or interval methods. As research data on the effectiveness of PAP on campus boards, and climber's training in general, are scarce, the purpose of this study was to determine a performance-enhancing effect of PAP stimulus on climbing-specific upper body power exercises.

MATERIALS AND METHODS

After providing a written informed consent, a total of 16 climbers (including five females), aged 22–31 (M = 27.44, SD = 2.76) were recruited to the study. All were members of two athletic teams (n = 10 and n = 6) in one of the bouldering gyms in Katowice, south Poland. All participants were advanced climbers practicing from 5 to 15 years, familiarized with campus board exercises. Their climbing performance level was determined based on self-reported best red-point (RP) climbs ranging from 7b+ to 8c in a French grading system or 22–31 in the International Rock Climbing Research Association (IRCRA) Reporting Scale, so they could be classified as advanced-to-elite (Draper et al., 2011). Detailed characteristics of the participants are presented in **Table 1**. The climbers were randomly assigned to PAP-stimulus condition (experimental group) or to the control group. There were no significant differences in climbing experience [$t_{(14)} = 0.35$, $p = 0.730$], the level of advancement [$t_{(14)} = 0.22$, $p = 0.976$], body weight [$t_{(14)} = 1.99$, $p = 0.066$], height [$t_{(14)} = 1.84$, $p = 0.087$] or BMI [$t_{(14)} = 1.16$, $p = 0.266$]. The only variable that differentiated both groups was age [$t_{(14)} = -2.17$, $p = 0.048$]. Detailed data are presented in **Table 1**.

As all the exercises were previously regularly performed by the participants as a regular part of their training program, no

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

	All	Experimental	Control
Age (years)	27.4 ± 2.8	26.4 ± 2.7	29.2 ± 1.9
Experience in climbing (years)	8.69 ± 3.03	8.9 ± 3.4	8.3 ± 2.5
Body mass (kg)	66.9 ± 10.7	70.7 ± 10.5	60.7 ± 8.21
Height (cm)	173.9 ± 6.1	175.9 ± 6.0	170.5 ± 5.0
BMI	22.2 ± 2.2	22.7 ± 2.2	22.2 ± 2.2
Climbing level (IRCRA Reporting Scale)	25.1 ± 3.2	25.2 ± 3.2	24.8 ± 3.4

BMI, body mass index.

familiarization session was included in the present study. Prior to testing, the participants were instructed to perform a warm-up according to their individual preferences in order to prepare for intense campus exercises. They were not required to do a standardized warm-up protocol as we assumed that, as advanced climbers, they were experienced enough to know how to prepare themselves best for particular climbing efforts. The participants could use wooden and resin hangboards, i.e., Beastmaker 2000 (Beastmaker, United Kingdom) and MocArt (MocArt, Poland), respectively. There was a campus board with two kinds of rungs, a system wall with big sloper-like rungs and wooden hemispheres, boulder walls, the Moon system wall, TRX suspension system, gymnastic rings, a pull-up bar, and a set of dumbbells. After the warm-up, the test of 5RM (repetition maximum) pull-up exercise was performed using a direct assessment method with 2 min rests between trials. Participants performed pull-ups on a Beastmaker 2000 fingerboard using two deep four-finger pockets held with a half-crimp grip and spaced 56 cm apart measured between their outer edges. They were instructed to do the pull-ups starting with their arms fully extended to a position in which the chin reached the level of the holds. The value of the external load corresponding to 5RM ranged from 10 to 45 kg (M = 25.40, SD = 10.70). The test session was performed after a one-day break, during the successive training session. IRCRA Power Slap (IRCRA, 2015), chosen as a power test, was performed on a board on which a scale with distances in centimeters was drawn. A 2.5-cm deep rung (Modell 2 by Tripoint, Tripoint, Poland) was placed at the bottom of the board. The rung allowed curling the fingers over its grip ("positive grip") to minimize the possibility of slipping off the rung during the pulling movement. According to the IRCRA recommendations, the manual climber's task was to hold on the rung with straight arms and initiate an explosive pull-up and slap as high as possible with one, dominant, arm. The performance was measured by a direct measurement method using the magnesia mark left by the climber's hand. To ensure greater accuracy and minimize the risk of blurring earlier magnesia traces, each climber was video-recorded (**Figure 1**).

Participants from the experimental group were instructed to perform one set of 5RM pull- ups with a pre-determined load. Pull-ups were to be done in a row, without stopping. Power Slap test started after a 4-min break (POST4). Break duration was chosen for two reasons. Firstly, according to Lowery et al. (2012), rest periods of 4–8 min are close to optimal (Wilson et al., 2013). Secondly, 4 min is a typical rotation time in bouldering competitions and during establishing the study protocol we had to bear in mind a practical aspect of our research. The test was repeated twice, i.e., after 6th (POST6) and 8th (POST8) minute of the PAP exercise – again to simulate the rotation time in bouldering competitions. Before each trial climbers were allowed to use chalk – the one which they usually use in their climbing.

The study protocol was approved by the Ethics Committee of Biomedical Research at the Academy of Physical Education in Katowice – resolution no 1/2019.

DATA ANALYSIS

Assumptions of normality and homogeneity of variance were tested with the Shapiro–Wilk and Levene's tests, respectively. The student t-test for independent samples was used to compare characteristics of control and experimental groups. Repeated measures ANOVA with Tukey *post hoc* test was used to assess the effects of the PAP exercise (pull-ups) on muscle power output. All statistical analyses were conducted using Statistica 13.3 (Statsoft, Poland) software.

RESULTS

Descriptive statistics (means, standard deviations, and confidence intervals) of the study results are presented in **Table 2**.

TABLE 2 | Comparison of Power Slap results in centimeters (M, SD, CI's) between two groups, PAP and control in PRE and POST conditions.

	Experimental				Control			
	Mean	SD	−95% CI	+95% CI	Mean	SD	−95% CI	+95% CI
PRE	94.5	12.1	85.8	103.2	85.8	10.2	75.1	96.5
POST4	101.0	13.5	91.3	110.7	85.0	10.5	74.0	96.0
POST6	100.5	15.9	89.1	111.9	84.2	9.2	74.5	93.8
POST8	100.5	16.2	88.9	112.1	85.0	11.4	73.0	97.0
post hoc	PRE–POST4: $p < 0.001$				PRE–POST4: $p = 0.896$			
	PRE–POST6: $p < 0.001$				PRE–POST6: $p = 0.390$			
	PRE–POST8: $p < 0.001$				PRE–POST8: $p = 0.428$			

POST4, POST6, and POST8 – Power Slap at 4, 6, and 8 min after PAP (for the PAP group) or after resting time of the same duration as the PAP (for the control group).

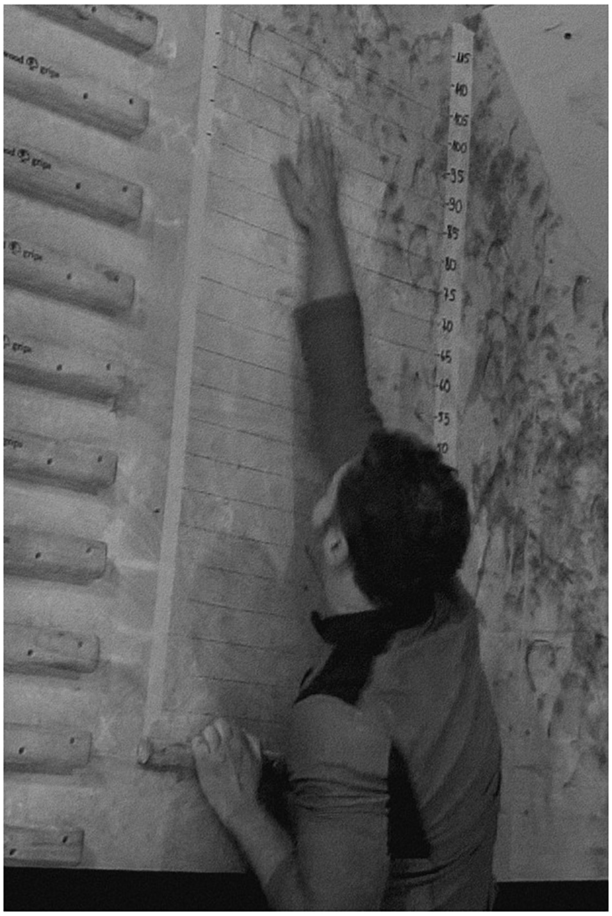

FIGURE 1 | The finishing position of the Slap test.

The difference in distances obtained by both groups during the PRE trial was not statistically significant [$t_{(14)} = 1.46$, $p = 0.166$]. PRE-POST comparisons revealed a significant effect of PAP stimulus on the Power Slap exercise on a campus board, $F_{(3,42)} = 6.26$, $p < 0.001$, $\eta^2 = 0.24$, non-centrality = 4.45. Compared to the baseline, none of the three successive trials was significantly different in the control group whereas in the experimental group all three tests differed significantly ($p < 0.001$). No significant differences were revealed between POST4, POST6, and POST8 tests in both groups.

The mean improvement in the first POST test in the experimental (PAP) group was +6.5 cm while in the control group a slight decrease of −0.83 cm was observed. It should be noted that each participant in the experimental group improved while the control participants obtained the same distance, except for one climber whose result decreased by approximately 5 cm.

DISCUSSION

The phenomenon called PAP has drawn attention of sports scientists, athletes, and sports coaches for years. Its essence is "the increase in muscle force and RFD that occurs as a result of previous activation of the muscle, as well as the force and power of evoked high velocity shortening contractions, and the maximum velocity attained by evoked shortening contractions under load" (Lorenz, 2011, p. 235). Although the issue remains controversial, previous studies reported a possible ergogenic effect of PAP on acute performance and chronic conditioning strategy, i.e., the so called complex training (Docherty and Hodgson, 2007; Tillin and Bishop, 2009; Wilson et al., 2013; Helena et al., 2019). Most studies were conducted on pairs of lower body activities like squats and vertical jumps, squats and sprints, loaded sprints and unloaded sprints etc. (Tillin and Bishop, 2009; Dobbs et al., 2019). Fewer studies examined the effects of PAP on the upper body exercises (Ebben, 2002) like bench press and ballistic push-ups (Farup and Sørensen, 2010; Liossis et al., 2013; Seitz and Haff, 2016) where the movement predominantly involved some "pushing" action. For that reason their findings cannot be directly translated into climbing in which "pulling" actions are typical. The only study which, to our knowledge, investigated the effects of PAP on pulling movement patterns was that of Gołaś et al. (2016); the authors determined the impact of Latissimus pull down exercise performed on the Keiser Power Rack at 50% 1RM and dumbbell row at 80% 1RM (three sets of four reps with a 90 s rest interval) on the luge start. It was found that the PAP protocol of dumbbell rows significantly improved power during the Keiser Pull Down following 6 min of recovery and that a very significant correlation existed between the power generated during the Latissmus Pull Down and the luge start. While these findings are in accordance with other studies, it should be pointed out that Lat pull-down is a type of an open kinetic chain manoeuvre (the trunk stabilized, bar pulled toward the chest) that creates different kinematic conditions and different stimuli than in pull-up movements characteristic of climbing (Johnson et al., 2009; Doma et al., 2013). For that reason findings of Gołaś et al. (2016) might not apply to climbers' training and pre-competition warm-up protocols.

Therefore, the purpose of this survey was to assess acute effects of PAP in a climbing-specific power exercise, performed on one of the most popular training devices, namely the campus board, which is also suggested to be the testing tool in power and power endurance assessment. The power exercise chosen for this study, consisted of pulling up explosively from a hanging position with straight arms, and reaching with one dominant hand as high as climbers could touch. This test is recommended by IRCRA to assess the upper body power as it simulates explosive movements done in climbing. Considering the criterion of biomechanical similarity between complementary exercises (PAP-eliciting resistance exercise and the target explosive exercise), resisted pull-ups on a fingerboard were chosen. It was not without significance that this kind of exercise is among the most frequently performed resistance exercises in climbers' preparation and is familiar to the most, if not all, advanced climbers. The intensity of the pull-ups was 5RM, which corresponded to ca. 85–87% of 1RM, i.e., the intensity within the range considered as the most effective for eliciting PAP (Carter and Greenwood, 2014). The results showed that loaded pull-up done for 4 min before the "power slap" had a positive effect on the latter, allowing the athlete to reach higher than without such preconditioning. Moreover, this potentiating effects last up to 8 min after the PAP stimulus, which may be an important consideration for climbers taking part in bouldering competitions during which a period for completing the problem, known as a "rotation time" lasts 4 min in the final round. A time course found in this study is comparable to the findings of Nibali et al. (2015), who compared 4, 8, and 12 min intervals in PAP response of jump squats and found that, despite individual variations, the 4-min interval displayed the greatest magnitude and frequency of potentiation. However, at this stage one should refrain from recommending any time interval as optimal.

To the best of our knowledge, this is one the first studies in which the effects of PAP on the climbing-specific upper body power exercises were assessed. Therefore, the comparison between the findings of the present study and other literature reports is hardly possible. The only study for comparison is our previous one (Sas-Nowosielski and Kandzia, 2018), which was however, conducted without a control group and with only one time point after PAP stimulus. Although similar findings had been obtained, not all participants had responded positively to the stimulus (a few climbers showed no improvement). In fact, such variations in response were also observed in other studies involving such exercises like squats and jumps (Duthie et al., 2002; Gourgoulis et al., 2003). Such variable responses to preload stimuli have been attributed to strength and training status of athletes, with stronger individuals usually showing greater PAP response than the weaker ones, or to different proportions of slow- and fast muscle twitch fibers in various individuals (Tillin and Bishop, 2009; Seitz and Haff, 2016; Chen et al., 2017). In the latter case it is suggested that the fast twitch fibers react with greater phosphorylation of regulatory light chains and may therefore be more prone to positive response to PAP stimulus (Tillin and Bishop, 2009). All experimental group climbers in our study responded positively and only differed as to the magnitude of the improvement.

LIMITATIONS

There are a few shortcomings of this study that need to be considered when interpreting its results. Firstly, quite a small number of subjects limits data analysis as the PAP group climbers could not be further divided into subgroups of different strength levels. It has been previously reported that PAP response could be influenced by the level of strength, with stronger individuals exhibiting stronger response. It would be interesting to check whether this also applies to campus board performance. Secondly, the analysis was limited to one parameter, i.e., the distance obtained in the "Slap" test; other parameters, such as power or velocity were not assessed. Finally, after random allocation of the participants into the PAP and control groups, they were measured once, while it would be more informative if cross-over measurements had been performed. While it was a consequence of participants availability, in the future research the cross-over measurement should be also considered.

PRACTICAL APPLICATIONS

Based on the results of the present study, the use of PAP can be recommended to acutely enhance the upper body power performance of climbers. It is especially important when we consider bouldering contests which tend to feature at least one of the "problems" as highly dynamic. Efficient problem solving largely depends on climbers' abilities to exert high RFD. While bouldering is, by definition, associated with power, lead climbing is considered an activity to test climbers' anaerobic and mixed aerobic/anaerobic endurance. However, one should bear in mind that a shift toward a more spectacular, dynamic-style is also seen in lead climbing. As a consequence, the lead climber is forced to perform one or even several jumps and dynos. It can be perceived as a new challenge for lead climbers, who may also benefit from including PAP-eliciting exercises into their pre-competition warm-up protocol.

CONCLUSION

Although PAP and its impact on various exercises and activities (vertical jumps, sprints, long jumps, and dynamic push-ups) have been studied for many years, its application to sport climbing performance has received less attention. We believe that the present study is noteworthy for coaches and climbers as it confirms that this phenomenon may find application in acute power performance. Still, more research is needed to determine the best strategy for using PAP in climbing – both regarding its acute and chronic effects. A list of problems that deserve attention may include, for example, long term effects of using PAP in training, delayed potentiation, optimal time and loading protocols of exercise pairs in sports climbers' training and pre-contest conditioning.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Bioethical Commission of the Academy of Physical Education in Katowice. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

KS-N and KK contributed conception and design of the study, organized the database, and read and approved the submitted version. KS-N performed the statistical analysis and wrote the first draft of the manuscript.

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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.

frontiers in Psychology

BRIEF RESEARCH REPORT
published: 28 May 2020
doi: 10.3389/fpsyg.2020.01025

The Visual Search Strategies Underpinning Effective Observational Analysis in the Coaching of Climbing Movement

James Mitchell[1], Frances A. Maratos[1], Dave Giles[1,2], Nicola Taylor[1], Andrew Butterworth[1] and David Sheffield[1]*

[1] Human Sciences Research Centre, College of Life and Natural Sciences, University of Derby, Derby, United Kingdom,
[2] Lattice Training Ltd., Chesterfield, United Kingdom

Despite the importance of effective observational analysis in coaching the technical aspects of climbing performance, limited research informs this aspect of climbing coach education. Thus, the purpose of the present research was to explore the feasibility and the utility of a novel methodology, combining eye tracking technology and cued retrospective think-aloud (RTA), to capture the cognitive–perceptual mechanisms that underpin the visual search behaviors of climbing coaches. An analysis of gaze data revealed that expert climbing coaches demonstrate fewer fixations of greater duration and fixate on distinctly different areas of the visual display than their novice counterparts. Cued RTA further demonstrated differences in the cognitive–perceptual mechanisms underpinning these visual search strategies, with expert coaches being more cognizant of their visual search strategy. To expand, the gaze behavior of expert climbing coaches was underpinned by hierarchical and complex knowledge structures relating to the principles of climbing movement. This enabled the expert coaches to actively focus on the most relevant aspects of a climber's performance for analysis. The findings demonstrate the utility of combining eye tracking and cued RTA interviewing as a new, efficient methodology of capturing the cognitive–perceptual processes of climbing coaches to inform coaching education/strategies.

Keywords: eye tracking, think-aloud, sport, education, expertise, gaze behavior, coaching

OPEN ACCESS

Edited by:
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****Correspondence:***
James Mitchell
J.mitchell@derby.ac.uk

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *02 December 2019*
Accepted: *24 April 2020*
Published: *28 May 2020*

Citation:
Mitchell J, Maratos FA, Giles D, Taylor N, Butterworth A and Sheffield D (2020) The Visual Search Strategies Underpinning Effective Observational Analysis in the Coaching of Climbing Movement. Front. Psychol. 11:1025. doi: 10.3389/fpsyg.2020.01025

INTRODUCTION

Climbing's acceptance as an Olympic event in Tokyo 2020 is recognition of the sports' increasing popularity and professionalization (Bautev and Robinson, 2019). As demand increases, so too will the need for effective coaching, thus requiring coach educators to consider how coaching expertise is developed (Sport England, 2018). Climbing coaches employ a range of complex and inter-related strategies to facilitate physical, technical, mental, and tactical improvements (Currell and Jeukendrup, 2008). However, to date, climbing research has predominantly focused on the physiological and the psychological aspects of performance, somewhat neglecting the importance of the technical components of climbing (Taylor et al., 2020). Furthermore, the process by which climbing coaches facilitate technical improvements in their athletes is wholly under-researched.

The characteristics that define expertise in the coaching of climbing movement, and the process by which expertise is developed, have yet to be explored. Wider expertise research has sought to identify the key characteristics of expert performance; among others, one of the key hallmarks that define expert performance is superior visual search behavior (Ericsson, 2017). Research in a variety of sporting contexts (i.e., athletes, officials, and coaches) has demonstrated that experts have a superior ability to pick up on salient postural cues and detect patterns of movement and can more accurately predict the probabilities of likely event occurrences (Williams et al., 2018, p. 663). The superior visual search behavior of expert coaches is thought to be due to more refined domain-specific knowledge and memory structures (Williams and Ward, 2007). Declarative and procedural knowledge, acquired through extensive deliberate practice, enables expert coaches to extract the most salient information from the visual display to identify the key aspects of the athlete's performance that can subsequently be targeted for improvement (Hughes and Franks, 2004).

Yet without a systematic approach to observational analysis, coaches potentially threaten the validity of their analysis (Knudson, 2013). To understand how coaches analyze and evaluate climbing performance, it is argued that a fundamental step in this process is characterizing the underlying cognitive–perceptual mechanisms that underpin expertise (Spitz et al., 2016). To enable this, the study of expertise in sport has commonly adopted the "Expert Performance Approach" (EPA) (Ericsson and Smith, 1991). In EPA, the superior performance of experts is captured, identifying the mediating mechanisms underlying their performance by recording process-tracing measures such as eye movements and/or verbalizations (Ford et al., 2009). Such advances have begun to enable significant insight into the cognitive–perceptual mechanisms underlying expert performance (Gegenfurtner et al., 2011). For example, lightweight mobile eye tracking devices provide a precise, non-intrusive, millisecond-to-millisecond measurement of where, for how long, and in what sequence coaches focus their visual attention when viewing athlete performance (Duchowski, 2007).

Gegenfurtner et al. (2011) conducted a meta-analysis of 65 eye tracking studies to identify the common characteristics of expert performance. They concluded that the superior performance of experts, across a variety of different domains (sport, medicine, aviation, etc.), could be explained by a combination of three factors: First, experts develop specific long-term working memory skills because of accumulated deliberate practice. Second, expert coaches can optimize the amount of processed information by ignoring task-irrelevant information. This allows for a greater proportion of their attentional resources to be allocated to more task-relevant areas of the visual display (Haider and Frensch, 1999). Finally, they suggest that expert–novice performance differences in visual search are explained by an enhanced ability among experts to utilize their peripheral vision.

To date, however, there has been no eye tracking studies conducted on the visual search strategies of climbing coaches. Yet in other sports, eye tracking technology has yielded insight into differences between expert and novice coaches, which can be used to inform coaching strategies. Here eye tracking research conducted with coaches in basketball (Damas and Ferreira, 2013), tennis (Moreno et al., 2006), gymnastics (Moreno et al., 2002), and football (Iwatsuki et al., 2013) has demonstrated that expert coaches focus on distinctly different locations. Experts fixate their attention on the most salient areas of the visual display as compared to novices (Williams et al., 1999). Additionally, experts demonstrate fewer fixations of greater duration in relatively static tasks/sports (Mann et al., 2007; Gegenfurtner et al., 2011).

Most eye tracking research has, nonetheless, been conducted in laboratory settings, leading some researchers to challenge the ecological validity of the approach (Hüttermann et al., 2018). Adding to this, Mann et al. (2007; see also Gegenfurtner et al., 2011) argue that the more realistic the experimental design is to the realities of the sporting context, the more likely it is that experts will be able to demonstrate their enhanced cognitive–perceptual skills afforded by their increased context-specific knowledge (Travassos et al., 2013). Thus, some researchers have cast doubt on whether the results of laboratory studies can be transferred beyond their immediate context into the complex realities of the coaching environment (Renshaw et al., 2019). Moving forward, therefore, the use of mobile eye tracking technology potentially enables researchers to capture the expert performance of coaches in naturalistic coaching environments, thus enhancing ecological validity and ensuring transferability to coaching practice.

Although eye tracking enables researchers to investigate the processes of visual attention, the relevance of specific gaze location biases to the coaching process still requires elaboration, that is, eye tracking gaze data can tell us *where* someone is looking, but importantly not *why*. Over-reliance on averaged and uncontextualized gaze data potentially oversimplifies and limits our understanding of the coaching process (Dicks et al., 2017). Indeed one of the main conceptual concerns with sports expertise research is the relative neglect of the cognitive processes underpinning expert performance (Moran et al., 2018). As Abernethy (2013) identifies, there remains a lack of evidence on the defining characteristics of sports expertise and how such characteristics are developed. Hence, additional methodological approaches are needed to complement eye tracking if the mechanisms underpinning the superior cognitive–perceptual skills of expert coaches are to be captured.

Currently, two such methodologies are proposed. These are concurrent think-aloud (CTA)—and retrospective think-aloud (RTA). In CTA, the participants verbalize their thought process during the actual task (e.g., Ericsson et al., 1993), whereas in RTA, the participants verbalize their thought process immediately after the task (e.g., Afonso and Mesquita, 2013). In critique, as we can mentally process visual stimuli much faster than we can verbalize our observations, it is argued that, when using CTA, verbalizations are often incomplete (Wilson, 1994). Furthermore, attempting to verbalize complex cognitively demanding tasks while simultaneously performing them affects the user's task performance and associated gaze behavior (Holmqvist et al., 2011). The alternative, to record participants thinking aloud after the task, circumvents this disruption to the participants' performance in the primary task. However, due to the time-lag between the primary task and RTA, a "loss of detail from memory or fabulation" may occur (Holmqvist et al., 2011, p. 104). The limitations of RTA are, however, potentially negated when it is combined with eye tracking technology.

Cued RTA utilizes eye tracking gaze data, as an objective reference point to stimulate memory recall, and structure RTA, reducing loss of detail from memory and fabulation (Hyrskykari et al., 2008). Furthermore, cued RTA provides explicit detail as to the declarative and procedural knowledge that underpin the coach's visual search strategies, adding depth and meaning to otherwise uncontextualized gaze data (Gegenfurtner and Seppänen, 2012). Cued RTA can therefore be adopted for both empirical and theoretical reasons. First, cued RTA is confirmatory in that RTA data enable the researcher to verify the gaze data for accuracy (e.g., fixation location and allocation of attention), and gaze data provide an objective location to reduce memory loss and fabulation when conducting RTA. Second, cued RTA enables the researcher to elicit a greater level of insight into the cognitive–perceptual mechanisms that underpin the visual search strategies of coaches. It is therefore proposed that cued RTA is potentially more effective than either eye tracking or RTA methodologies applied in isolation.

Thus, in the present study, we explored the feasibility and the utility of a novel methodology, combining eye tracking technology with cued RTA, to capture the cognitive–perceptual mechanisms underpinning the visual search behaviors of climbing coaches. As this was a first trial of the combined methodology, three expert and three novice coaches were asked to observe and analyze the live climbing performances of intermediate boulderers in a naturalistic and ecologically valid setting.

MATERIALS AND METHODS

Participants

A total of six UK climbing coaches were recruited for the present study based on their level of expertise (see Moreno et al., 2002). The "expert" group (successful elite, as defined by Swann et al., 2015) consisted of three national team coaches with a minimum of 5 years of professional coaching experience (three males; 8.3 ± 1.5 years). The "novice" group (Nash and Sproule, 2011) consisted of three club-level coaches, with a minimum of 1 year of coaching experience (one female, two males; 3.6 ± 2.1 years). All the participants had normal or corrected-to-normal vision and voluntarily agreed to participate following the local University of Derby ethical approval.

Materials

Climber/Bouldering Problems

The coaches were asked to observe the same intermediate (V4/F6B) climber (male; 21 years) climb four different boulder problems (2 × vertical, 1 × slab, 1 × roof) at a grade of V4/F6B (Draper et al., 2016) at a national center climbing wall. Each boulder problem was repeated three times, requiring the coach to view a total of 12 attempts lasting approximately 16 s each (15.87 ± 0.81 s). The boulder problems were of a maximum height of 4 m and ranged from six to eight moves for each problem. The problems were selected in consultation with an independent national-level coach to ensure that they were judged to be of an appropriate level for the grade and representative of a normal coaching setting.

Visual Gaze Behavior

Mobile eye tracking glasses (SMI ETG 2.0; SensoMotoric Instruments, Tetlow, Germany; binocular, 60 Hz) were used to record the coaches' visual gaze behavior. The gaze data were collected *via* a lightweight smart recorder (Samsung Galaxy 4) using SMI IViewX software. This enabled the recording of visual gaze data in a real-world setting. Prior to capturing eye tracking data, a three-point calibration procedure was implemented by placing three targets in a triangular configuration at a distance of 5 m. The coaches were placed 5 m away from the base of each boulder problem; i.e., at the optimum viewing angle for each specific problem (as decided by an independent national-level coach), and instructed to remain stationary. However, they could move their heads to ensure that the climber remained in the eye-tracker's recordable visual field. To validate the accuracy, a nine-point calibration grid was placed on each boulder problem, with the markers placed at the outermost areas of the visual field that the coach would be required to observe. This ensured that the gaze data were accurate across the entire visual field. The dependent variable data collected included fixation count, fixation duration, and fixation location.

Retrospective Think-Aloud Data Capture

Retrospective think-aloud was conducted using gaze data to cue responses from the coaches: i.e., the coaches were asked to explain individual fixation locations during their analysis of the climber's performance, verbalizing their relevance to their coaching process. The gaze data were presented to the coach as video replay with the coach's own visual gaze scan-path superimposed (see **Figure 1**). This scan-path showed the most recent 2-s of gaze data appearing to the coaches as a connected string of fixations (circles) and saccades (connecting lines). Each attempt was replayed at 100% speed and then slowed down to 25%.

Other Materials

A demographic questionnaire captured the coaches' prior experience: i.e., highest level of coaching experience, accumulated coaching experience, and current coaching role/responsibilities.

Procedure

Once the participants had completed the demographic questionnaire, they were fitted with mobile eye tracking glasses and undertook the calibration process. The coaches were then instructed to observe the climber to assess their quality of movement and identify movement errors. It was further explained that they would be required to verbalize their analysis of the climber's performance later in the experiment. Each coach observed the same climber climb four different boulder problems at a grade of V4, viewing three attempts for each problem. Once each coach had observed all 12 attempts, gaze data were downloaded for further review using SMI BeGaze (V3.2, SensoMotoric Instruments, Tetlow, Germany)

FIGURE 1 | Example of how the gaze data were presented to coaches to cue retrospective think-aloud: visual gaze data super-imposed as 2-s scan path [a connected string of fixations (circles) and saccades (connecting lines)] to cue verbal responses (i.e., why coaches focus on specific fixation locations).

analysis software. Using the BeGaze RTA function, the cued RTA interviews were conducted immediately after the collection of gaze data using video replay with the gaze data super-imposed to cue verbal responses. After viewing the gaze data in real time, the participants were asked to scroll through gaze data at 25% speed, explaining why they focused on specific fixation locations and their relevance to the analyses. The fixations discussed were self-selected by the participant in order to reduce researcher bias. The gaze data were replayed until each coach had exhausted all fixations they could recall.

Analyses

The eye tracking metrics analyzed were: (a) "fixation rate" (i.e., average number of fixations per second), (b) "average fixation duration" (i.e., average fixation duration of all fixations throughout the entire viewing period), and (c) "total fixation duration" (i.e., total duration of a viewer's fixations landing on a given visual element throughout the entire viewing period) within pre-defined areas of interest. Visual fixations were defined as periods where the eye remained stable in the same location (within 1° degree of tolerance) for a minimum of 120 ms (Catteeuw et al., 2009). The visual gaze data were analyzed using the "semantic gaze mapping" function of SMI BeGaze to manually code fixations against three predefined areas of interest. These were the hands, the feet, and the core regions. Only the gaze data collected while the climber was attempting the problem were included in analysis. As the length of recordings differed for individual coach's visual gaze behavior due to small variations (±5%) in the athlete's performance, the data were normalized by cropping the recordings so that each trial was of equal duration to the shortest trial. This enabled the eye tracking metrics (e.g., "total fixation duration") to be analyzed for comparison between coaches/groups. To enable comparison in visual search strategy, the aggregated gaze data as a function of expert or novice group were used to produce heat maps (Holmqvist et al., 2011). Additional analysis was pursued using Microsoft Excel (Version 15.37, Santa Rosa, CA, United States). Due to the small sample size, the magnitude of differences was determined using Cohen's d (Cohen, 1988).

The cued RTA data were recorded concurrently, ensuring that the interview responses were not separated from the context of the coaches' individual gaze data. The cued RTA data were transcribed verbatim, and inductive thematic analysis was conducted in accordance to the six-step process outlined by Braun and Clarke (2006). Two members of the research team initially conducted thematic analyses independently before comparing and auditing the analysis process (i.e., first- and second-level codes and final themes). Issues of credibility and transferability were addressed by a process of member checking to ensure a good "fit" between the coaches' views and the researchers' final interpretation of themes, as well as ensuring that the themes transfer to the wider coaching context (Tobin and Begley, 2004).

RESULTS

Gaze Data

The eye tracking data quality was 98.6% (±0.9), i.e., 98.6% of the samples were captured. An analysis of the gaze data revealed distinct differences between expert and novice groups. The experts demonstrated slower fixation rates (experts 2.23 ± 0.20/s, novices 2.44s ± 0.37/s; d = 0.71) and greater average fixation durations (experts 315 ± 30 ms, novices 261 ± 59 ms; d = 1.07) than their novice counterparts. In other words, the experts demonstrated fewer fixations but of greater duration.

Furthermore, distinct differences were identified in the locations that the groups allocated attentional resources to. The experts allocated a greater proportion of their attention to the proximal (core) features of the climber's body, demonstrating a greater number of fixations (experts 58.7 ± 24.5, novices 17.4 ± 1.4; d = 2.4) and longer total fixation durations to core body areas (experts 23.6 ± 14.5 s, novices 4.5 ± 1.2 s; d = 1.9). The experts additionally placed less attention on the climber's hand placements than the novices did, with fewer total fixations (experts 41.0 ± 25.9, novices 69.5 ± 27.6; d = 1.1) and shorter total fixation durations (experts 16.6 ± 11.6 s, novices 25.8 ± 0.4 s; d = 1.1) toward hand placements. Finally, the experts spent more time fixating their attention on the climber's foot placements than the novices did, with greater numbers of total fixations (experts 44.7 ± 14.6, novices 38.5 ± 14.9; d = 0.4) and longer total fixation durations (experts 20.2 ± 4.7 s, novices 11.1 ± 1.4 s; d = 2.6) toward foot placements. These differences between the expert and the novice coaches' visual search strategy were evident from the aggregated heat maps (**Figure 2**), which illustrate that the experts focused more attention on proximal features (e.g., hips, lumbar region, and center of back), whereas the novices almost solely focused on distal features (e.g., feet and hands).

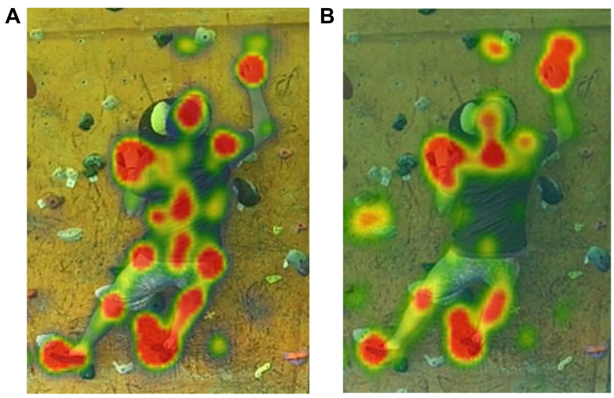

FIGURE 2 | Aggregated heat maps of expert **(A)** and novice **(B)** coaches' gaze behavior over 12 boulder problems illustrate notable differences in the allocation of visual attention to different regions of the climber's body.

TABLE 1 | Organization of data codes from the thematic analysis.

Themes	Second-level codes	First-level codes
Cognizance of visual search	Ability to relate gaze data to stimulate recall	Recognition of gaze data, enabling distinct recall of visual search strategy
		Unable to recognize own gaze behavior or use gaze location to assist recall of visual search strategy
	Detail in verbalizations	Detailed analysis of rationale for attending to individual/groups of specific fixation locations
		Basic description of rationale for attending to specific fixation locations
Knowledge of principles of movement and their application	Nature/angle of wall in relation to principles of movement	Affordances (i.e., shape, texture, spacing of hold, angles of wall, etc.)
		Types of move/problems
		Rules of thumb for movement
	Naive v's sophisticated view of movement	Complex relationships
		Isolated/discrete skills
	Limiting factors in climber's performance	Strength/power in physical performance
		Mobility in performer
		Tactical factors of performance (e.g., route reading)
Systematic visual search strategy	Hierarchy of skill complexity	Techniques and difficulty of order
		"Ticking off" abilities to perform certain actions
		Varying search strategy (i.e., different components of skill)
	Top-down *vs.* bottom-up visual search	Goal-driven visual search
		Stimulus-driven visual search
	Diagnosis of errors	Secondary search to diagnose the cause of symptoms (i.e., of movement errors)
		Knowledge of common errors
		Sequencing and transitioning of movements (i.e., identifying what came before/after)

Retrospective Think-Aloud Data

The interview durations (min) differed noticeably between the expert and the novice coaches (experts 75.3 ± 12.3, novices 38.0 ± 11.5; $d = 3.1$), reflecting the level of detail that each group was able to provide while explaining their visual gaze data. The thematic analyses revealed three themes: "cognizance of visual search behavior," "knowledge in the principles of movement and their application," and "systematic visual search strategy." **Table 1** illustrates the first- and second-level codes that contribute to the three main themes.

In respect to the first theme, the expert coaches were far more cognizant of their visual search behavior, being able to verbalize their thought process and provide rationale that explains how the gaze data relate to their coaching process. For example, one expert coach stated:

> *"I can tell immediately these are my eye movements. . . You can see I am going through my standard functional movement screening process here. This point here, I am looking at whether hip mobility limiting the climber's ability to rock-over." (participant E3)*

The novice group, by comparison, was often unable to make any link between their gaze data and their coaching process, simply passing no comment or stating: "I'm not sure why I was looking there" (participant N2). One coach was particularly candid by stating:

> *"To be honest, I don't really know what I'm looking for when I'm coaching. I know to look for messy footwork, so that's what I look for. Beyond that, I don't know what to look for." (participant N3)*

Considering the second theme, the expert coaches demonstrated a far greater understanding of the principles of movement and their application. Here they demonstrated more complex frameworks and principles of movement that applied to the nature and the angle of the problem. For example, one expert coach succinctly described their process as follows:

> *"Climbing is a really complex 3D interrelationship between the climber and infinitely varied points of contacts, at differing and changing angles. I try to think of how those points of contact can be used in conjunction, so that the climber can move their center of mass into the optimal position for that particular situation. When the climber is not achieving that position, I try to diagnose secondary factors that may be prohibiting them." (participant E2)*

By comparison, the novice coaches often discussed specific aspects of technique in isolation. For example, participant N1 stated: "So I'm looking for bad footwork here, then I'm looking for if they are holding the hold in the right way." Comments relating to isolated aspects of technique were common among the novice group with little to no reference to the complex interrelationships between the components of the movement system and their interaction with the environment.

Finally, in reference to the third theme, the expert coaches eluded to a hierarchy of skills that guided their priorities for analysis. Participant E2 observed that:

> *"If you can see, I am looking at completely different areas during each attempt. . .looking at different aspects of their performance. I start by looking at the most basic aspects of technique, building up a picture of their ability, working through to more complex skills. When I start to see errors creeping in, I look to see if it is a consistent pattern or just a one-off. If there is a consistent pattern, that is usually the aspect of their climbing I look to address first."*

By contrast, the process of the novice coaches was continually described as a process of search for foot placement errors and search for hand placement errors, continually repeating this cycle. Thus, while both groups eluded to the skills that they prioritized, the above quote highlights how expert verbalizations were more comprehensive and demonstrated a logical/systematic progression in skill complexity. By comparison, novice verbalizations demonstrated a limited and rudimentary grasp of the critical factors that underpin the climbing movement.

DISCUSSION

Despite the importance of observational analysis in the coaching of climbing movement, the cognitive–perceptual mechanisms underpinning the visual search behavior of climbing coaches have not previously been explored. This study sets out to explore the feasibility and the utility of a previously underutilized methodology within sports expertise research, namely, if mobile eye tracking data, captured in a naturalistic and ecologically valid coaching environment, combined with cued RTA interviews can effectively capture the mechanisms that underpin the visual search behavior in expert and novice coaches. Here the results revealed that the gaze behavior of expert climbing coaches is characterized by fewer fixations, but fixations that were of longer duration than those of novice coaches. Additionally, that experts coaches tend to focus a greater proportion of their attention on proximal regions, whereas the novice coaches typically focused on distal regions. Finally, the RTA analysis revealed that the experts were more cognizant of their visual search strategy, detailing how their visual gaze behavior is guided by a systematic hierarchical process underpinned by complex knowledge structures relating to the principles of climbing movement.

A major finding of the current research was that visual attentional strategies differed between expert and novice climbing coaches. We observed that the expert coaches demonstrated fewer fixations—but these were of greater duration, suggesting that the accumulated context-specific experience of the expert coaches enables them to develop a more efficient visual search behavior. The expert coaches selectively attend to only the most task-relevant areas of the visual display, requiring them to make fewer fixations (of longer duration) to efficiently extract relevant information from specific gaze locations (Ericsson and Kintsch, 1995; Haider and Frensch, 1999). These findings accord with previous studies investigating the visual search strategies of coaches in similar self-paced individual sports (e.g., coaching a tennis serve; Moreno et al., 2006).

The current research further highlighted the relevance of specific fixation locations to more efficient visual search. The proportion of attentional resources that coaches allocated to specific locations varied distinctly between experts and novices. The experts spent nearly five times as long focusing on the proximal regions of the climber's body (or core) as compared to the novice coaches (refer again to **Figure 2**), supporting Lamb et al. (2010) notion that the observational strategies of coaches may be overly influenced by the motion of distal segments due to the greater range of motion and velocities than that of proximal segments. It is therefore proposed that the climber's core represents one of the most salient areas upon which to analyze a climbing performance. Fluency of the center of mass, as defined by the geometric index of entropy, has been shown to be an important performance characteristic (Cordier et al., 1994; Taylor et al., 2020). Identifying the most salient areas to analyze a climbing performance may provide a viable means to inform future coach training, helping novice coaches make their visual search behaviors more efficient (Spitz et al., 2018). However, identifying gaze location alone is of limited practical value to developing coaches unless its relevance is made explicit (Nash et al., 2011).

The addition of cued RTA to the eye tracking methodology revealed three themes that provide insight into the cognitions underpinning the visual attentional strategies of novice *vs.* expert coaches. First, the expert coaches were far more cognizant of their visual search behavior, providing a far more explicit rationale for how their gaze data related to their coaching process. The inability of novice coaches to recall and elaborate on their visual gaze data suggests a randomized and inefficient visual search strategy, that is, they were unclear as to *why* they fixated on specific locations or *what* information they hoped to acquire by doing so. Second, the experts were able to provide rich descriptions of the critical factors that underpin successful movement and relate such principles to their gaze data. Here they demonstrated more complex frameworks and principles of movement applied to the nature and the angle of the problem. Comparatively, the novice coaches provided very little detail on how principles of movement guide their visual search, suggesting that a lack of knowledge regarding the critical factors that underpin climbing movement may be a key factor that limits the effectiveness of their observational analysis. Finally, the experts were more proactive and systematic in their analysis, with their visual search strategy underpinned by a hierarchy of skills (Gegenfurtner et al., 2011). It is likely that the lack of a systematic approach to observational analysis observed among novice coaches potentially limits the validity and the effectiveness of their analysis (Knudson, 2013).

Based on the insights above, it is proposed that the use of cued RTA interviews potentially offers a deeper insight into the cognitive–perceptual process of coaches than the use of eye tracking or think-aloud methodologies employed in isolation. By capturing the declarative and the procedural knowledge that expert coaches utilize to guide their visual search strategy, valuable insight is acquired as to the systematic processes that expert coaches employ to analyze a climbing performance, that is, *where* the most salient areas of the visual display are and *why* they are important to the analysis of a climbing performance. Coach educators may be able to utilize such insights to provide developing coaches with a more explicit rationale to guide their visual search, enhancing the efficiency and the quality of their observational analysis.

CONCLUSION

In sum, the present results demonstrate the utility of combining eye tracking technology and cued RTA as a methodology for capturing the cognitive–perceptual processes of climbing coaches. In combining these methods, a range of different cognitions and perceptual behaviors were observed as a consequence of coaching expertise. Combining these technologies potentially offers a valid and a reliable method to capture the processes underpinning the observational analysis of a climbing movement. Indeed the same methodological approach could be applied in a variety of coaching contexts. This stated, a number of limitations and recommendations for future research are highlighted. Despite the ecological validity of the present research, the results must be interpreted tentatively given the small sample size. Furthermore, viewing the live performance of a single athlete presents challenges to study repeatability. Researchers will need to weigh the benefits of ecological validity against replicability. Future research would also benefit from exploring whether the visual search strategies of coaches remain consistent with a greater number of athletes of varying ability, anthropometrics, and style. This will help a comprehensive framework for the observational analysis of a climbing movement to be developed.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Human Sciences Research Ethics Committee, University of Derby. 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 manuscript.

AUTHOR CONTRIBUTIONS

JM, DG, and NT contributed to the design of the study and in data collection. JM and NT performed data analysis and wrote the first draft of the manuscript. JM, FM, DS, DG, and NT revised the manuscript to produce the final draft, which was subsequently reviewed by all the authors.

FUNDING

Funding for open access fees is being provided internally through research budgets associated with the Human Sciences Research Centre, College of Life and Natural Sciences, University of Derby.

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Conflict of Interest: DG was employed by the company Lattice Training Ltd.

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.

frontiers in Psychology

ORIGINAL RESEARCH
published: 28 May 2020
doi: 10.3389/fpsyg.2020.00902

OPEN ACCESS

Edited by:
Vanesa España-Romero,
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Northern Michigan University,
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Eva Lopez-Rivera,
University of Castilla-La Mancha,
Spain

***Correspondence:**
Eloisa Limonta
eloisa.limonta@unimi.it

†ORCID:
Eloisa Limonta
orcid.org/0000-0001-7246-2819
Maurizio Fanchini
orcid.org/0000-0001-7398-5443
Susanna Rampichini
orcid.org/0000-0001-9510-1653
Emiliano Cé
orcid.org/0000-0003-0691-3153
Stefano Longo
orcid.org/0000-0001-5806-8305
Giuseppe Coratella
orcid.org/0000-0001-7523-9102
Fabio Esposito
orcid.org/0000-0002-4420-2611

Specialty section:
This article was submitted to
Movement Science and Sport
Psychology,
a section of the journal
Frontiers in Psychology

Received: 31 January 2020
Accepted: 14 April 2020
Published: 28 May 2020

Citation:
Limonta E, Fanchini M,
Rampichini S, Cé E, Longo S,
Coratella G and Esposito F (2020)
On-Sight and Red-Point Climbing:
Changes in Performance
and Route-Finding Ability in Male
Advanced Climbers.
Front. Psychol. 11:902.
doi: 10.3389/fpsyg.2020.00902

On-Sight and Red-Point Climbing: Changes in Performance and Route-Finding Ability in Male Advanced Climbers

Eloisa Limonta[1,2†], Maurizio Fanchini[3†], Susanna Rampichini[1†], Emiliano Cé[1,2†], Stefano Longo[1†], Giuseppe Coratella[1†] and Fabio Esposito[1,2†]*

[1] Department of Biomedical Sciences for Health, University of Milan, Milan, Italy, [2] IRCCS Galeazzi Orthopedic Institute, Milan, Italy, [3] Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy

Aim: In lead climbing, the ascent of the route can be defined as on-sight or red-point. On-sight is the more challenging style since it demands greater physiological and psychological commitment. The differences between the two modes in advanced climbers have not been studied much. Two essential skills needed to optimize performance, in both on-sight and in red-point climbing, are route interpretation (RI) ability and movements sequence recall. Therefore, this study aimed to compare performance between on-sight and red-point ascent in advanced climbers and evaluate how a climber's RI ability and movement sequences recall might change before and after on-sight and red-point climbing.

Methods: Eighteen advanced male climbers (age 29.2 ± 4.7 years, body mass 67.8 ± 3.6 kg, stature 175.2 ± 2.4 cm, best red-point and on-sight grades 7b+/8a and 7a+/7b+, respectively) were video-recorded during the route ascent in on-sight and red-point modes to evaluate performance and to measure static and dynamic action times. RI ability and movement sequence recall were assessed before and after each climb. Level of anxiety was evaluated via a self-report questionnaire. Heart rate (f_H), lactate concentration, ($[La^-]$), and rating of perceived exertion (RPE) were detected during and after each climb.

Results: Compared to on-sight, an improvement in performance was observed in a red-point climb: the ascent was faster (148.7 ± 13.6 s and 179.5 ± 12.5 s, respectively, $P < 0.05$), smoother (significant reduction in exploratory moves and in stops times, $P < 0.05$), less demanding physiologically (lower f_{Hpeak} and $[La^-]_{peak}$, $P < 0.05$), and psychologically (lower RPE, cognitive and somatic anxiety and higher self-confidence, $P < 0.05$). The RI ability was improved in red-point versus on-sight and, in the same mode, between pre and post ascent.

Conclusion: Red-point climbing was found to be less demanding than on-sight, both physiologically and psychologically, under the conditions investigated by this study. Our findings suggest that RI is a trainable skill and underscore the importance of including specific techniques in training programs designed to improve interaction between perceptual, psychological, and physiological factors.

Keywords: sport climbing, lead climbing, bouldering, route preview, movement sequence recall, climbing performance, climbing style

INTRODUCTION

Sport climbing is an emergent discipline that will be included for the first time in the 2020 Olympic Games official program in Tokyo. The fast growth of climbing as a competitive sport has attracted research interest as well. This multidimensional activity differentially incorporates physiological and psychological skills (Morrison and Schöffl, 2007; Hodgson et al., 2009; Draper et al., 2011) in three distinct specialties: lead, boulder, and speed. In lead climbing, the climber's goal is to move vertically until the end of the itinerary (pitch or route) outlined on an artificial wall with handholds and footholds. The ascent can be performed in one of two styles depending on the safety procedures: lead or top-rope. In lead climbing, the climber secures his ascent at the belays prepositioned throughout the wall, using a safety rope fitted to a harness (Orth et al., 2016). In case of a mistake or exhaustion, the climber will fall below the last anchor point used. In top-rope climbing, the rope is passed through an anchor at the top of the route prior to the ascent (Orth et al., 2016). In case of error or exhaustion, the climber will not fall but will remain hanging by the rope. Moreover, as regards knowledge of the route, the ascent can be defined as on-sight or red-point mode. The climb is on-sight when the pitch is lead first time without a single fall, without any previous practice and without the climber having any useful information about the characteristics of the route (Sanchez et al., 2019). The climber is allowed to visually inspect the on-sight ascent from the ground up, but with no prior pointers from an outside source. Any subsequent attempt to the climb is referred to as red-point.

For climbers, the purest and more demanding style of ascent is an on-sight lead climbing (Draper et al., 2008) since it involves greater physiological and psychological commitment due to the fear of falling and lack of knowledge of the route characteristics (Aras and Akalan, 2014). Being the most challenging approach, the on-sight lead climbing is the standard style used during final rounds of lead competitions, according to the International Federation of Sport Climbing rules (International Federation of Sport Climbing, 2020).

Sport climbing has become the recent subject of scientific studies, with most having focused on its physiological aspects and a few others having assessed the level of psychophysiological stress associated with different climbing styles (lead and top-rope, on-sight, and red-point) (Draper et al., 2008, 2011; Hodgson et al., 2009; Fryer et al., 2013; Aras and Akalan, 2014).

Overall, comparison between leading and top-rope climbing has shown that novice and intermediate climbers find leading climbing more stressful both physiologically and psychologically than top roping (Hardy and Hutchinson, 2007; Draper et al., 2008; Hodgson et al., 2009; Aras and Akalan, 2014), whereas advanced and elite climbers don't seem to experience significantly greater anxiety in lead than in top-rope climbing (Fryer et al., 2013).

To our knowledge, only one study to date has analyzed the differences between on-sight and red-point climbing (Draper et al., 2008) and found that climb times, lactate concentrations, and self-reported pre-climb somatic and cognitive anxiety are higher in on-sight mode. Lack of information about and experience of the pitch elicit greater anxiety about falling and impair route interpretation (RI), problem solving ability, and movement sequence recall (Watts, 2004; Giles et al., 2006).

In on-sight lead climbing, RI strategies of the climber before the ascent and problem-solving ability during the ascent are the essential skills needed to optimize the performance (Boschker et al., 2002; Sanchez et al., 2012; Ferrand et al., 2006). For this reason, during competition and training, climbers visually inspect the route from the ground (route preview), in order to understand and visualize the optimal sequence of movements they will need to climb it. Route preview errors can be considered one of the major reasons for falling during climbing (Boschker et al., 2002; Sanchez et al., 2012). In red-point lead climbing, the ability to memorize (i.e., retain the information acquired during the on-sight ascent) is also a crucial skill (Sanchez et al., 2012). Therefore, exploratory behavior, which is influenced by past experiences and motor, perceptive, and mnemonic skill, is a potential indicator of learning and performance. Though route preview and recall ability are fundamental skills, whether and how they are trainable has not yet been determined. Hence, this study had two aims: to compare the performance during on-sight and red-point leading climbing in advanced climbers, on a route matching their best on-sight skill; and to evaluate change from before and after on-sight vs. red-point lead climbing performances related to RI and movement sequences recall ability in advanced climbers.

MATERIALS AND METHODS

Subjects

Eighteen male climbers participated in this study. All were climbing instructors, with a coaching experience of at least 4 years. Two were excluded from the study because of inadequate performance in the trials, so the final sample was 16 participants. As described in Draper et al. (2011), they were classified as advanced on the basis of their self-reported best red-point and on-sight rates, for the last year, 7b+/8a and 7a+/7b+,respectively, according to the French Rating Scale of Difficulty. The average age was 29.2 ± 4.7 years (range: 24–35 years) and the average height and body mass were 175.2 ± 2.4 cm (range: 172–179 cm) and 67.8 ± 3.6 kg (range: 64–73 kg), respectively. Their climbing experience was 9.2 ± 3.8 years and training frequency was 11.2 ± 3.2 h/week.

At the time of the study, all were clinically healthy with no musculoskeletal disorders. After receiving a full explanation of the experimental procedures and aims of the study, they gave their written, informed consent to participate. The study was approved by the University of Milan ethical committee and performed in accordance with the principles of the 1975 Declaration of Helsinki.

Experimental Protocol

Two experimental sessions were conducted 1 week apart, in an indoor climbing gym. For each session, the participants were asked to refrain from caffeine or other similar beverages for at least 4 h prior to testing and to refrain from any form of strenuous physical exercise in the previous 48 h. All sessions were completed as lead climbs.

In the first session, the participants attempted the on-sight condition. The difficulty of the pitch was close to their best on-sight level (7a+/7b+) but they were unaware of the degree. A professional certified route setter was used on an artificial indoor climbing wall in such a way that technical and physical difficulties were distributed along the entire route. All the routes were similar in average slope (10 ± 2° overhanging), overall length (17 ± 2 m of maximal height), and number of handholds (38 ± 2).

In the second session, the participants climbed the same route, now in red-point mode.

Before and after the two ascents (on-sight and red-point), the participants were assessed for their RI and movement sequence recall abilities and evaluated for their state of anxiety via a self-report questionnaire. The climbing performance, moreover, was assessed by ascent time, rate of perceived exertion (RPE), and physiological parameters (heart rate, f_{H}; lactate concentration, $[\mathrm{La}^-]$).

Experimental Procedures

In the first session, at rest, f_{H} was monitored by electrocardiography (Mod. Delta 1 PLUS, Remco Italia Cardioline, Italy) and whole blood lactate concentration was measured on an enzymatic amperometric system (LabTrend, BST Bio Sensor Technology, Berlin, Germany). The lactameter was calibrated and checked against standard solutions before each trial to ensure consistent data. The blood samples (20 μL) were collected from the little finger of each climber to minimize the impact on grip during the climb. The RPE was measured on a 6–20 Borg scale (Borg, 1982). After a semi-standardized warm-up (which included jogging, dynamic mobility exercises, and a lower grade practice climb), the participants were allowed 6 min to preview a route. Although set up on an artificial wall, together with others, the pitch was easily recognizable by the color of the holds. After previewing the route, the participant sat in front of a computer screen that displayed a black and white image of the wall (**Figure 1**). To test his route identification ($\mathrm{RI}_{\text{pre on-sight}}$) ability, the participant was asked to identify the holds (handholds and footholds) of the pitch, to simulate a sequence of movements, and how he would grasp each hold. He was also asked to make an estimate about his ability to either complete the route successfully or where he might fail. The participants then completed the Competitive State Anxiety Inventory 2 (CSAI-2). The CSAI-2 is a sports-specific anxiety inventory that comprises three 9-item subscales that measure cognitive anxiety (mental component of anxiety caused by negative expectations about success or negative self-evaluation), somatic anxiety (associated with the physiological or affective component of anxiety), and

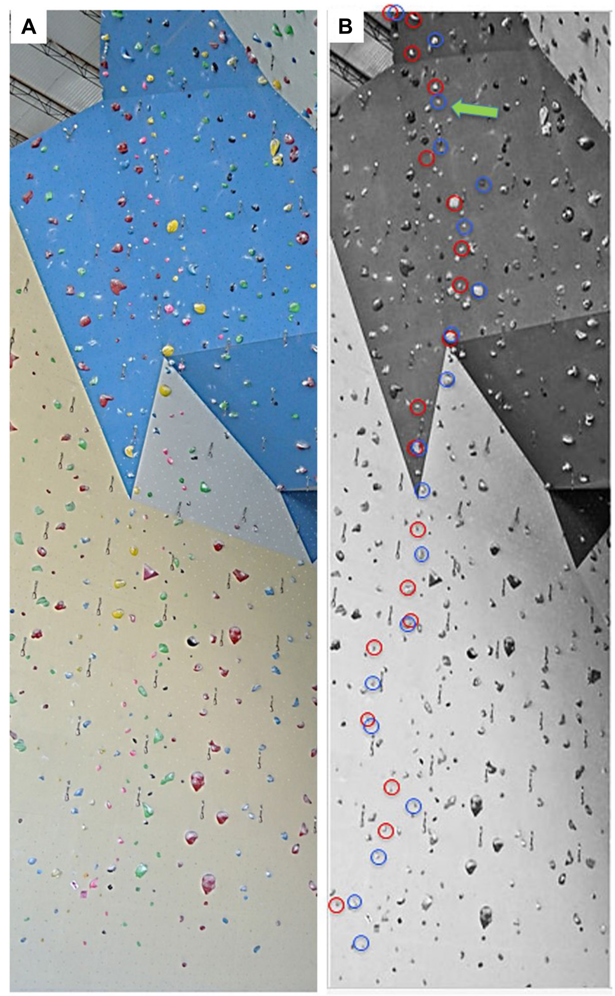

FIGURE 1 | Artificial indoor climbing wall with one of the routes used for the test (yellow, 7b) **(A)**. The black and white image **(B)** is the same image as the one shown to the climbers before and after the on-sight and the red-point ascent. The handholds that climbers planned to grasp are circled (red = left hand, blue = right hand). The green arrow indicates the spot where a climber expected to fall.

self-confidence (i.e., self-efficacy perception) (Martens et al., 1990; Cox et al., 2003). Each item is scored on a four-point scale from 1 (not at all) to 4 (very much so). The total scores range for each subscale is from 9 to 36, with 9 indicating low anxiety (high confidence) and 36 indicating high anxiety (low confidence).

Then, on lead, each participant climbed the route as an on-sight. The climbers were given no specific ascent instructions, except to self-pace and climb fluently. If a fall occurred prior to finishing two-thirds of the route or in the last third of the route, the climber abseiled to the ground and the trial data were either excluded or included, respectively, from the final analysis. Accordingly, the data from two of the 18 participants were subsequently excluded from the analysis.

The ascents were video-recorded with a digital video camera and timed. During the climb, f_H was monitored continuously by electrocardiography. Immediately after finishing the climb, the RPE was assessed, the blood lactate concentration was measured at minutes 1, 3, and 5, and the route identification test (RI $_{post\ on-sight}$) was re-administered.

In the second session, after the f_H and $[La^-]$ measurement at baseline and RPE assessment, the participants performed the same warm-up as in the first session. Subsequently, each climber had a total of 60 min and a maximum of four attempts to ascent and study the route. At the end of this time, the $RI_{pre\ red-point}$ and the CSAI-2 were re-administered. Finally, on lead, the climbers completed the red-point condition, and immediately post-climb retook the $RI_{post\ red-point}$ test.

Data Analysis and Statistic

Statistical analysis was performed using a statistical software package (SigmaStat for Windows, v3.11, Systat Software Inc., United States). A Kolgomorov–Smirnov test was applied to check for normal distribution of the data. A sample size of 14 participants was selected to ensure a statistical power higher than 0.80.

The ascent time in the two climbing modes was measured. The start was set when the climber took his feet off the ground and the end was set when he passed his safety rope in the chain at the top of route or where he fell. In the event of a fall, the climb time for the pitch common to the modes was entered in the data analysis. To evaluate the accuracy of a climber's prevision of success, the highest number of the handholds grasped was compared against the estimated pre-climb number.

To evaluate the climbing performance, static and dynamic actions were counted (Flahaut and Loslever, 2000; Pijpers et al., 2005), as applied in sport climbing analysis by Sanchez et al. (2012). The coding of performance consisted of measuring the duration of movements during the climb, divided into: performatory (necessary for ascent, measured from the release of a handhold to the moment of contact with another handhold) or explorative (unnecessary for ascent but useful for choosing the next movement. The handholds and footholds were touched without being used as a support). The duration of stops was measured and divided into appropriate stop (partial resting points) or inappropriate stop (static phases due to indecisions or errors but not useful for resting). Two independent operators viewed the video-recordings, rated the participants' performance, and compared it with the RI test.

Heart rate was monitored continuously from the basal condition to the end of the on-sight and the red-point climb. The basal (average over 1 min, in rest conditions, before warm-up), the peak during the climb (average over 10 s), and the average over the entire ascent time were calculated. $[La^-]$ level at baseline and peak after the ascent were measured.

To compare the RI test results and the video-recordings, for the on-sight and the red-point climbs we calculated the number of holds incorrectly identified on the black and white image shown on the computer screen, and the number of handholds grasped during the climb that differed from those previewed on computer screen image. The values are expressed as a percentage of the total number of holds taken during the route. From the RI test we also obtained the prevision of route success indicated by the participants before the red-point and the on-sight climbs, while from the video we verified the actual success.

Descriptive statistics [mean; standard deviation, (SD); standard error, (SE)] were used to describe the perceptive, psychological, and physiological variables, and the RI test results. Possible differences in perceptive, psychological, and physiological variables between the on-sight and the red-point climbs were checked using a one-way (modality) analysis of variance (ANOVA) for repeated measures. A two-way (time × modality) analysis of variance (ANOVA) for repeated measures was applied to determine differences in RI test results. The *post hoc* Bonferroni test was selected when necessary to locate the differences. Statistical significance was set at $P < 0.05$.

Pearson Correlation test was applied to identify associations between time to ascent, physiological parameters (f_H, $[La^-]$), and perceptual variables (RPE, cognitive anxiety, somatic anxiety, and self-confidence).

RESULTS

The ascent time was significantly shorter in red-point than in on-sight mode (148.7 ± 13.6 s and 179.5 ± 12.5 s, respectively, $P < 0.05$). **Table 1** presents the performance variables (performatory and exploratory move time; appropriate and inappropriate stop times). Significantly fewer ($P < 0.05$) exploratory moves and appropriate/inappropriate stop times were observed for the red-point compared to the on-sight climb. Performatory move times were also shorter for the red-point climb, albeit not significantly.

Table 2 presents the physiological (f_H, $[La^-]$) and perceptual parameters (RPE, CSAI-2). There was no difference in baseline values between the two climbing modes. Significantly lower ($P < 0.05$) peak values of f_H and $[La^-]$ were measured after the red-point climb, whereas no difference in f_{Hmean} was observed between the two climbing modes.

Regarding perceptual parameters, the climbers declared a lower cognitive and somatic anxiety and a higher self-confidence before the red-point ascent. RPE was lower after the red-point climb.

TABLE 1 | Total ascent time and duration of dynamic (performatory and exploratory moves) and static phases (appropriate and inappropriate stops time) in the on-sight and the red-point climb.

	On-sight lead climb	Red-point lead climb
Total ascent time (s)	179.5 ± 12.5	148.7 ± 13.6*
Performatory moves (s)	141.4 ± 11.0	128.8 ± 12.1
Exploratory moves (s)	15.4 ± 9.6	6.7 ± 4.2*
Appropriate stops (s)	42.2 ± 11.4	31.0 ± 8.9*
Inappropriate stops (s)	5.5 ± 2.3	1.2 ± 1.8*

*Mean ± SD *P < 0.05 vs. on-sight.*

TABLE 2 | Physiological and perceptual parameters at baseline, during, and post on-sight and red-point lead climb.

		On-sight lead climb	Red-point lead climb
	Physiological parameters		
f_H (bpm)	*basal*	71 ± 4	67 ± 5
	peak	186 ± 7	175 ± 9*
	average	166 ± 8	160 ± 7
[La⁻](mmol/l)	*basal*	1.08 ± 0.40	1.02 ± 0.41
	peak	6.81 ± 1.78	5.06 ± 1.08*
	Perceptive parameters		
RPE	*basal*	8 ± 1	7.5 ± 1
	post	17 ± 1.5	15.5 ± 1*
CSAI-2 (pts)	*cognitive anxiety pre climb*	17.4 ± 3.2	12.0 ± 4.6*
	somatic anxiety pre climb	15.1 ± 4.2	11.3 ± 5.0*
	self-confidence pre climb	28.2 ± 3.4	30.8 ± 4.1*

*f_H, heart rate; [La⁻], blood lactate concentration; RPE, rate of perceived exertion; CSAI-2, competitive state anxiety inventory 2. Mean ± SD *P < 0.05 vs. on-sight.*

Pearson correlation tests showed significant correlation between f_{Hpeak} and [La⁻] in both conditions ($r = 0.638$; $P = 0.044$ and $r = 0.577$; $P = 0.048$ in on-sight and red-point, respectively) and between [La⁻] and total ascent time ($r = -0.338$; $P = 0.043$ and $r = -0.377$; $P = 0.039$ in on-sight and red-point, respectively). Moreover, total ascent time in both conditions was correlated with cognitive ($r = 0.541$; $P = 0.046$ and $r = 0.699$; $P = 0.024$ in on-sight and red-point, respectively) and somatic anxiety ($r = 0.854$; $P = 0.001$ and $r = 0.832$; $P = 0.002$ in on-sight and red-point, respectively). No significant correlations were found among the other variables.

Figure 1 (panel A) displays the indoor climbing wall with one of the routes used for the trials (yellow holds, graded 7b according to the French Rating Scale of Difficulty). The black and white image on the right (**Figure 1**, panel B) is the same as that shown on the computer screen before and after the on-sight and the red-point climbs to assess RI ability. The participants were asked to identify all the holds on their route, indicating in red the handholds they planned to grasp with their left hand and in blue the ones they planned to grasp with their right hand. The point where a participant assumed he would fall was indicated by the green arrow.

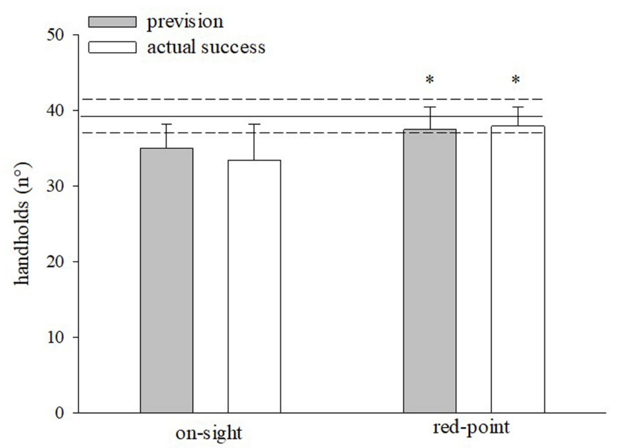

FIGURE 2 | Number of the handholds grasped by the climber in the on-sight and the red-point ascent (before finishing the route or before falling) and the pre-climb prevision. Mean ± SD *P < 0.05 vs. on-sight.

Figure 2 compares the number of the handholds the participant grasped in the on-sight and the red-point climbs (before finishing the route or before falling) and the pre-climb prevision. The number of handholds grasped during the red-point climb was significantly higher ($P < 0.05$) compared to the on-sight, both for the pre-climb prediction and the actual climb. In both modes, the prevision was consistent with the effective results (i.e., with the real performance achieved by the climber).

Figure 3 presents the main results of the RI test. The percentage of incorrectly identified holds on the route (panel A) was significantly lower ($P < 0.05$) between pre and post red-point climbs compared to pre and post on-sight climbs. Fewer mistakes between pre and post ascent, in both styles, were observed ($P < 0.05$). The percentage of the holds used differently during the climb from the holds stated on the RI test was significantly reduced ($P < 0.05$) in the RI pre and post red-point compared to the pre and post on-sight climb. Significantly fewer mistakes ($P < 0.05$) in both climbing modes were made between the pre and the post trials. Between the $RI_{\text{post on-sight}}$ and $RI_{\text{pre red-point}}$ there was a lower percentage of unidentified holds and a higher percentage of modified moves ($P < 0.05$).

DISCUSSION

Preliminary Considerations

To the best of our knowledge, this is the first study to compare physiological and perceptual parameters during on-sight and red-point climbing performance in advanced climbers on a maximum on-sight grade route. We chose a protocol that comprised different lead climbing styles as they might occur during indoor or outdoor climbing.

Climbers displayed an improvement in red-point performance, characterized by a smoother, faster, and more successful ascent. The physiological commitment and perceptual

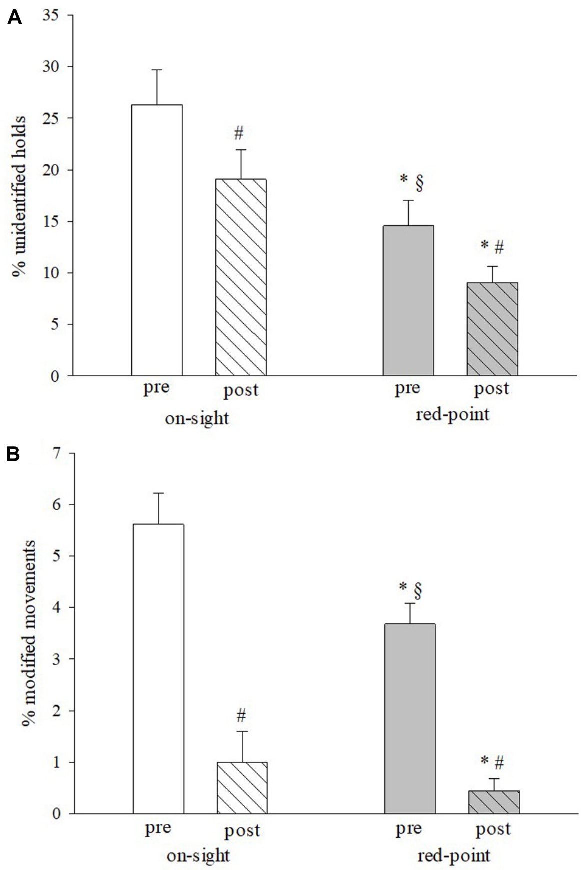

FIGURE 3 | Percentage of incorrectly identified holds on the route **(A)** in the two test conditions and the percentage of the holds used differently during the climb from that stated on the RI test **(B)**. Mean ± SE $^{*}P < 0.05$ vs. on-sight; $^{\#}P < 0.05$ vs. pre; $^{\S}P < 0.05$ vs. post on-sight.

involvement showed a reduction in peak values, except for self-confidence in which there was an increase.

This is also the first study to evaluate how the route preview changes over time when climbing performance is repeated. Our results indicate that RI skills are trainable and that route preview is important not only before on-sight performance but also for optimization of red-point climbing.

On-Sight and Red-Point Climbing Performance in Advanced Climbers

On-sight lead climbing is the more demanding style of ascent in sport climbing (Draper et al., 2008). When climbers attempt to push their limits beyond their current ability level during an on-sight attempt, they are unlikely to succeed without falling (Aras and Akalan, 2014). Next, they will begin to analyze the highly varied and individual movement sequences, focusing on the crux or personally most difficult sequential foot- and hand-hold arrangements. Once climbers deem their analysis of the route complete, they will attempt a red-point ascent, making use of the information and physical experience acquired during prior attempts. A climber's ability to interpret a route, recall movement, and incorporate motor learning skills into the ascent is essential to reduce the number of attempts to reach the desired goal (Sanchez et al., 2019). A climber's experience and level of performance strongly influence these abilities.

Only one study to date has compared the physiological and psychological aspects of an on-sight lead climb and a second lead climb (Draper et al., 2008). In their study, however, Draper and colleagues observed only novice, inexperienced climbers who climbed a route far below their skill level, which they were all able to finish in the on-sight attempt. Our study, however, involved highly experienced climbers, both athletes and instructors. Moreover, the route they climbed matched their best skills. Finally, between the first (on-sight) and the second (red-point) attempt, they had time to study and optimize the entire climb in all its parts, as normally done in sports climbing.

As expected, an improvement in performance between the on-sight and red-point climbs was observed, as demonstrated by the greater maximum height reached by climbers in the red-point than in the on-sight ascent (**Figure 2**) and by the significantly shorter ascent time (**Table 1**). With regard to the movements, there were significantly fewer exploratory moves and appropriate/inappropriate stop times in the red-point ascent. Moreover, performatory move time was also shorter in the red-point climb, albeit not significantly.

The move and stop times during climbing performance was compared by Sanchez et al. (2012) on pitches that differed in difficulty and were climbed in on-sight mode with or without route preview. They observed that while visual inspection does not influence how successfully a route is finished, it enhances movement fluency with faster speed, shorter stops, and less searching for foot and hand holds. These observations are in agreement with Dupuy and Ripoll (1989) who noted an improvement in expert climbers, with a shortening of pauses/inspection phases during a climb preceded by route preview, compared to one not previewed.

Our study adds interesting information about the influence of RI and the on-sight ascent on red-point climb. Experiential knowledge gained from preview and physical practice of the route enabled the climbers to considerably reduce the number of unnecessary moves and the static phases (appropriate and inappropriate stops). In addition, the climbers tended to perform the moves useful to the ascent faster, because they had practiced and optimized them. Both route preview and physical experience surely helped to make interpretation of the movement sequences faster and the execution smoother and more economic. Nevertheless, with this protocol, we were unable to define the influence of each aspect on the dynamic and static phases.

About the physiological parameters, peak f_H was significantly lower in the red-point ascent, whereas no difference in f_{Hmean} was observed between the two climbing modes. The lower peak f_H could be due to a reduced psychological involvement in the harder sections of the route, as observed in top-rope compared to lead climbing (Aras and Akalan, 2014). Moreover, the knowledge of the movement sequences makes climbing smoother and less expensive, limiting the f_H increase (Sanchez et al., 2012).

Peak blood lactate concentrations were lower in the red-point than in the on-sight climb. This could have been due to the optimization of moves and the reduction in stops times that imply a shorter duration of the upper limbs muscles in isometric, high-intensity contraction (Limonta et al., 2018). Isometric contractions are known to increase f_{H} and lactate concentration more than dynamic contractions, especially when the upper limb muscles are involved (Rowell et al., 1996; Astrand et al., 2003; Kuepper et al., 2009). As climbing speed increases, the isometric phase of upper limb muscles contraction shortens and this phenomenon may be attenuated (Limonta et al., 2018).

The perceptive parameters were in line with the physiological variables. The higher RPE at the end of the on-sight climb reflects the greater physical commitment (Pérez-Landaluce et al., 2002; Rodríguez-Marroyo et al., 2012) and anxiety it elicits (Morgan, 1994; Garcin et al., 2006). Anxiety is the chief psychological factor that affects athlete performance (Balagué, 2000; Craft et al., 2003; Woodman and Hardy, 2003; Aras and Akalan, 2014). Pijpers et al. (2005) observed significant differences in performance associated with high anxiety levels in novice climbers, but also élite climbers reported anxiety to be detrimental to successful performance because it induces rigid posture and jerky movements (Ferrand et al., 2006). The non-flowing movements lead to an increase in the physiological load which entails a greater energy expenditure and an inappropriate level of fatigue.

Cognitive and somatic anxiety were found to be higher and self-confidence lower in lead climbing compared to top-rope climbing (Aras and Akalan, 2014). Consistent with these findings, Draper et al. (2008) observed higher cognitive and somatic anxiety in on-sight lead climb, than in a second lead climb, with no differences in self-confidence.

Our data show less cognitive and somatic anxiety and greater self-confidence pre red-point climb compared to on-sight. The trends are consistent with previous studies, although the levels of cognitive and somatic anxiety seem to be lower on average and the self-confidence higher. A plausible explanation is that the climbers in our sample were more experienced and therefore better able to control their emotional responses to stress.

Route Preview and Movement Sequence Recall in On-Sight and Red-Point Climbing

In on-sight lead climbing, RI strategy (route preview) before the ascent is an essential skill set to optimize the performance (Boschker et al., 2002; Ferrand et al., 2006; Sanchez et al., 2019). Climbers use route preview to plan the order of climbing movements, determine the best climbing path, improve speed and efficiency, and find rest spots during the route (Boschker et al., 2002). Route finding skills are related to past experiences and motor and perceptive ability. For example, advanced climbers are able to perceive accurately the maximum distance they can reach and program their movements accordingly whereas novices underestimate their reaching capacity (Boschker et al., 2002). In addition, expert climbers are skilled in performing a wider range of technical movements (Sanchez et al., 2019).

Route preview mistakes are one of the major reasons for falling during climbing (Boschker et al., 2002; Sanchez et al., 2012). Indeed, a badly programmed movement during the climb results in: (i) the need for more complex and therefore less economical movements than necessary, (ii) the need to go down to a previous position and to re-set the correct move (with consequent energy expenditure), (iii) a fall, due to excessive complexity of the movement and/or inability to go down. Path strategy planning is linked to strategic effort management (Sanchez et al., 2019).

Previous studies analyzed the influence of route preview only in on-sight climbing (Dupuy and Ripoll, 1989; Sanchez et al., 2012; Seifert et al., 2017). However, when an on-sight climb is unsuccessful, climbers use route preview for the subsequent attempts. It allows the climber to mentally rehearse the move sequences and to reprogram the distribution of effort without physical and psychic expenditure as happens when physically working a route. After the failure of an on-sight climb, the climber can reduce the number of attempts to finish the pitch in red-point mode by optimizing the route preview. This is very important in lead climbing, where the value of performance, both indoor and outdoor, is higher when fewer attempts are needed. It is even more important in bouldering, in both competition and training, in which a key factor in performance is to preserve energy by minimizing the number of attempts on each boulder (White and Olsen, 2010).

In our study, the climbers performed both an on-sight and a red-point ascent preceded and followed by route preview. Analysis of the RI test results indicate that the route-finding skill and the ability to recall movement sequences improve after on-sight ($\mathrm{RI}_{\mathrm{post\ on-sight}}$) and before and after red-point ascent ($\mathrm{RI}_{\mathrm{pre\ red-point}}$ and $\mathrm{RI}_{\mathrm{post\ red-point}}$). We noted a significant decrease in the number of holds incorrectly identified on the route and in the number of holds grasped differently during the climb than previewed (**Figure 3**). How much these improvements are due to the route preview rather than physical ascent of the pitch is not easy to measure. Nonetheless, the different trend for the two parameters in the $\mathrm{RI}_{\mathrm{pre\ red-point}}$ compared to the $\mathrm{RI}_{\mathrm{post\ on-sight}}$ suggests that identification of the hand and foot holds and of the best path are easy to retain and to recall, even after time. However, the choice of moves seems more likely to be influenced by short-term motor experience. The technical-physical ability to climb and the interpretative capacity, therefore, may be considered to be trainable and mutually influential aspects.

Study Limitations

With this experimental protocol, we compared the differences in the on-sight and red-point climb on a route matching the best on-sight skill of each climber. However, we were unable to quantify the influence of the physical experience of climbing from that of RI.

Moreover, we analyzed improvement in RI ability based on an analysis of the dynamic and static phases during ascent and RI test results. We are unable to determine exactly whether the participants used different visual and interpretative strategies. Nevertheless, when we interviewed the participants about their strategies, their accounts agreed with the results of published studies (focus on functional aspects related to movements rather than structural characteristics and spatial information)

(Boschker et al., 2002; Pezzulo et al., 2010; Sanchez et al., 2012, 2019; Seifert et al., 2017).

The choice, as participants, of climbers who were both athletes and coaches, may have partially influenced the results. However, the participants having already familiarized themselves with the route preview process and optimization of red-point ascent allowed us to have a uniform sample and to avoid confounding factors.

Perspectives and Practical Applications

Our findings are shared by recent studies (Sanchez et al., 2012, 2019; Seifert et al., 2017) that reported that route preview ability is a key skill in performance. This is linked also to the new setting trends that draw move sequences in which coordination and motor creativity are increasingly involved, making route preview training methods a priority for coaches and athletes. Furthermore, because optimization of route preview, as mentioned above, has a direct effect on both the economy of individual performances and the overall management of effort during the competitive season, training of this ability will be even more important in view of the new, demanding Olympic combined format.

For this purpose, it could be useful to apply ideo-motor training (Smyth and Waller, 1998; Boschker et al., 2002; Stock and Stock, 2004; Sanchez and Dauby, 2009; Magiera et al., 2013; Sanchez et al., 2019) not only in the usual indoor environment but also in the varying "game context." For example, climbing in on-sight mode in a natural environment further stimulates the RI ability of the climber, both before and during the ascent, because the movements are not forced by the arrangement and characteristics of the holds set. Even the memory, in the outdoor environment, is further trained, because the wall does not allow easy identification of handholds and footholds as in the climbing-gym. Close to the competition period, in the climbing-gym exercises of RI /movement sequences recall, similar to the tests that we designed for this study, could be proposed. Using visual or technological support, the climber may be asked to retain information, draw paths, propose alternative solutions to the same sequence of holds (as an instructor does with his athletes), or vice-versa imagine different holds sequences that can be resolved with the same motor pattern. Manipulating task and environmental properties, training methods must push the climber out of his comfort zone, to stimulate unusual strategies and solutions to expand his motor and mental patterns.

Previous research (Smyth and Waller, 1998; Boschker et al., 2002; Pezzulo et al., 2010; Seifert et al., 2017) observed that during the route preview, climbers do not focus on the same aspects but rather take advantage of different visual and interpretative strategies. Some try to map the sequencing of holds and determine the spatial objectives useful for climbing, while others focus on weight redistribution and upper and lower limb coordination when planning single economic moves, still others primarily study more complex move sequences. Generally, expert climbers are more focused on the functional aspects of the ascent and novices on the structural characteristics of holds (Boschker et al., 2002).

Overall, differences in climbing skill levels seem to correspond to differences in visual perception and memory. This supports the concept that route preview is a trainable skill and strongly linked to technical-physical abilities. Future evolution of this study could compare the differences in performance and RI ability among climbers of different levels and/or experience.

Furthermore, it could be investigated whether gender influences route preview processes. Several studies showed, both in climbing (Asci et al., 2006) and in other sports (Rice et al., 2019), that female athletes have higher levels of anxiety than males and that this factor affects performance. It is possible, therefore, that higher anxiety in females also affects route preview and interpretative strategies.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Milan Ethical Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

EL: conception and design of the study, data acquisition, analysis and interpretation, and drafting of the manuscript. MF: conception and design of the study and data acquisition. SR, EC, SL, and GC: data analysis and interpretation. FE: drafting of the manuscript. All authors reviewed and approved the manuscript.

ACKNOWLEDGMENTS

The authors wish to thank all the volunteers that took part in the study for their committed participation.

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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.

frontiers in Psychology

ORIGINAL RESEARCH
published: 05 June 2020
doi: 10.3389/fpsyg.2020.00997

Effect of Height on Perceived Exertion and Physiological Responses for Climbers of Differing Ability Levels

Jan Gajdošík[1], Jiří Baláš[1] and Nick Draper[2]*

[1] *Faculty of Physical Education and Sport, Charles University, Prague, Czechia,* [2] *School of Health Sciences, College of Education, Health and Human Development, University of Canterbury, Christchurch, New Zealand*

Purpose: The purpose of this study was to examine differences in perceived exertion (RPE) and physiological responses for climbers of different abilities completing an identical route low and high above the ground.

Materials and Methods: Forty-two male (N = 18) and female (N = 24) sport climbers divided into three groups, lower-grade (N = 14), intermediate (N = 14), and advanced climbers (N = 14), completed two visits to a climbing gym, separated by 7 days. In a random order, the climbers completed a close-to-the-ground ascent (treadwall) and climb to height (climbing gym). Immediately after the test, climbers provided their RPE (6–20). Indirect calorimetry was used to assess physiological response during the ascent and recovery.

Results: The mean (±standard deviation) RPE was higher for lower-grade climbers when ascending the route on the wall (RPE = 12 ± 1) when compared to the treadwall route (RPE = 11 ± 1, P = 0.040; d = 0.41). For all ability groups, the physiological response was higher on the climbing gym wall as opposed to the treadwall: ventilation (P = 0.003, $\eta_p{}^2$ = 0.199), heart rate (HR) (P = 0.005, $\eta_p{}^2$ = 0.189), energy cost (EC) (P = 0.000, $\eta_p{}^2$ = 0.501). The RPE demonstrated a moderate relationship with physiological variables (R^2 = 0.14 to R^2 = 0.45).

Conclusion: Climbing to height induced a greater metabolic stress than climbing at a low height (treadwall) and led to higher RPE for lower-grade climbers. In this study, RPE appeared to be a good proxy measure of the physiological demands for advanced climbers but not for intermediate and lower-grade climbers. Therefore, using RPE in climbing with less experienced athletes may perhaps overestimate actual exercise intensity and should be interpreted carefully.

Keywords: sport climbing, energy cost, indirect calorimetry, treadwall, indoor climbing

OPEN ACCESS

Edited by:
Nick J. Davis, Manchester Metropolitan University, United Kingdom

Reviewed by:
Shakiela K. Davies, University of South Wales, United Kingdom
Michael John Hamlin, Lincoln University, New Zealand

****Correspondence:***
Jiří Baláš
balas@ftvs.cuni.cz

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *30 January 2020*
Accepted: *21 April 2020*
Published: *05 June 2020*

Citation:
Gajdošík J, Baláš J and Draper N (2020) Effect of Height on Perceived Exertion and Physiological Responses for Climbers of Differing Ability Levels. Front. Psychol. 11:997. doi: 10.3389/fpsyg.2020.00997

INTRODUCTION

Sport climbing is a sport that can improve aerobic fitness and health (Rodio et al., 2008; Aras and Akalan, 2016). In recent years, indoor climbing has become more popular than rock climbing due to the increasing availability of indoor facilities such as indoor climbing gyms, bouldering walls, or treadwalls (Heil, 2019). Indoor climbing walls try to replicate outdoor rock climbing conditions, utilizing artificial holds and structures to create predefined routes typically of 15–25 m in height. In ascending a route at an indoor wall, climbers are exposed to physiological and psychological stress, according to the overall difficulty and climbing style used (Hodgson et al., 2009; Draper et al., 2010; Dickson et al., 2012; Fryer et al., 2013). In contrast, treadwalls, mechanical or motorized ergometers equipped with climbing holds, provide a physiological challenge where the risk of fall or fear from height is minimal. This type of ergometer enables the analysis of physiological responses to climbing in a controlled setting. Treadwalls can be altered to assess the effect of speed or inclination at submaximal or maximal intensity on physiological response in climbers (Watts and Drobish, 1998; España-Romero et al., 2009; Fryer et al., 2018; Limonta et al., 2018; Heil, 2019).

To date, research regarding the psychophysiological response to climbing suggests that fall potential increases somatic anxiety (autonomous hyperactivity and somatic tension such as breathlessness, cold sweat, and trembling), plasma cortisol, blood lactate and catecholamine concentrations, heart rate (HR), and oxygen cost and is associated with lower self-confidence for lower-grade and intermediate climbers but not for elite athletes (Hodgson et al., 2009; Draper et al., 2010; Dickson et al., 2012; Fryer et al., 2013; Baláš et al., 2017). Differences in stress response might not have resulted solely from the safety protocol (top-rope vs. lead climbing) but may simply result from the effect of height. When prescribing training programs or developing a research intervention, coaches, fitness instructors, and researchers should consider whether physiological responses are due to physical effort alone or the result of a combination of psychological and physiological factors. This is especially important when prescribing exercise intensity in health-oriented programs, as apparently high-intensity exercise (due to increased HR from psychological stress) may induce low or no muscle adaptation changes.

Subjective scales such as the rating of perceived exertion (RPE) are widely used instruments to assess exercise intensity and have been validated against several physiological outcomes (Chen et al., 2002). For instance, the American College of Sport Medicine (ACSM, 2014) guidelines use Borg's scale of RPE along with HR and oxygen consumption for exercise intensity prescription. Although RPEs were initially created to score exercise intensity, it has been shown that RPE is affected additionally by psychological variables such mood state (anxiety, neurosis, and depression) or competitive strategy (Morgan, 1973; Robertson and Noble, 1997). When exercise intensity is low, the perception of effort is influenced primarily by non-physiological factors; when exercise intensity is high, physical demands mainly affect effort perception (Hall et al., 2005). Therefore, submaximal climbing from low to moderate intensity should induce differences in RPE if the same route is completed at height and close to the ground. We hypothesized that RPE and physiological response will differ for lower-grade climbers in the situation of stress from height, but not for intermediate and advanced climbers.

The purpose of this study was to compare RPE and physiological response in lower-grade, intermediate, and advanced climbers during climbing an identical route on the ground and ascending to height.

MATERIALS AND METHODS

Participants

Forty-two male (N = 18) and female (N = 24) sport climbers participated in the study. Participants were divided into three groups, lower-grade (N = 14), intermediate (N = 14), and advanced climbers (N = 14), according to self-reported best red point grade in the last 3 months (Draper et al., 2016). Anthropometric and training characteristics are shown in **Table 1**. All subjects were asked to avoid intense exercise for 24 h prior to visits and to restrain from caffeine the day of testing. All participants gave written informed consent at the beginning of the study. The local university's ethics committee granted approval for the study.

Study Design

All participants completed the routes on two separate visits on the climbing wall and with 7 days between each test. During a visit, they performed, in a randomly assigned order, a test on a treadwall (low over the ground) or on an indoor climbing wall (high over the ground). The testing started with standardized warm-up exercises (5 min running, 5 min mobilization exercises, and climbing low over the ground to learn the climbing sequence). Ten minutes of seated rest was provided to assess resting physiological response. Then, a climb of a 19.5-m-long route on the climbing wall and on the treadwall was completed at given speed (4 m·min^{-1}). Immediately after completing the route, participants were asked to rate their exertion; then a further 10 min of seated rest was provided to assess excess postexercise oxygen consumption (EPOC).

Climbing Routes

Treadwall and indoor wall routes both were vertical and have the same configuration of holds. Three identical sequences were repeated on the 19.5-m length and were graded 7 on the International Rock Climbing Research Association (IRCRA) scale. On the indoor wall route, climbers were belayed by an experienced instructor through a preinstalled rope (top-rope condition), and the risk of fall was minimal. To control the speed of ascent, the route was labeled with colored marks every meter. These marks had to be attained after 15 s; moreover, the instructor navigated the climbers acoustically. During treadwall climbing (ClimbStation generation 1, Forssa, Finland), participants completed the ascent without the need for safety equipment such as a harness or rope. During the treadwall ascent, climbers' feet were maximally 0.5 m above the landing mat.

Perceived Exertion and Physiological Response

Perceived exertion was assessed on a scale from 6 to 20 as suggested by Borg (1982). Immediately after the test, climbers

TABLE 1 | Anthropometric and training characteristics (mean ± SD) in lower-grade, intermediate, and advanced female and male climbers.

Females	**Lower grade (*N* = 12)**	**Intermediate (*N* = 8)**	**Advanced (*N* = 4)**
Age (years)	31.6 ± 11.3	25.7 ± 4.3	31.3 ± 7.5
Body mass (kg)	62.6 ± 6.0	56.4 ± 7.1	53.5 ± 1.3
Height (cm)	168.1 ± 4.6	169.6 ± 7.2	162.8 ± 7.6
Climbing ability (IRCRA)	9.0 ± 1.3	13.5 ± 1.2	19.8 ± 1.3
Climbing experience (years)	9.7 ± 12.4	5.6 ± 3.8	10.0 ± 5.6
Males	**Lower grade (*N* = 2)**	**Intermediate (*N* = 6)**	**Advanced (*N* = 10)**
Age (years)	26.3 ± 4.4	29.6 ± 2.6	31.3 ± 6.5
Body mass (kg)	75.5 ± 6.4	74.2 ± 5.5	69.2 ± 5.5
Height (cm)	182 ± 5.7	183.3 ± 6.6	178.3 ± 8.1
Climbing ability (IRCRA)	9.5 ± 0.7	12.6 ± 0.6	19.2 ± 1.6
Climbing experience (years)	1.8 ± 0.4	3.1 ± 2.1	13 ± 5.2

were shown a table with numbers and corresponding verbal description of the exertion and indicated their exertion rating to the researcher.

Physiological responses were assessed using a breath-by-breath portable metabolic system (MetaMax 3B, Cortex Biophysik, Germany). The device was worn by climbers on the chest with a harness (total weight 1.4 kg). Gas calibration was performed using a reference gas (15% O_2 and 5% CO_2), and volume calibration was performed using a 3-L syringe. Breath-by-breath data were averaged at 20-s intervals and exported to Excel for further analysis.

Oxygen uptake (VO_2), carbon dioxide production (VCO_2), expiratory ventilation (V_E), and breath frequency (BF) were measured by MetaMax 3B. Respiratory exchange ratio (RER) was computed by dividing VCO_2 by VO_2. EPOC was calculated from 10 min of sitting rest as total recovery VO_2 minus resting VO_2. The net climbing energy cost (EC) was computed from net climbing VO_2 and EPOC using the energy equivalent for oxygen of 4.924 kcal. The chest belt (Polar Electro OY, Finland) was used for monitoring the HR, which was transmitted automatically to the MetaMax 3B.

Statistical Analysis

Descriptive statistics (mean ± standard deviation) was used to characterize RPE and physiological response low and high over the ground in all ability groups. Differences between climbing conditions and ability groups were assessed by a 2 × 3 mixed model ANOVA with climbing route as the within-subject factor and ability as the between-subject factor. When significant, pairwise comparisons with Bonferroni corrections were applied. As unequal number of males and females completed the study across ability groups, the possible effect of sex was evaluated by ANCOVA with sex as the between-subject factor and climbing ability as the covariate. Statistical significance was set to $P \leq 0.05$. Effect size was calculated using partial eta squared ($\eta_p{}^2$) and Cohen's *d*, where values of 0.05, 0.10, and >0.20 represent small, intermediate, and large effects and 0.2, 0.5, and >0.8 represent small, moderate, and large differences for $\eta_p{}^2$ and Cohen's *d*, respectively.

RESULTS

Perceived exertions were higher when climbing to height as opposed to climbing low to the ground on the treadwall (+5.3%, $P = 0.013$, $\eta_p{}^2 = 0.149$). Pairwise comparisons revealed statistical differences only for lower-grade climbers ($P = 0.040$; $d = 0.41$) (**Figure 1**). The physiological response was higher for ascending to height in comparison to climbing low to the ground for V_E (+7.7%, $P = 0.003$, $\eta_p{}^2 = 0.199$), HR (+4.5%, $P = 0.005$, $\eta_p{}^2 = 0.189$), and EC (+14.0%, $P = 0.000$, $\eta_p{}^2 = 0.501$). However, pairwise comparisons indicated statistical differences in all ability groups only for EC: lower-grade climbers ($P = 0.003$, $d = 1.26$); intermediate climbers ($P = 0.001$, $d = 0.43$); and advanced climbers ($P = 0.006$, $d = 0.67$) (**Figure 1** and **Table 2**).

Lower-grade climbers perceived greater exertion than intermediate ($P < 0.001$, $d = 1.29$) and advanced climbers ($P < 0.05$, $d = 1.86$) for both climbing conditions. Moreover, lower-grade climbers demonstrated greater physiological response for BF ($P = 0.001$, $d = 1.54$), V_E ($P = 0.002$, $d = 1.56$), and HR ($P < 0.001$, $d = 1.58$) than advanced climbers (**Figure 1** and **Table 3**). Additionally, intermediate climbers showed higher HR ($P = 0.005$; $d = 1.18$) than advanced climbers (**Figure 1**). No significant differences in EC between ability groups were stated.

No interaction of climbing ability and climbing condition was found. RPE and physiological variables demonstrated a moderate relationship ($R^2 = 0.14$–0.45; **Table 3**).

Due to an uneven distribution of males and females in ability groups, sex comparison is presented in **Table 4**. Estimated marginal means did not show any difference between males and females for RPE and physiological variables except for BF.

DISCUSSION

The aim of our study was to compare RPE and physiological demands to ascent identical routes low and high over the ground for climbers of differing ability. Climbing to height induced higher RPE than climbing low over the ground in lower-grade climbers. The differences in RPE were not repeated for higher-ability climbers. Moreover, RPE was only moderately related to

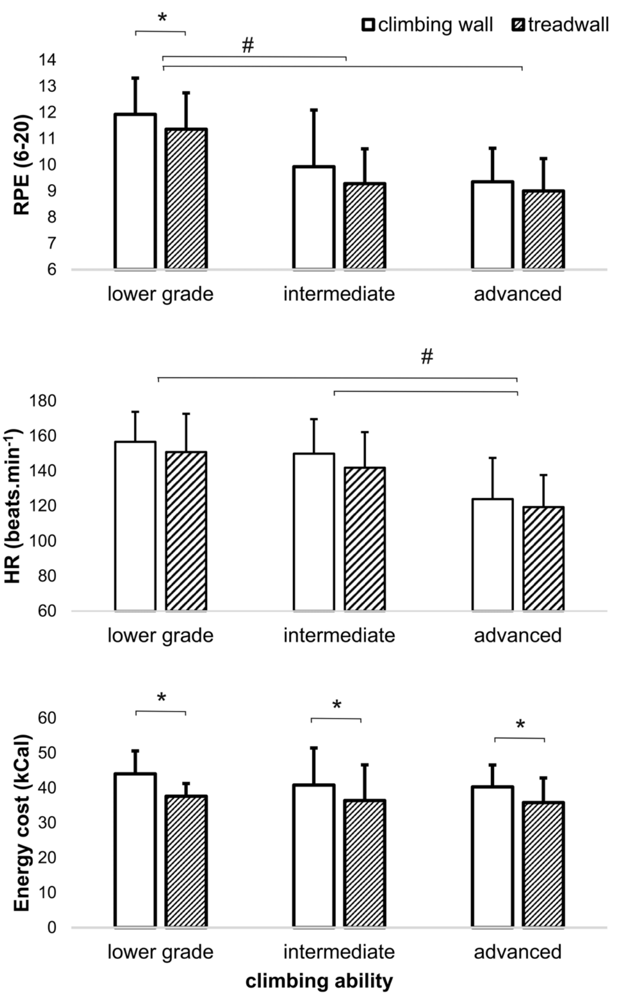

FIGURE 1 | Mean (±SD) perceived exertion (RPE), heart rate (HR), and energy cost (EC) during climbing in height (climbing wall) and low (treadwall) to the ground. *Significant differences between climbing in height and low to the ground at $P < 0.05$. #Significant differences between ability groups at $P < 0.05$.

physiological responses and consequently may not be a good indicator of physiological demands in climbing.

The results confirmed our hypothesis that height represents an important stress factor in climbing even in a top-roping condition where the risk of a fall is minimal. Interestingly, RPE when ascending to height was only elevated for lower-grade climbers, although metabolic stress was increased in all ability groups. Furthermore, results of Pearson product–moment correlations revealed only a moderate relationship between RPE and physiological variables, which means that factors other than mental stress induced elevated metabolic response when climbing to height or that the use of RPE in this situation was not specific or accurate enough. Elevated metabolic responses may be partially due to wearing a harness, the weight of which ranged from 250 to 600 g. Different movement patterns and different work/relief ratio on the treadwall and indoor wall might have also influenced the physiological response as suggested previously (Donath et al., 2013; Fryer et al., 2013). However, movement analysis was not performed due to the relatively large number of participants.

Perceived exertions during climbing in both conditions were moderately related to HR (R^2 = 0.17–0.29). Lower-grade and advanced climbers rated both climbs as fairly light and very light on the RPE scale (∼12 and 9) which corresponded to HRs of ∼154 and 122 beats·min^{-1} and VO_2 of ∼26 and 25 ml·min^{-1}·kg^{-1}, respectively. In a study by Scherr et al. (2013) with a large cohort of participants, an equation for HR estimate from RPE was proposed: HR (beats·min^{-1}) = 69.34 + 6.23 × RPE (R^2 = 0.55), which would correspond to values of 144 and 125 beats·min^{-1} for fairly light and very light RPEs in the current study. This estimate is valid for advanced climbers; however, lower-grade climbers demonstrated greater HR with respect to the prediction formula. HR was greater by ∼32 beats·min^{-1} in lower-grade climbers compared to advanced climbers while VO_2 was elevated only by 1 ml·min^{-1}·kg^{-1}. This disproportionate rise of HR to VO_2 was described by Mermier et al. (1997) and Sheel (2004) when climbing easy and more difficult routes and was explained by handgrip isometric contractions, arm position over the head, and psychological stress. Additionally, this disproportion was more elevated with a more intense handgrip contraction (Fryer et al., 2013). Therefore, to estimate subjectively physiological measures during climbing, RPE may be a valid tool in advanced climbers on easy climbs, irrespective of height of the ascent. However, in lower-grade and intermediate climbers or on more difficult ascent, RPE underestimates HR response.

In our study, climbing to height on an indoor climbing wall was metabolically more demanding than climbing low over the ground. The largest differences between the two conditions occurred for lower-grade climbers (Δ 10 kcal·kg^{-1}) and the lowest for advanced climbers (Δ 6 kcal·kg^{-1}). Lower-grade climbers were also the only group where significant differences in RPE were revealed. It is possible that the differences in EC in the two climbing conditions were due to a combination of psychological and technical factors. As this ability group has the lowest experience with the sport, climbing to height might have presented a more mentally demanding condition resulting in changes in the use of forces on hold during ascent. Previously, it has been demonstrated that less experienced climbers disproportionally load their arms than their legs, thereby increasing their physiological response when compared with higher-grade climbers (Baláš et al., 2014). In agreement with this difference, RPE has been found to be higher during arm exercise than with leg exercise (G. Pandolf et al., 1984; Borg et al., 1987).

Interestingly, differences in VO_2 between ability groups or climbing conditions did not reach significance as expected (Bertuzzi et al., 2007). A possible explanation for between-group VO_2 similarity might be related to the higher proportion of females in the lower-grade group and males in the advanced group. In previous research, female climbers have demonstrated more economical movement and, therefore, lower VO_2 for the same climbing task (Heil, 2019). The intraindividual variation

TABLE 2 | Mean (±SD) oxygen consumption (VO_2), pulmonary ventilation (V_E), breath frequency (BF), respiratory ratio (RER), and energy cost (EC) during climbing in height and low to the ground in lower-grade, intermediate, and advanced climbers.

	VO_2 (ml·min^{-1}·kg^{-1})	V_E (L·min^{-1})	BF (breaths·min^{-1})	RER	EC (kcal·kg^{-1})
lower grade$_{treadwall}$	26.2 ± 2.6	48.8 ± 7.2**¤**	36 ± 6***¤**	0.90 ± 0.06**¤**	0.59 ± 0.07*
lower grade$_{indoor\ wall}$	26.4 ± 4.5	53.1 ± 11.2**¤**	37 ± 8***¤**	0.93 ± 0.09#**¤**	0.69 ± 0.08*
intermediate$_{treadwall}$	24.9 ± 4.6	43.3 ± 12.0	34 ± 8¤	0.86 ± 0.06¤	0.57 ± 0.09*
intermediate$_{indoor\ wall}$	26.4 ± 3.6	45.0 ± 12.7	33 ± 9	0.86 ± 0.06#	0.64 ± 0.11*
advanced$_{treadwall}$	24.6 ± 3.2	35.9 ± 6.4**¤**	24 ± 7¤**¤**	0.81 ± 0.04¤**¤**	0.56 ± 0.08*
advanced$_{indoor\ wall}$	25.9 ± 2.3	39.8 ± 8.9**¤**	27 ± 4**¤**	0.83 ± 0.07**¤**	0.62 ± 0.06*

Significant differences between climbing in height and low to the ground at $P < 0.05$. #Significant differences between lower-grade and intermediate climbers at $P < 0.05$. ¤Significant differences between intermediate and advanced climbers at $P < 0.05$.* **¤*Significant differences between lower-grade and advanced climbers at $P < 0.05$.*

TABLE 3 | Relationship between perceived exertion (RPE) and mean oxygen consumption (VO_2), pulmonary ventilation (V_E), heart rate (HR), breath frequency (BF), respiratory ratio (RER), and energy cost (EC) during climbing in height and low to the ground.

	VO_2	V_E	HR	BF	RER	EC
RPE$_{treadwall}$	0.287	0.481*	0.542*	0.377*	0.490*	0.245
RPE$_{indoorwall}$	0.047	0.439*	0.414*	0.669*	0.627*	0.380*

**Significant relationship at $P < 0.05$.*

TABLE 4 | Differences between males and females in perceived exertion (RPE), heart rate (HR), oxygen consumption (VO_2), pulmonary ventilation (V_E), breath frequency (BF), and energy cost (EC).

	Males	Females	P	η_p^2
RPE (6–20)	10.0 ± 0.4	10.2 ± 0.3	0.706	0.004
HR (beats·min^{-1})	133 ± 5	145 ± 4	0.054	0.092
VO_2 (ml·min^{-1}·kg^{-1})	26.5 ± 0.8	25.2 ± 0.6	0.231	0.037
V_E (L·min^{-1})	47.9 ± 2.2	41.9 ± 1.8	0.052	0.093
BF (breaths·min^{-1})	28.8 ± 1.6	33.5 ± 1.3	0.038*	0.106
EC (kcal·kg^{-1})	0.62 ± 0.2	0.61 ± 0.2	0.786	0.002

*Data are presented as estimated marginal means (±standard error) from treadwall and indoor wall climb with a correction for a common covariate (climbing ability = 13.8 IRCRA scale). *Significant differences at $P < 0.05$.*

in VO_2 between climbing low and high to the ground did not reach significance either. However, when including EPOC in calculation, we found significant differences in EC, which was greater after climbing to height, and this might be related to more pronounced anaerobic isometric contractions and/or greater catecholamine efflux.

The effect of sex on RPE and physiological variables was assessed by ANCOVA with control for climbing ability level. Females may have a different psychological approach than males to the climb, and it was, for example, discussed that males and females may rate physical exertion differently (Robertson and Noble, 1997). Our results did not show any differences between males and females for RPE, EC, and VO_2; however, BF was significantly higher in females, and HR and V_E were close to significance level. V_E should be higher in males as they have larger body mass; however, HR and BF are not influenced by body shape. We acknowledge that some sex differences in stress responses may have been presented but were not detected by RPE. For future studies, design including only males and then females should be conducted to assess the effect of stress conditions on RPE.

Some other limitations have to be acknowledged. The route was climbed at one given speed in vertical profile. Climbing at a range of speeds on walls of altered inclinations might have provided different results. Climbers were divided into three ability groups, but the ratio of female and male climbers in these groups was not even. This might have led to bias for between-group comparisons. Nevertheless, the main purpose was to examine intraindividual differences, and the relatively large sample size and controlled settings will likely have increased the internal validity of the research.

CONCLUSION

Climbing height induced greater metabolic stress than climbing low to the ground and, moreover, led to higher RPE in lower-grade climbers. The differences in RPE were not seen in higher-ability-level groups. RPE was a good indicator of physiological demands in advanced climbers on easy routes. With increasing difficulty or in lower-grade and intermediate climbers, RPE underestimated HR response.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

JG developed the theoretical framework, conceived the study, collected the data, analyzed the data, and wrote the manuscript.

JB developed the theoretical framework, conceived the study, analyzed the data, guided the analyses, and provided critical feedback on the drafts. ND provided critical feedback on drafts and edited the final manuscript for submission.

FUNDING

This study was supported by the Charles University program GAUK, Adventure activities and movement deficiency in youth.

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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.

frontiers in Psychology

BRIEF RESEARCH REPORT
published: 07 July 2020
doi: 10.3389/fpsyg.2020.01364

Heart Rate Behavior in Speed Climbing

Franz Konstantin Fuss[1]*, Adin Ming Tan[1], Stefanie Pichler[2], Günther Niegl[3] and Yehuda Weizman[1]

[1] Smart Products Engineering Program, Swinburne University of Technology, Melbourne, VIC, Australia, [2] Institute of Sports Science, University of Vienna, Vienna, Austria, [3] Climb-on-Marswiese, Sportstättenverein Marswiese, Vienna, Austria

Speed climbing is an Olympic discipline within the combined sport climbing event in 2020 for the first time. Speed climbing is a high-speed and anaerobic exercise against gravity over a few seconds with extreme psychological pressure. Although there is some literature on heart rate (HR) when lead climbing, there is no literature on the behavior of the HR when speed climbing. The HR of seven near-elite participants was measured with a Polar HR monitor while climbing a 10- and 15-m wall, respectively, three times each, with pauses of 5 min between the first and last three climbs and a 20-min pause between the third and fourth climb. The average climbing times on the 10- and 15-m walls were 9.16 ± 3.06 s and 14.95 ± 3.14 s, respectively (data pooled between climbing heights). The peak HR on the 10- and 15-m walls were 164.57 ± 7.45 bpm and 176.43 ± 8.09 bpm. The rates of change in HR were as follows: average HR acceleration before peak HR, 2.53 ± 0.80 bpm/s; peak HR acceleration before peak HR, 4.16 ± 1.08 bpm/s; and average HR deceleration after peak HR, −0.98 ± 0.30 bpm/s. The average HR during the pauses ranged from 105.80 to 117.89 bpm. From the results, in comparison to the literature, we conclude that athletes, trained for sustaining high physical exertion and psychological pressure, have a far smaller HR acceleration than untrained people during light and unstressful exercises. Furthermore, the current rule that athletes shall have a minimum resting time of 5 min between climbing attempts during a speed climbing competition seems justified as sufficient time for HR recovery.

Keywords: speed climbing, heart rate, psychological pressure, anaerobic, acceleration, rules of climbing

OPEN ACCESS

Edited by:
Vanesa España-Romero, University of Cádiz, Spain

Reviewed by:
Scott Nolan Drum, Northern Michigan University, United States
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****Correspondence:***
Franz Konstantin Fuss
fkfuss@swin.edu.au

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *02 December 2019*
Accepted: *22 May 2020*
Published: *07 July 2020*

Citation:
Fuss FK, Tan AM, Pichler S, Niegl G and Weizman Y (2020) Heart Rate Behavior in Speed Climbing. Front. Psychol. 11:1364. doi: 10.3389/fpsyg.2020.01364

INTRODUCTION

Speed climbing is one of the three disciplines of combined sport climbing, an Olympic discipline in 2020 for the first time. Speed climbing is a unique sports discipline that requires high-speed, high-power, and precise non-cyclic movements with a full-body workout (all four limbs), by lifting the body center of mass by ∼13 m (on the 15-m wall) against gravity at maximum possible speed, concentration, and extreme psychological pressure. These are conducted over a very short period of time, specifically only over a couple of seconds, and with a very high risk of failure. The current world records (as of the submission of this paper) are 5.48 s for men and 7.10 s for women (International Federation of Sports Climbing [IFSC], 2019a), corresponding to an average climbing speed of 2.74 and 2.11 m/s, respectively.

There is no other Olympic discipline comparable to the intensity of speed climbing. Other highly anaerobic disciplines include the following:

- Running, 100-m sprint. It has the same cyclic movements of the legs over the entire distance (starting excepted) and low failure risk as compared to climbing. In addition, the cumulative vertical upward displacement of the body center of mass (COM) is small compared to speed climbing [Usain Bolt: 41 steps over 100 m (Maćkała and Antti, 2013), average and maximal vertical displacement of the COM per stride equals 45 and 49 mm, respectively (Čoh et al., 2018), resulting in a total upward displacement of 1.85–2 m over 100 m];
- Speed skating, 500-m sprint. Same as running, with zero vertical upward displacement of the COM;
- Cycling, flying 200-m time trial. Same as running, with minimal failure risk and zero vertical upward displacement of the COM;
- Wheelchair racing, 100-m sprint. Same as cycling, but using the arms instead of the legs;
- Swimming, 50-m freestyle. Same as cycling, but with zero failure risk, and with movements of all four limbs.

There is some literature on how the heart rate (HR) behaves in short anaerobic actions, mostly shown by means of HR profiles, i.e., plotting the HR against time.

For example, Svensson (2007) investigated the HR behavior in blocks *"consisting of 5 running cycles of short (2 m × 15 m) and long (50 m) high-speed runs with a 90-s rest period in between blocks."* However, the actual running time is not shown with respect to the HR profile.

Bogdanis (1994) investigated the HR in sprint cycling and compared the "peak heart rates" of the different tests. However, the "peak heart rates" were measured in general only every 30 or 60 s, with one datum at the end of a sprint. This method can be deceptive and be misinterpreted in the sense that the peak HR always occurs at the end of the exercise, with a subsequent immediate decrease.

This is not the case as shown by the following:

- Weinstein et al. (1998) in the 30-s Wingate Anaerobic Test on a cycle ergometer, where the peak HR occurred within 5 s after the end of the test.
- Casuso et al. (2014) in swimming, "*5 repetitions of maximal 100 m swimming bouts separated by 5 min of recovery,*" where the "*HR peak was located during the last 10 s of the sprint and the first 10 s of the recovery.*"

Sandvei et al. (2012) investigated the HR behavior in "*Sprint interval training consisting of 30 s sprints…with a 3 min rest between each sprint.*" The authors did not indicate the sprint time with respect to the HR profile. However, from **Figure 1** in their paper (Sandvei et al., 2012), it became clear that the HR peaked ~30 s after the end of the sprint, thereby still increasing over the first half minute of the rest period. Subsequently, the HR decreased over the next 2 min, leaving ~30 s for preparing for the next sprint (in the test persons of Sandvei et al., 2012). This pattern of HR behavior raises the question whether a 3-min rest between the sprints suffices for reducing the HR to a steady state, or whether the HR would have dropped further if it was not for the preparation phase for the next sprint.

FIGURE 1 | Climbing walls used in this study; **(a)** 10-m walls; **(b)** 15-m walls; **(c)** hand- and foothold pattern of the 15-m wall according to the IFSC (International Federation of Sports Climbing [IFSC], 2014), and **(d)** participant climbing the 15-m wall.

Considering this issue for speed climbing, according to the IFSC Rules (International Federation of Sports Climbing [IFSC], 2019b), specifically Rule 9.14, "*…competitors shall be afforded a minimum resting time of five (5) minutes between attempts on the route(s).*" Are these 5 min selected adequately, if not based on scientific proof, for allowing the HR to reach a steady state, i.e., a relatively constant HR over an acceptable amount of time?

To the best of the authors' knowledge, there is no literature source on the behavior of the HR during speed climbing.

However, there is some general literature on the HR in climbing. In fact, even one HR profile while lead climbing was published (Figure 4.4 of Giles, 2017), where the HR seemed to decrease immediately after completing the climb. The behavior of the HR in lead climbing is covered in detail by literature review paper such as Sheel (2004) and by two recent reviews: Michael et al. (2019) and Saul et al. (2019). As such, only the most important aspects of the HR in lead climbing are summarized subsequently.

The increase in the HR in climbing is multifactorial and depends on the following factors:

(1) The *difficulty of the route*—the more difficult the route, the higher the HR (Sheel et al., 2003). The more inclined an overhanging wall is, the more difficult the climbing route is (Fuss and Niegl, 2008b), which affects the HR (Baláš et al., 2014).

(2) Repetitive *isometric contractions* of the forearm musculature impede the local blood flow and lead to a higher heart rate and blood pressure (Astrand et al., 2003).
(3) While climbing, the *arms* are held *in the overhead position* for most of the time, which increases the HR (Mermier et al., 1997).
(4) *Psychological stress and anxiety* produce a higher HR (Mermier et al., 1997; Booth et al., 1999; Sheel, 2004; Draper et al., 2008).
(5) The more *experienced* rock climbers are, the lower the heart rate is (Sheel, 2004; Baláš et al., 2014).
(6) *Outdoor climbing* evoked a higher heart rate response than indoor climbing (Booth et al., 1999).

The aims of this research result from the knowledge gap identified above:

(1) How does the HR behave while speed climbing, and how does the HR profile look like, when climbing the same route several times, separated by a 5-min resting period?
(2) Are 5-min resting periods sufficient for recovery of the HR before the next climb?

METHODS

Rationale of the Method

This study was conducted *during* the training of speed climbing, and the HR was measured *during* speed climbing bouts and pauses (intervals) between the bouts. Point to note is that this study is not related to research into *interval training programs*, let alone *HR-based interval training programs*. The reason for this approach is twofold:

(a) The initial aim of this study was to conduct the collection of data during a speed climbing competition. Although we would have had access to many speed climbers in the same place and at the same time, the intended approach was not advisable, if not impossible, for various reasons. Instrumenting the participants with wearable devices would have severely disrupted the competition. Several ECG-based chest belts (Polar H7) were required, and it takes ∼10 min for preparing one climber by putting the chest belt on, explaining the procedure, and having the consent form filled in. Neither the judges of the speed climbing competition nor most of the participants would have approved wearing the chest belt as a certain tension is required for maintaining a good contact between the ECG electrodes and the skin. This belt tension could have distracted the climbers if they are not used to wearing such a belt. From own experience, climbers are very sensitive to distractions during competitions and become highly emotional when failing (falling off the wall) because of a distraction. It would have been probably easier to conduct HR measurements during competitions with optical HR sensors incorporated in smartwatches. However, it is well established that these optical sensors grossly underestimate the HR (Duking et al., 2016). Thus, ECG-based chest belts are the preferred option for collecting accurate data. As such, the study had to be carried out during speed climbing training. One could argue that the level of arousal is different under training and competition conditions, but investigating this under competition conditions had been ruled out as stated earlier. Two of the authors of this paper have experienced these problems before, namely, longer disruptions of a competition because of incorrect placement of an instrumented handhold (Fuss and Niegl, 2008a).
(b) The interval lengths (pauses between climbing bouts) were selected based on the international rules of speed climbing (IFSC, International Federation of Sports Climbing [IFSC], 2014), namely that the rest periods between two climbs must be at least 5 min. The objective of applying these rest periods was to verify that the HR decreases during these 5 min and by how much it actually decreases. During competitions, not all the participants have to go through two or more climbing ascents and therefore are not exposed to at least 5-min pauses. A properly designed study, carried out during a training process in contrast to during a competition, with a predefined number of pauses related to climbing ascents on 10- and 15-m wall, will provide more consistent numbers of datasets across the participants. From a physiological point of view, the minimum pause of 5 min seems to be correctly selected, as speed climbing is a short (5–15 s) "all-out" full-body exertion, whose primary energy system in use is the adenosine triphosphate–phosphocreatine system (ATP-PCr; Foss and Keteyian, 1998; Wilmore and Costill, 1999; Conley, 2000; McArdle et al., 2001). Periods of 3–5 min are necessary for the complete recovery and replenishment of the ATP-PCr energy system (MacDougall and Sale, 2014; Carmer et al., 2015). Conley (2000) suggested that work-to-rest ratios of 1:12–1:20 should be applied to 5–10-s long high-intensity exercises. Lloyd Jones et al. (2019) applied work-to-rest ratios of 1:8, 1:10, and 1:12 to 6-s exercise bouts of high-speed cycling. Along these lines, applying a work-to-rest ratio of 1:12 to a speed climbing bout of 15 s results in a 3-min pause required for replenishing the ATP-PCr energy system. A 5-min pause, prescribed by the rules, seems therefore appropriate. However, it is unknown how the HR behaves over these 5-min pauses. At least, it can be expected that the HR increases further immediately upon completion of the speed climb. At this point, the excess postexercise oxygen consumption (EPOC; Carmer et al., 2015) is established and highly engaged during the 5-min recovery. This increased rate of oxygen intake, along with perceived psychological stress, will continue to drive up heart rate after the climb. As such, both psychological overload and physiological stress will cause a rise in HR immediately after "all out" exertion. In this context, the behavior of the HR immediately after the climb and at the beginning of the pauses was of particular interest in this study.

In this study, recruiting the number of participants was a challenge: (1) participants have to agree to participation (consent according to Research Ethics); (2) in contrast to lead climbing and bouldering, the number of speed climbers is far less, as speed climbing is athletically very demanding and is not suited for casual climbers (whereas for the other two climbing disciplines, most active climbers are casual ones); (3) a climbing gym is required that has both speed walls at their disposal (10-m wall, and the international 15-m wall, considering that 15-m walls are very rare); (4) the participants must be preferably members of a national or regional team and participating in national or regional competitions, to guarantee at least a subelite level; and (5) all the participating speed climbers should be organized by their local climbing gym, and preferably by their coach, so that the HR data can be collected during their standard training process (and not having an experiment staged which could have a different psychological effect than their standard training process). Furthermore, working with each climber required a time commitment of 70 min in total (including preparation and debriefing).

The number of participants could have been solved when measuring participants of a speed climbing competition; however, this was already ruled out based on other concerns, as outlined above.

Despite having only seven participants, we see this preliminary study as a starting point for further research into speed climbing, specifically for multicenter trials to achieve a higher number of participants, with a tested and established method—outlined subsequently.

Speed Climbing Route

The climbing routes used in this study were a 10-m wall (top-roping with belayer; **Figure 1a**) and a 15-m wall (top-roping with automatic rope brake; **Figures 1b–d**). Both routes complied with the international rules, composed of one specific hold type with the standard handhold pattern as specified by the IFSC (International Federation of Sports Climbing [IFSC], 2014; **Figure 1c**). The reason why both 10- and 15-m speed climbing routes were used was to investigate the difference in reduction in HR after a 10- and a 15-m climb.

Participants

The HR of seven climbers was measured [5 female and 2 male climbers; 19.7 ± 2.1 years; speed climbing experience, 2.38 ± 3.45 years; best 15 m speed climbing time, 12.88 ± 4.07 s; body height, 1.68 ± 0.05 m; body mass, 61.4 ± 10.8 kg; body mass index (BMI), 21.55 ± 2.69 kg/m^2].

This study was granted ethics approval by the Swinburne University Human Ethics Committee (approval no. 20191290-1680) and adhered to the Declaration of Helsinki.

Experimental Procedure

The HR data were measured during the speed climbers' standard training process with a chest-worn Polar H7 chest belt, which is an ECG-based heart rate monitor (Polar, Kempele, Finland). The chest belt was placed directly below the sternal part of the pectoralis major muscle (as per recommendations of the manufacturer; Polar, 2020), centered around the xiphoid process. The data from the chest belt were transmitted to a Polar A300 receiver, which is usually worn on the wrist but was attached to the climbers' harness at the waist level in this study. The HR data were recorded at a sampling rate of 1 Hz. After each climb, the data were downloaded from the Polar A300 to the laptop via Polar Flow web service.

The Polar system and a stopwatch were switched on simultaneously ∼3 min before the first climb and switched off 10 min after the last climb. After a warm-up session, the participants had to climb the 10-m wall three times, with 5-min pauses in between, followed by a 20-min rest interval. Subsequently, the participants climbed the 15-m wall three times, equally with 5 min pauses in between. The stopwatch served for recording the split times at the beginning and end of each climb, in order to synchronize the climbing actions with the HR data. The accuracy of the data synchronization process was verified in the lab over 40 min, by switching on the Polar system and the stopwatch simultaneously, and at every full minute, the Polar sensor was put on the chest for 5 s.

Measurements of the HR with a Polar heart rate monitor (e.g., H7) are common in climbing, used, e.g., by Baláš et al. (2014) and Giles (2017). The Polar H7 was validated by Giles and Draper (2017), against three-lead ECG as a gold standard for correction methods of RR intervals. Gaynor et al. (2019) validated Fitbit Charge HR, Polar H7 heart rate sensor, and Masimo SET Rad-5v against a three-lead ECG during continuous and interval exercise. The Polar H7 heart rate sensor exhibited the highest accuracy with the ECG, with a bias of 0 ± 1 bpm (Bland–Altman method) during both exercises. Unsurprisingly, the H7 Polar belt was used as a gold standard in several studies, such as by Hernando et al. (2018), who validated the Apple Watch against the Polar H7; and by Schubert et al. (2018), who validated an optical heart rate sensor (Polar® OH1) against the Polar H7.

Data Processing

The HR raw data were synchronized to the stopwatch data, and the following parameters were determined:

(a) Climbing time from start to finish (unit: s); time data of unsuccessful climbs (slipping off the wall) were discarded;
(b) Climbing speed, i.e., climbing time per unit climbing height (unit: m/s);
(c) Peak HR (unit: bpm) related to each climb;
(d) Time to peak HR after each climb (unit: s);
(e) Rate of change in heart rate, i.e., the increase or decrease in the HR per unit time (unit: bpm/s), specifically average bpm/s for the ascent (phase c and 3, **Figure 2**) and descent (phase 5, **Figure 2**), and peak bpm/s for ascent;
(f) Increase in HR during the climb and after the climb until peak HR is reached;
(g) average HR (bpm) during the pauses, before the first climb, and after the last climb.

Statistics

From the data of the different parameters, the averages, standard deviation, minima, and maxima were determined for each of the

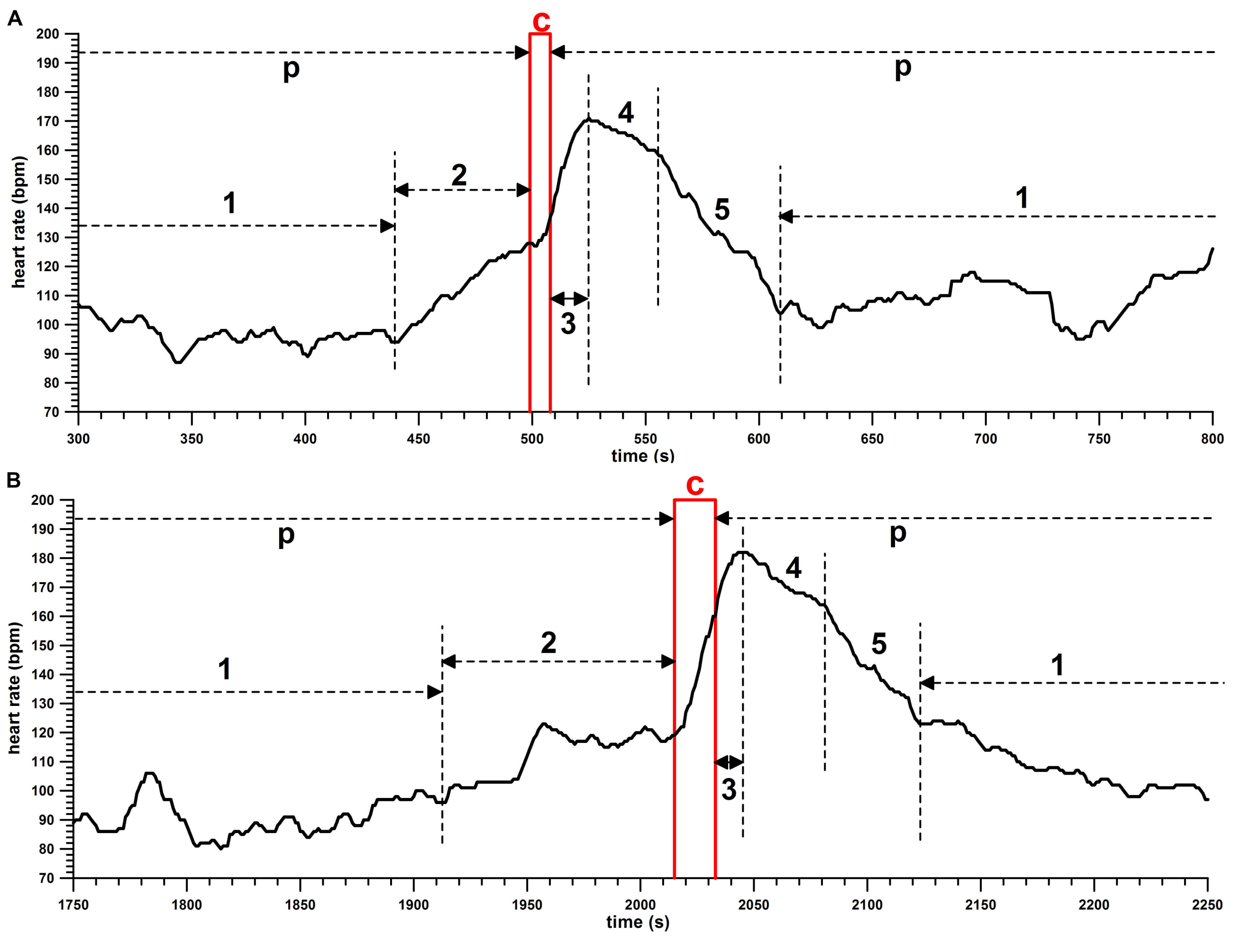

FIGURE 2 | Heart rate (HR; bpm) against time (s), samples of HR profiles of **(A)** 10-m and **(B)** 15-m climbs; p, pause; c, climb; 1, rest with low HR; 2, prestart activation immediately before the climb; 3, time to peak HR after the climb; 4, slowly decreasing HR after the peak; 5, fast decreasing HR.

six climbs across the seven participants, each climbing height, each pause, and each participant.

The averages were compared and significant differences detected ($p < 0.05$), by means of the following statistical tests:

(a) For comparison of averages of two correlated samples (complete datasets only), the Wilcoxon rank-sum test was used, as data specific to each climber had to be compared.
(b) For comparison of averages of two samples (incomplete datasets only), the Mann–Whitney *U* test was used, if data were missing (malfunction of the HR monitor; or unsuccessful climbs), which prevented the comparison of climber-specific data.
(c) For comparison of averages of more than two samples, such as the peak HR (six climbs) and the pause HR (seven pauses in total), the Friedman rank-sum test for multiple correlated samples (complete datasets) was used, followed by the Conover *post hoc* test, with *p*-values adjusted by the Holm familywise error rates (FWERs) and Benjamini–Hochberg false discovery rate (FDR) methods. A test for the correlated sample was selected, as data specific to each climber had to be compared.

RESULTS

Heart Rate Profiles

The HR profiles are shown in **Figures 2**, **3**.

In general, the HR during the pauses between the climbs is in most cases at the steady state (phase 1, **Figure 2**). Before the climb, the HR increases due to prestart activation immediately before the climb (phase 2, **Figure 2**). The prestart activation can be missing, as seen in the first and last climb in **Figure 3A**. The HR starts to increase at the beginning of the climb (c) and continues to rise after the climb until reaching a peak (phase 3, **Figure 2**). Subsequently, the HR decreases, in most cases with a flatter drop first (phase 4), followed by a steeper one (phase 5).

Figure 3 displays the HR profiles of all participants. Due to rapid and high-intensity movements of the arms and the shoulders, the HR monitor got detached from the skin, either

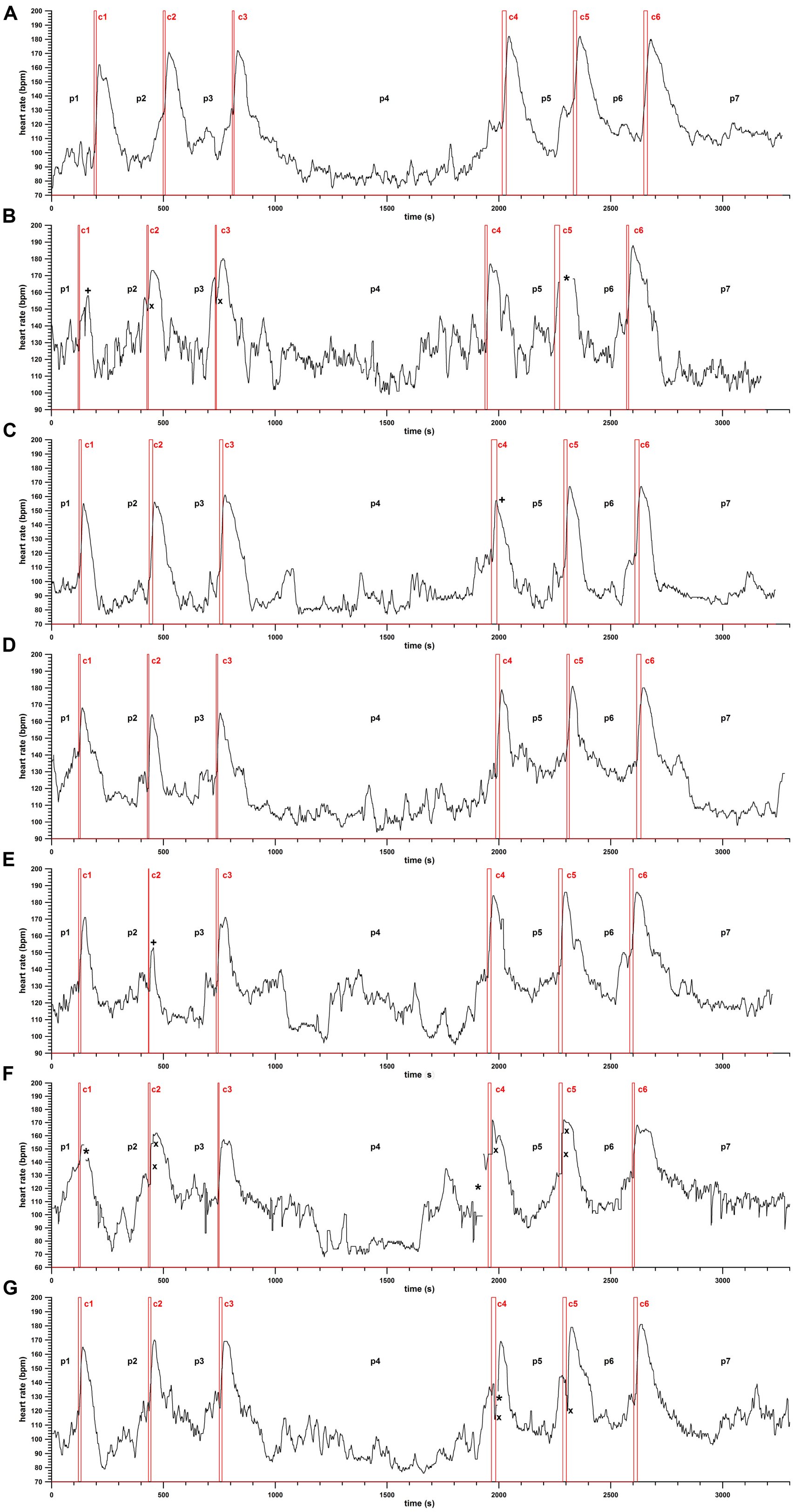

FIGURE 3 | Heart rate (HR; bpm) against time (s), HR profiles of climbers 1–7 (from top to bottom, **A–G**); c1–c6, the six climbs per participant (c1–c3 = 10 m, c4–c46 = 15 m); p1–p7, pauses between the climbs; *, lost data; ×, artifacts; +, unsuccessful climbs.

resulting in intermittent data loss or HR artifacts (sudden jumps over tens of beats per minute).

Climbing Time and Speed

The climbing times of the 10- and 15-m training runs were the following:

> 10 m: 9.16 ± 3.06 s (5–16 s), average climbing time of 9.16 s over 10 m corresponds to 1.092 m/s.
> 15 m: 14.95 ± 3.14 s (9–19 s), average climbing time of 14.95 over 15 m corresponds to 1.004 m/s.

Climbing speed of the 10- and 15-m training runs:

> 10 m: 1.209 ± 0.395 m/s (0.625–1.667 m/s);
> 15 m: 1.055 ± 0.264 m/s (0.789–1.500 m/s).

Although the average speed over 10 m seems faster, there was no significant difference between the two speed averages ($p = 0.1096$, Mann–Whitney test, $U = 173.5$). The reason why the two speed averages are different from the speed calculated from the two climbing time averages lies in the fact that the climbing speed is a reciprocal function of the climbing time and therefore non-linearly related to the climbing time.

Peak Heart Rate

The peak heart rate occurs only after the climbing ascent was completed. The statistical data of the peak heart rate are the following:

> 10 m: 164.57 ± 7.45 bpm (153–180 bpm);
> 15 m: 176.43 ± 8.09 bpm (157–188 bpm).

The difference between the two averages of the peak heart rate was highly significant ($p = 0.0001$; Wilcoxon signed-rank test, $W = -225$, $n_{s/r} = 21$, $z = -3.9$).

The individual averages (HR^{avg}) at each single consecutive climb seem to increase continuously: 10 m (10a,b,c): $HR^{avg}{}_{10a} = 161.17$ bpm, $HR^{avg}{}_{10b} = 164.14$ bpm, $HR^{avg}{}_{10c} = 167.86$ bpm; 15 m (15a,b,c): $HR^{avg}{}_{15a} = 174.29$, $HR^{avg}{}_{15b} = 176.43$ bpm, and $HR^{avg}{}_{15c} = 178.57$ bpm (**Figure 4A**).

In order to investigate this further, the Friedman rank sum test for the six correlated HR samples (10a,b,c and 15a,b,c) was significant ($p = 0.0004$), with *post hoc* tests delivering the following significantly ($p < 0.05$) different pairs ("<" and ">" denote a significant difference between two HR^{avg}; "=" denotes an insignificant difference): $HR^{avg}{}_{10a} < HR^{avg}{}_{15abc}$; $HR^{avg}{}_{10b} < HR^{avg}{}_{15abc}$; $HR^{avg}{}_{10c} < HR^{avg}{}_{15bc}$; $HR^{avg}{}_{10a} < HR^{avg}{}_{10c}$ (FDR method only). $HR^{avg}{}_{10c} = HR^{avg}{}_{15a}$, as these two climbs were consecutive ones, and also separated by the 20-min pause.

Time to Peak Heart Rate After Each Climbing Ascent

The time lag between the completion of the climb and the peak of the heart rate were as follows:

> 10 m: 12.95 ± 7.10 s (5—31 s);
> 15 m: 13.32 ± 4.04 s (8–22 s).

There was no significant difference between the two speed averages ($p = 0.3371$; Mann–Whitney test, $U = 224.5$).

Rate of Change in Heart Rate

The average HR "accelerations" (before reaching the peak HR) were as follows:

> 10 m: 2.44 ± 0.84 bpm/s (0.99–3.76 bpm/s);
> 15 m: 2.60 ± 0.77 bpm/s (1.67–4.22 bpm/s).

There was no significant difference between the two average rates of change ($p = 0.6241$; Mann–Whitney test, $U = 220$).

The peak HR "accelerations" (before reaching the peak HR) were as follows:

> 10 m: 4.24 ± 0.88 bpm/s (2.83–6.33 bpm/s);
> 15 m: 4.08 ± 1.26 bpm/s (2.33–6.67 bpm/s).

There was no significant difference between the two average rates of change ($p = 0.5687$; Mann–Whitney test, $U = 291$).

The average HR "decelerations" (after the peak HR) were as follows:

> 10 m: −0.99 ± 0.27 bpm/s (−1.51–0.54 bpm/s);
> 15 m: −0.96 ± 0.33 bpm/s (−1.66–0.49 bpm/s).

There was no significant difference between the two average rates of change ($p = 0.4473$; Mann–Whitney test, $U = 209$).

Increase in HR During and After Climb Before the Peak HR

HR increase during the climb:

> 10 m: 18.33 ± 13.20 bpm (−7–45);
> 15 m: 29.75 ± 9.38 bpm (10–41).

The difference between the two averages was significant (Mann–Whitney test, $p = 0.0093$, $U = 220$).

HR increase after the climb up to the peak HR:

> 10 m: 21.82 ± 9.96 bpm (0-37);
> 15 m: 18.36 ± 7.41 bpm (8–34).

The difference between the two averages was not significant (Mann–Whitney test, $p = 0.1096$, $U = 97$).

Comparing the HR increase during and after the climb:

> 10 m: not significant (Wilcoxon rank-sum test $p = 0.2187$, $W = -57$), as averages (18.33 and 21.82 bpm) are too close and therefore statistically similar;
> 15 m: significant (Wilcoxon rank-sum test $p = 0.0135$, $W = 96$), as averages (29.75 and 18.36 bpm) were different.

The reasons for these results are the following:

(1) If neither the average HR "deceleration" nor the average time to peak HR are not different on 10- and 15-m walls, then the HR increase after the climb is not expected to be different either;
(2) The climbing time on the 10-m wall is too short to have the HR increase during the climb exceed the HR increase after the climb.

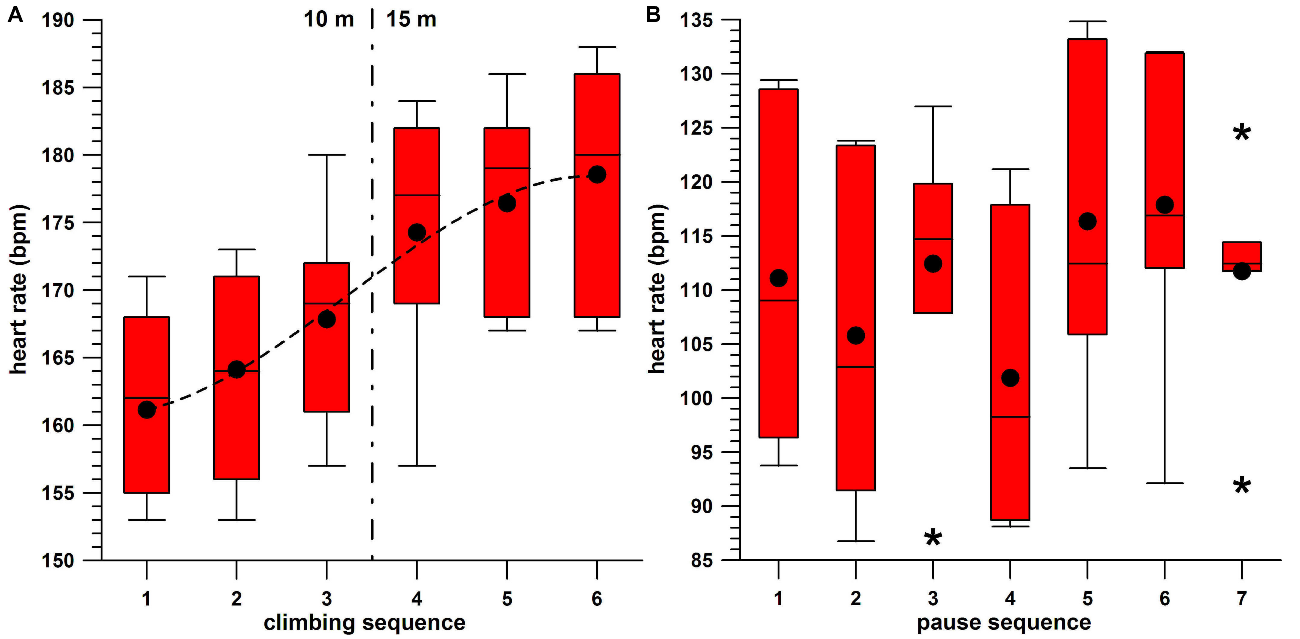

FIGURE 4 | (A) Peak heart rate against the sequence of the six climbs per participant, box-and-whisker plots, average (•), and cubic fit function (dashed line); **(B)** pause heart rate against the sequence of the seven pauses per participant, box-and-whisker plots, average (•), and outliers (*).

Pause Heart Rate

The heart rate data of the seven pauses (**Figure 4B**) are as follows:

p1: 111.12 ± 14.99 bpm (93.77–129.42);
p2: 105.80 ± 15.84 bpm (86.76–123.82);
p3: 112.43 ± 12.56 bpm (87.19–126.98);
p4: 101.87 ± 13.83 bpm (88.11–121.16);
p5: 116.36 ± 16.36 bpm (93.51–134.83);
p6: 117.89 ± 13.90 bpm (92.13–132.02);
p7: 111.73 ± 9.74 bpm (92.02–124.66).

Comparing the HR of the seven different pauses (p1–p7) with the Friedman rank sum test for seven correlated samples indicated significant differences ($p = 0.0028$).

The *post hoc* tests resulted in the following significantly ($p < 0.05$) different pairs.

The HR^{avg} of the long pause p4 ($HR^{avg}{}_{p4} = 101.87$), which was the lowest of all seven pauses, was different from the HR^{avg} of p1, p3, p5, p6, and p7 (p1, p3, and p7 in the FDR method only), but not from $HR^{avg}{}_{p2}$. $HR^{avg}{}_{p2}$ (105.8), the second lowest one, was different from the $HR^{avg}{}_{p5}$ and $HR^{avg}{}_{p6}$ (116.36 and 117.89), the two highest ones.

The difference between the two HR^{avg} of p2 + p3 combined (two pauses of 10 m, 109.12 bpm) and p5 + p6 (two pauses of 15 m, 117.12 bpm) was highly significant ($p = 0.003$; Wilcoxon signed-rank test, $W = -95$, $n_{s/r} = 14$, $z = -2.97$).

DISCUSSION

This paper describes, for the first time, the HR behavior and profiles during speed climbing. The limitations of this study were already outlined at the beginning of the Section "Methods," resulting in low numbers of participants and gender inequity. In terms of uneven gender distribution, a hypothetical difference in HR behavior between female and male participants could not be evaluated. However, Panissa et al. (2016) investigated the behavior of the HR during all-out high-intensity cycling and did not find a significant difference between 9 female and 10 male participants. Another limitation of our study was that maximum and baseline values of HR of the participants were not determined in a prestudy. This should be included in the protocol of further similar studies.

The main finding is that the HR increases, after climbing a 10- or 15-m wall, for another 13.13 ± 5.74 s (5–31 s). As the primary energy system for short (5–15 s) "all-out" full-body exertions is the ATP-PCr system, and as EPOC is engaged immediately after the climb, the increase in HR is expected to result entirely from the combined effect of psycho-physiological overload.

Another main finding of this research is the behavior of the HR acceleration and deceleration, which has been paid little attention in the literature.

Fisher et al. (1983) investigated "*the maximal rate of...tachycardia development...to distinguish accurately between sinus and ventricular tachycardia.*" Sinus tachycardia was induced in test persons who "*rushed up 100 stairs as rapidly as possible*," and found, during the first second of this exercise, that the rate of change in heart rate was 20 bpm/s on average. In contrast to this, Fisher et al. (1983) encountered a far higher rate of change in heart rate in spontaneous episodes of ventricular tachycardia, namely, 88 bpm/s on average. Twenty beats per minute per second within the first second seems excessively high; however, the test persons' lifestyle activity ranged from sedentary to limited regular physical activity. It was explained to them before the experiments that there is a necessity for sudden maximal effort, and they were encouraged to ascend two stairs with every step. Rushing up a flight of 100 stairs can be compared to speed climbing in terms of vertical movement, insofar as if the height of a stair is 0.2 m, then 100 stairs represent a height of 20 m. However, there is a difference between the participants of our study and the one of Fisher et al. (1983). Speed climbers have a slower start compared to running up a staircase, and our participants were near-elite speed climbers. In fact, in some climbs, we saw a slight decrease in the HR by a couple of beats per minute before the HR rose rapidly. The rate of change in heart rate (HR acceleration) we found was 2.5 bpm/s (average acceleration across the entire HR increase) and 4.2 bpm/s (average peak acceleration).

Knox (1940) used a tolerance test in medical students who were not in training ("*the subject rises to his feet, steps five times up and down two steps each ten inches high and then sits down again and relaxes*") to determine the "*acceleration of the heart rate in beats-per-minute per second.*" Knox (1940) obtained an average HR acceleration (from baseline to maximum HR) of 3.0 ± 0.9 bpm/s (1.4–5.3 bpm/s). It is surprising that "*in healthy young men performing a very light exercise*" (Knox, 1940) and without any psychological pressure, the average HR acceleration was as high as 3.0 bpm/s, whereas in near-elite speed climbers over an intense, maximal speed and high-power exercise, the average HR acceleration was only 2.5 bpm/s. The average peak HR of both cohorts was 130 bpm (Knox, 1940) and in speed climbing was 165–175 bpm (10 and 15 m, respectively). It can, therefore, be concluded that although an intense exercise in near-elite athletes elicits higher HR, their HR acceleration is nevertheless smaller than in untrained men performing a very light and unstressful exercise. Considering this, the 20 bpm/s found by Fisher et al. (1983) does not seem excessive. It can be hypothesized that the more trained the athletes are and the greater their experiences with accommodating psychological pressure, the slower their HR acceleration is.

Whether or not the 5-min pauses (IFSC Rule 9.14; International Federation of Sports Climbing [IFSC], 2019b) are appropriate between climbs of a speed climbing competition can be addressed in the following way.

Comparing the average HR of the pauses with the Friedman test including the *post hoc* tests delivers the following result. The longer pause (p4) exhibits less HR on average compared to the other six pauses. In addition to this, $HR^{avg}_{p1} > HR^{avg}_{p4}$ (FDR method only), and $HR^{avg}_{p5,6} = HR^{avg}_{p1}$. This means that HR^{avg} in the last 3 min before the first climb (and after warming up) is higher than HR^{avg} in the 20-min pause between the 10- and 15-m climbs. However, HR^{avg} of the two pauses p5 and p6 combined (between the three 15-m climbs) is statistically as high as the one of p1. Additionally, from **Figure 3A**, the HR reaches a steady state (constant signal amplitude, on average) in most of the pauses. From the average data, a 5-min pause seems to be sufficient. This statement is made since the HR after the climbs (in pauses p2–p7) were not significantly different from the average HR before the first climb (p1, which served as a baseline), except for the HR in p4, which was the long pause (20 min) after climb 3.

Addressing this problem from the worst-case scenario (longest possible HR recovery period), instead of from the average data, the following parameters (15-m climb only) have to be considered:

- Time to peak HR: 13.32 ± 4.04 s on average, with a range of 8–22 s;
- Average HR deceleration: −0.96 ± 0.33 bpm/s (−1.66–0.49);
- HR of pauses p5 + p6: 117.12 ± 14.60 bpm (92–135); and
- Peak HR: 176.43 ± 8.09 (157–188).

Out of these parameter ranges, the worst cases (for a prolonged HR recovery period) are 188 bpm peak HR, 22 s time to peak HR after the climb, and the HR drops from 188 to 92 bpm at a rate of −0.5 bpm/s. This drop lasts for 192 s, plus the 22 s time to peak HR results in 214 s or 3.57 min after the climb. This still leaves 1.4 min for a steady-state HR, which does not include the time for prestart activation. In light of this, it can be confidently stated that 5 min recovery time between the climbs is sufficient. This applies to the HR only and not to other physiological parameters. Yet, the limitation of this worst-case scenario is that the data were taken from training climbs. It is unknown whether these data are applicable to the competitions, with a higher level of psychological stress.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors to any qualified researcher, if they have obtained Ethics Approval for secondary use of existing data through a Consent Waiver.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Swinburne University Human Ethics Committee (approval no. 20191290-1680), Swinburne University, Hawthorn, VIC, Australia. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

FF, AT, SP, GN, and YW contributed equally to the design of the study, execution of the experiment, performing of data analyses, and writing and editing of the manuscript. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We would like to thank all the climbers participating in the speed climbing training study and the staff of the climbing gyms. Furthermore, we would like to thank the two reviewers for their invaluable comments and suggestions to improve the quality of the manuscript and for their engagement in discussing our revisions.

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Conflict of Interest: GN is employed by company Sportstättenverein Marswiese.

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.

frontiers in Psychology

ORIGINAL RESEARCH
published: 23 July 2020
doi: 10.3389/fpsyg.2020.01550

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Attentional Differences as a Function of Rock Climbing Performance

Inmaculada Garrido-Palomino[1], Simon Fryer[2], Dave Giles[3], Javier J. González-Rosa[4,5] and Vanesa España-Romero[1,5]*

[1] MOVE-IT Research Group, Department of Physical Education, Faculty of Education Sciences University of Cádiz, Cádiz, Spain, [2] School of Sport and Exercise, University of Gloucestershire, Gloucester, United Kingdom, [3] Lattice Training Ltd., Chesterfield, United Kingdom, [4] Neuroimaging and Psychophysiology Group, Department of Psychology, University of Cádiz, Cádiz, Spain, [5] Biomedical Research and Innovation Institute of Cádiz (INiBICA), Puerta del Mar University Hospital, Cádiz, Spain

OPEN ACCESS

Edited by:
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***Correspondence:**
Inmaculada Garrido-Palomino
inma.garridopa@alum.uca.es;
inmapsic@hotmail.com

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: 18 November 2019
Accepted: 10 June 2020
Published: 23 July 2020

Citation:
Garrido-Palomino I, Fryer S, Giles D, González-Rosa JJ and España-Romero V (2020) Attentional Differences as a Function of Rock Climbing Performance. Front. Psychol. 11:1550. doi: 10.3389/fpsyg.2020.01550

The purpose of this study was to investigate the relationship between attention (using two different attention tasks) and self-reported climbing ability while considering potential confounding factors (sex, age, climbing experience, and cardiorespiratory fitness) in a group of experienced climbers. Accuracy of response (AC) and reaction time (RT) from two different attention tasks using the Vienna Test System, along with self-reported on-sight and red-point climbing ability, were assessed in 35 climbers. Linear regression revealed that climbers with the highest self-reported on-sight grade had better AC during the attention task. Linear regression models revealed, after controlling for potential confounders, that AC, measured using two attention tasks, was positively related to climbers' highest self-reported on-sight climbing ability ($\beta = 0.388$; $p = 0.031$). No significant differences were found between AC and self-reported red-point climbing ability ($\beta = 0.286$; $p = 0.064$). No significant relationship was found between RT and climbing ability ($\beta = -0.102$ to 0.020; $p = 0.064$). In conclusion, higher-level rock climbers appear to have an enhanced attention, which is related to on-sight lead climbing style, and thus, it may be an important component of climbing performance. Coaches should consider incorporating techniques to train attention based on on-sight climbing style in climbers.

Keywords: attention, climbing ability, physical condition, performance, on sight, red point, selective attention

INTRODUCTION

Attention is a central feature of all perceptual and cognitive functioning (Chun et al., 2011), which allows for the selection and processing of information (Kahneman, 1973; Lavie, 2005). Attention is composed of three distinct networks which are responsible for controlling different attentional functions; they are orienting, alerting, and executive control (Posner, 2017). Orienting is primarily responsible for the ability to prioritize sensory input by selecting a modality. Alerting serves to produce and maintain optimal levels of arousal and performance, a necessary prerequisite for other attention functions (Peterson and Posner, 2012). Finally, executive control is responsible for directing attention to relevant and useful information, away from irrelevant information, and also for inhibiting extraneous stimuli (Roderer et al., 2012). Collectively, these systems can be overloaded when individuals attempt to multitask and divide their attentional capacity between selecting information and deciding on action strategies. Consequently, it is unsurprising that in sports, attention appears to be related to sport practice (Kioumourtzoglou et al., 1998;

Williams and Davids, 1998; Heppe et al., 2016; Sanchez-Lopez et al., 2016; Qiu et al., 2018; Meng et al., 2019). This has been shown to be the case in sports such as martial arts (Sanchez-Lopez et al., 2016), basketball (Qiu et al., 2018), soccer (Heppe et al., 2016), and volleyball (Kioumourtzoglou et al., 1998). However, the differences in attention responses seem to depend on the influence of a variety of information processing demands associated with each sport's modality (Singer, 2000; Voss et al., 2010).

Specifically, in climbing, several authors have studied attention and climbing performance (Bourdin et al., 1998; Nieuwenhuys et al., 2008; Green and Helton, 2011; Young, 2011; Green et al., 2014). It has been suggested that climbing performance could be associated with attentional control (Young, 2011), which is associated with postural control and climbing route difficulty (Bourdin et al., 1998). Young (2011) demonstrated that while ascending, climbers who were distracted (via cognitive interference) by a task that necessitated a heightened degree of attention performed significantly worse (i.e., in terms of increased climbing time) than non-distracted climbers. Similarly, the effect of attentional interference on climbing performance was demonstrated by Green and Helton (2011). The authors suggested that when climbers use their attentional resources in a task other than climbing (i.e., a memory task), climbing efficiency and distance ascended decreased. It has also been shown that attentional demands increase with the difficulty of a climbing task, which further affects climbing efficiency (Bourdin et al., 1998). Despite the literature describing the influence of attention on different aspects of climbing performance, to date, data investigating the relationship between attention and climbing performance remain limited. Given the psychophysiological demands of rock climbing ability (Giles et al., 2014) which encompass physical and tactical elements combined with complex psychological traits such as a high self-confidence and low trait anxiety (Aras and Ewert, 2016), this lack of research seems unusual.

As rock climbing ability has previously been associated with a high cardiorespiratory fitness (CRF) (Aras and Ewert, 2016) and this is known to be related to attention (Colcombe and Kramer, 2003; Kramer and Colcombe, 2018), it may be that CRF also has some influence on climbers' attentional performance. Greater CRF appears to be associated with a better cognitive function, which is related to an increased ability of the heart to deliver oxygenated blood to cerebral structures (Colcombe and Kramer, 2003), cerebral blood flow (Brown et al., 2010), and a brain-derived neurotrophic factor (Vaynman et al., 2003). Luque-Casado et al. (2016) suggested that there is likely to be a relationship between CRF and sustained attention in sports performance. Those authors observed that cyclists and triathletes with higher CRF had shorter reaction times (RTs) than those with a lower CRF during a sustained attention task. Further, it has also been proposed that nonathletes with a high CRF may have a better ability to allocate attentional resources over time compared to nonathletes with a low CRF during a sustained attention task (Ciria et al., 2017). Further, Sanabria et al. (2019) speculated that the relationship between CRF and sustained attention may be dependent on the type of sport being conducted. Given that rock climbing has been shown to independently have both a high CRF (Fryer et al., 2017) and a high attention demand (Bourdin et al., 1998; Green and Helton, 2011), CRF may be a physiological mediator that could at least in part explain on-sight and red-point ability. To our knowledge, the relationship between ability level (on-sight and red-point), CRF, and attention in rock climbers has not yet been studied. Therefore, the main purpose of the present study was to investigate the relationship between attention (using two different attention tasks) and self-reported climbing ability, taking into account potential confounding factors (sex, age, climbing experience, and CRF) in a group of experienced climbers.

MATERIALS AND METHODS

Participants

Thirty-five sports climbers (10 women), mean age 34.7 ± 6.2 years, volunteered to take part in the study. All participants were healthy, were nonsmokers, and were not taking any vascular acting medication. Participants were asked not to consume food for 4 h prior to testing and to avoid caffeine and exercise for a minimum of 12 h. All testing sessions were conducted in the same week, in an environmentally controlled exercise laboratory. Participants read and signed the informed consent prior to participation in the study. The study protocol was approved by the Institutional Review Committee for Research Involving Human Subjects prior to recruitment; data collection was performed in accordance with the ethical standards set by the journal and the Declaration of Helsinki. Data from this study come from the High-Performance International Rock-Climbing Research Group (C-HIPPER).

Procedure, Apparatus, and Materials

Participants visited the laboratory once. During the visit, each participant completed forms for the determination of informed consent, health history, and demographic data. Detailed information on climbing experience (years), frequency (days per week), and self-reported rock climbing ability were recorded. Two attention tasks (Signal Detection and Determination Tasks) were administered (counterbalanced) with a 30-min break between each, using a laptop (15 in., 1,366 × 768 color screen) running the Vienna Test System software version 26.04 (Schuhfried, Austria). In addition, participants completed an incremental treadmill cardiorespiratory exercise test to determine CRF.

Self-Reported Climbing Ability

Rock climbing ability is most commonly expressed in terms of the best ascent of a route within the last 6–12 months. Routes are ascended as either on-sight (no prior knowledge or visual route inspection requiring a screening to find new holds) or red-point (pre-practiced where the athlete remembers the location of each hold and the movement required). Climbing ability was reported as the best grade achieved 6 months prior to the study. Self-report has been used for on-sight and red-point performance extensively within the literature (Baláš et al., 2017;

Fryer et al., 2017; Zarattini et al., 2018). It has been shown to be a valid assessment of on-sight ability level (Draper et al., 2011a). Climbers had a best 6-month on-sight ability ranging from 6a+ to 8a+ and from 6b to 8b+ for the best 6-month red-point ability based on the French grading system. In brief, this system is based on a scale of integers ranging from 4 (very easy) upward to 9 (very difficult) with letter subdivisions of a, a+, b, b+, c, and c+ from 6a to upward. In accordance with the Position Statement by the International Rock Climbing Research Association (IRCRA; Draper et al., 2016), performance grades were converted from French Sport to specific numerical values (IRCRA grades) to enable calculations and statistical analyses. The IRCRA scale ranges between 1 (very easy) and 32 (very difficult), for reporting climber ability (Draper et al., 2011a, 2016). Climbers had a best 6-month on-sight ability ranging from 12 to 24 and red-point from 13 to 26 based on the IRCRA scale (see **Table 1**).

Attention Tasks

Signal Detection Task

The Signal Detection Task (SIGNAL, 26.04 versions, Vienna Test System) was used to evaluate the accuracy of participants' response (AC) to a visual scanning and selective attention (Chong and Ong, 2015). This task was characterized by the presentation of an infrequent and unexpected target among frequent nontarget stimuli (distractors) for a relatively long period of time, requiring participants to be precise in order to detect the objective stimulus between the distractors. Specifically, during the SIGNAL task, white dots pseudorandomly disappear and appear on a black background. Participants were instructed to press the indicated key with the index finger of their dominant hand each time they detected a programmed stimulus constellation, created by four points that formed a square (see **Figure 1** for an illustration of technical terms). Climbers used headphones while performing the tasks to reduce distraction because of background noise.

The SIGNAL task had a total duration of 840 s (including the instruction and practice phases). The main practice phase had 1,000 point changes with a total of 60 stimulus constellations, this task being only trial. The number of correct responses on time as a measure of AC in the execution of the task was collected in the percentage for the final analysis.

TABLE 1 | Mean (SD) of the anthropometric, demographic, physical fitness, and performance data in the care tasks of the participants of this study.

	All (n = 35)	Male (n = 25)	Female (n = 10)
Age (years)	34.7 (6.2)	33.5 (6.5)	37.9 (4.2)*
Mass (kg)	64.5 (8.6)	68.3 (6.7)	55.2 (5)$^+$
Height (cm)	171.5 (8.0)	173.7 (8.0)	166 (4.9)$^+$
Experience (years)	11.1 (7.0)	11.5 (7.6)	10.1 (5.7)
Self-reported climbing ability			
Best 6-month on-sight grade (French)	7a (3.0)	7a$^+$ (2.9)	6b$^+$ (1.6)*
Best 6-month red-point grade (French)	7a+ (3.6)	7b (3.7)	6c$^+$ (1.6)*
Treadmill measures			
Cardiorespiratory fitness (ml · kg · min^{-1})	48.6 (5.3)	50.7 (4.9)	45.1 (4.6)*
Heart rate (bpm)	186.4 (10.5)	188.0 (10.9)	182.6 (8.9)

*$p < 0.05$; $^+p < 0.001$.

Determination Task

A modified version of the S12 Determination Task (DT, 32.00 version, Vienna Test Systems) was used to measure the speed of motor response, also called RT (Chong and Ong, 2015). This task was characterized by different temporal uncertainties of stimulus presentations. Specifically, the DT displayed 10 black-bordered white squares on a white background, arrayed in two horizontal rows of five. Each trial consisted of a square being temporarily filled with one of five different colors, namely, black, blue, green, yellow, or red, which appeared in one of 10 different locations (five in an upper row and five in a lower row). Participants were required to quickly press the corresponding colored button, using the dominant hand, to score a correct answer (see **Figure 2** for an illustration of appearance terms).

Regardless of the speed of participant response, the colored square would remain constant for 1,250 ms before being superseded by the next trial, with a different random square now colored and another participant response required. The DT had a total duration of 950 s (including the familiarization and instruction phases). Familiarization phases were 300 s long and consisted of 20 stimuli. The instruction phase with a duration of 650 s consisted of three different trials with a total of 540 stimuli (79 white, 74 yellow, 78 red, 78 green, and 74 blue). Each trial had 180 stimuli with durations of 1,582, 948, and 1,078 ms for the first, second, and third trials, respectively. The same random sequence of stimulus presentation was used for all participants. Speed response as a measure of RT in the execution of the task (ms) was collected from each condition for final data analysis.

Cardiorespiratory Fitness

Cardiorespiratory fitness was assessed by an incremental treadmill cardiorespiratory exercise test using the athlete-led protocol (Draper and Marshall, 2014). Oxygen uptake was measured using a portable breath-by-breath expired air analyzer (K4b^{2}Cosmed, Rome, Italy) weighing 1.5 kg. Data were transferred continuously via telemetry to a portable laptop. Breath-by-breath data were recorded continuously before, during, and after 5 min of running. Breath-by-breath data were averaged over 10-s intervals and exported to Excel and STATA for final data analysis. Heart rate and time to exhaustion were also collected.

Statistical Analyses

All data were found to be normally distributed by Shapiro–Wilk and had equal variances. Participant characteristics are presented as mean and standard deviation (SD) for continuous variables and frequencies for categorical variables. Potential sex differences for each dependent variable were analyzed by t-test for continuous variables and chi-square tests for categorical variables. Pearson correlations were used to examine the relationship between attention tasks and descriptive climbing parameters. The Mallow Cp (Mallows, 1973) statistic regression model was used to find the optimum descriptive variables for the forecasting of attention tasks and climbing ability. Linear

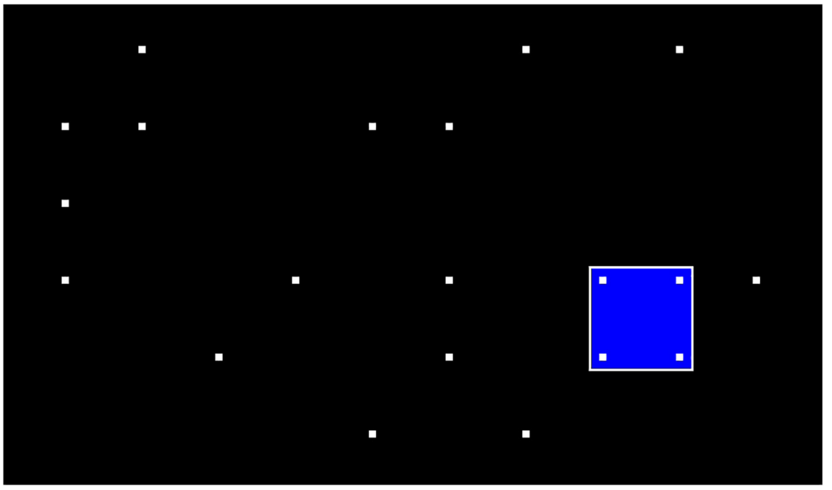

FIGURE 1 | Signal detection task from vienna test system.

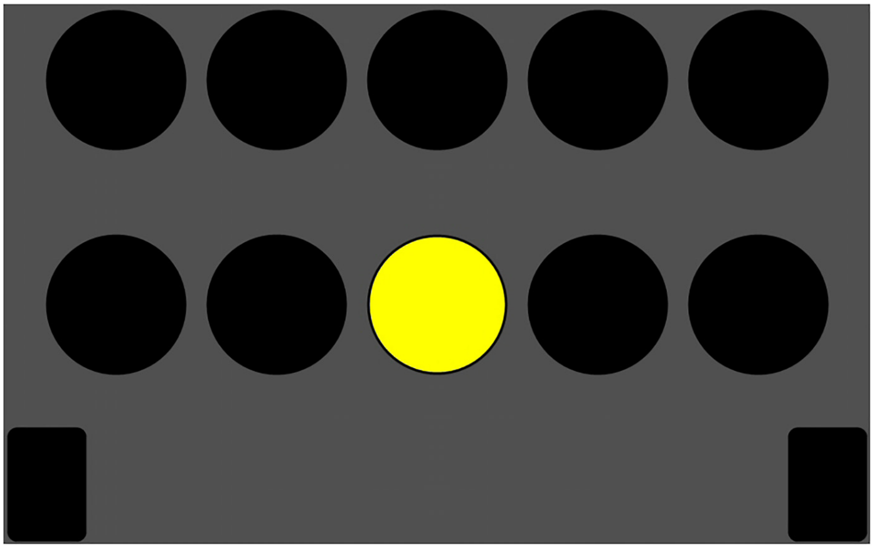

FIGURE 2 | Detection task (modified version) from vienna test system.

regression was performed to examine the association between climbing ability (on-sight or red-point) and attention task (AC or RT). In addition to the performance, covariates were included in the regression analyses. Specifically, three levels of adjustment were used: Model 1, unadjusted; Model 2, adjusted for sex, age, and climbing experience (years climbing); and Model 3, adjusted for sex, age, climbing experience (years climbing), and CRF (Cp Mallow: 3.38). Collinearity among the exposures was checked, and multicollinearity was not found in any of the models used. For all, the variance inflation factor was below 10, and the averaged variance inflation factor was close to 1 (Myers, 1990). It is important to highlight that two of the participants (both male) were excluded from just the RT (not AC) analyses because they were color blind. Statistical analyses were performed using STATA version 14.0 (Stata Corp, College Station, TX, United States). Statistical significance was set at $p < 0.05$.

RESULTS

Participant characteristics are shown in **Table 1**. Males were younger, heavier, and taller than females ($p < 0.05$). Moreover, males had a higher on-sight and red-point climbing ability with a greater CRF compared to females ($p < 0.001$ in all cases). Mean climbing experience was similar in both sexes.

Mean AC and RT measures in the attention tasks for all participants are presented in **Table 2**. No significant differences were found between male and female participants for any attention tasks, i.e., SIGNAL and DT.

The relationship between AC and self-reported on-sight climbing ability is shown in **Table 3**. Full linear regression model analysis revealed that AC (measured by SIGNAL detection task), was positively related with the highest self-reported on-sight ability (β = 0.388; p = 0.031). However, there was no significant relationship between AC and self-reported red-point ability (β = 0.286; p = 0.064) (see **Table 4**).

The relationship between RT and self-reported on-sight and red-point ability is presented in **Tables 5**, **6**. Linear regression analysis revealed that there were no significant relationships between RT and self-reported on-sight (β = −0.102 to 0.020; p = 0.304 to 0.680) or red-point ability (β = −0.089 to 0.007; p = 0.306 to 0.893).

DISCUSSION

The current study is the first to assess the relationship between attention and self-reported climbing ability (on-sight and red-point) in rock climbers. Further, it is the first to assess how potential confounding factors may affect the predictive attention functioning. The results suggested that attention is significantly related to on-sight but not red-point climbing ability.

Greater levels of attention in higher-ability climbers suggest two possibilities. First, there is a degree of self-selection, with the higher-ability climbers' performance occurring because of naturally greater levels of attention. Second, and more likely, is that higher-ability climbers develop better attention, through repeated practice of the climbing task that requires them to detect the hand and footholds when they climb on-sight, as suggested by the "cognitive abilities hypothesis." This hypothesis focuses on the direct relationship between sport practice and the cognitive abilities which could be associated with the interaction between the athlete and their specialized environment (Singer, 2000; Mann et al., 2007). The hypothesis suggests that if volitional and repeated practice is the driving force behind mechanisms of brain plasticity (Debarnot et al., 2014), then sport type may be

TABLE 2 | Mean (SD) attention tasks [accuracy of response (AC) and reaction time (RT)] for all participants and by sex.

	All (n = 35)	Male (n = 25)	Female (n = 10)
Accuracy of response (%)	87.6(6.1)	88.8(5.7)	84.8(6.1)
Reaction time (ms)[a]			
Trial 1	673.03 (50.59)	669.13 (56.4)	682 (34.58)
Trial 2	657.88 (48.07)	650.87 (49.99)	674 (41.15)
Trial 3	665.15 (46.65)	660 (46.71)	677 (46.68)
Total	665.8 (43.6)	660 (46.8)	679 (33.5)

[a]*Two daltonic participant were excluded from reaction time analyses, n = 33 (23 males).*

TABLE 3 | Relationship between accuracy of response (AC; dependent variable) and self-reported on-sight climbing ability (independent variable) in 35 experienced climbers.

	β	p	R^2	R^2 adj
Model 1	0.371	***0.028***	0.134	0.112
Model 2	0.278	*0.161*	0.191	0.083
Model 3	0.388	***0.031***	0.343	0.225

Model 1: unadjusted; Model 2: sex, age, and climbing experience (years); Model 3: sex, age, climbing experience (years), and $\dot{V}O_{2max}$. β, beta, regression equation; LCI, lower confidence interval (95%); UCI, upper confidence interval (95%).

TABLE 4 | Relationship between accuracy of response (AC, dependent variable) and self-reported red-point climbing ability (independent variable) in 35 experienced climbers.

	β	p	R^2	R^2 adj
Model 1	0.308	*0.072*	0.095	0.067
Model 2	0.170	*0.182*	0.160	0.047
Model 3	0.286	*0.064*	0.298	0.172

Model 1: unadjusted; Model 2: sex, age, and climbing experience (years); Model 3: sex, age, climbing experience (years), and $\dot{V}O_{2max}$. β, beta, regression equation.

TABLE 5 | Relationship between reaction time (RT; dependent variable) and self-reported on-sight climbing ability (independent variable) in 33 experienced climbers.

RT	β	p	R^2	R^2 adj
Model 1				
Trial 1	−0.086	*0.632*	0.008	−0.025
Trial 2	−0.075	*0.680*	0.006	−0.027
Trial 3	−0.102	*0.570*	0.011	−0.021
Model 2				
Trial 1	−0.033	*0.304*	0.154	0.033
Trial 2	0.015	*0.388*	0.133	0.009
Trial 3	−0.033	*0.519*	0.106	−0.022
Model 3				
Trial 1	−0.029	*0.442*	0.155	−0.002
Trial 2	0.020	*0.535*	0.134	−0.026
Trial 3	−0.024	*0.645*	0.111	−0.053

Model 1: unadjusted; Model 2: sex, age, and climbing experience (years); Model 3: age, climbing experience (years), and VO_{2max}; β, beta, regression equation; RT: reaction time.

TABLE 6 | Relationship between reaction time (RT; dependent variable) and self-reported red-point climbing ability (independent variable) in 33 experienced climbers.

	β	p	R^2	R^2 adj
Model 1				
Trial 1	−0.024	*0.893*	0.001	−0.032
Trial 2	−0.051	*0.780*	0.003	−0.030
Trial 3	−0.089	*0.621*	0.008	−0.024
Model 2				
Trial 1	−0.017	*0.306*	0.153	0.032
Trial 2	0.007	*0.389*	0.133	0.009
Trial 3	−0.066	*0.506*	0.108	−0.019
Model 3				
Trial 1	−0.010	*0.444*	0.155	−0.003
Trial 2	0.014	*0.536*	0.134	−0.026
Trial 3	−0.052	*0.637*	*0.113*	−0.051

Model 1: unadjusted; Model 2: sex, age, and climbing experience (years); Model 3: sex, age, climbing experience (years), and VO_{2max}; β, beta, regression equation.

also a potential moderator of the sport–cognition relationship (Fetz, 2007; Voss et al., 2010). As such, different sports appear to have different influences on cognitive functioning. For instance, Lum et al. (2002) observed that athletes from externally paced sports (i.e., soccer) were better at voluntarily orienting attention to locations where useful information was, whereas athletes from self-paced sports (i.e., swimming) and/or nonathletes were not as good at voluntary orienting attention. This may in part explain why dynamic sports place a high premium on voluntary allocation of spatial attention. Kioumourtzoglou et al. (1998) analyzed perceptual speed, prediction, selective attention, decision making, focused attention, estimation of speed and direction of a moving object, visual RT, and spatial orientation between experts and novice basketball, volleyball, and water polo players. The authors found that expert basketball players had better selective attention compared to novices. In addition, expert volleyball players had better focused attention, prediction, and estimation of speed and direction of a moving object compared to novices. Lastly, water polo players had significantly better decision making, visual RT, and spatial orientation than novices. As such, in the current study, the "cognitive abilities hypothesis" may in part explain why a better attention in higher-level climbers could be associated with the characteristics of a difficult route (i.e., small holds are more difficult to find).

Analyses, shown in **Tables 5**, **6**, revealed that there was no relationship between RT and either on-sight or red-point ability. The absence of a relationship between RT and ability, together with the differences found in AC, is consistent with the findings of Wang et al. (2013). Here, the authors suggest that differences in the execution of tasks and attention may be found depending on the nature of the sport, i.e., whether it is self-paced or externally paced. The absence of differences in RT measures between ability groups could indicate the type of perceptual–cognitive abilities required when climbing. The self-paced nature of climbing means that the athletes' performance is less influenced by temporal pressure and more by the AC. However, it is also possible that an expert performance would be characterized by a more strategic and adapted allocation of the attentional resources (Bourdin et al., 1998). Future research should investigate this using a sample encompassing athletes with a range of different abilities from a variety of sports. This would help to clarify the potential differences between ability levels and types of sport (self-paced vs. externally paced).

Previous research investigating the relationship between fitness and performance in attention tasks (Luque-Casado et al., 2016; Ciria et al., 2017) suggested that CRF was an important mediator. However, our results do not support such a relationship. This divergent finding may be because previous research used different attention tasks and has compared sedentary participants with trained athletes, whereas the present study used only trained athletes albeit with different ability levels. In addition, the importance of CRF and attention has been investigated in sports where CRF is the primary factor for performance, such as triathlon and cycling. However, our data provide evidence in favor of the "hypothesis of cognitive abilities" associated with the interaction between the athlete and their specialized environment (Singer, 2000).

Climbing is a sport that demands attention to progress along the path without falls or failures and without attending to factors external to the task (e.g., risk to fall) which could affect performance. These performance advantages in AC on the attention task could explain why better climbers are less affected by anxiety when on-sight climbing, as previously reported by Draper et al. (2011b), particularly given that anxiety results in part from the failure of the attention network (Ghassemzadeh et al., 2019). As such, the stronger relationship between attention and on-sight climbing ability could also be explained by the absence of anxiety seen in advanced climbers (Fryer et al., 2013), and thus, they may have an enhanced ability to focus on the physical movements. One possible explanation for this difference in the AC in the attention task could be the general training of climbers, since during climbing, long periods of attention (i.e., monitoring) are required for good performance (Bourdin et al., 1998). As suggested by Pijpers et al. (2006), emotional state (anxiety) affects the attentional control and realization of affordances, but the inverse may be also possible. In this sense, we hypothesized that climbers with better attention would be less affected by the negative effect of anxiety, by focusing only on the relevant aspects of a climbing task such as the hold type or foot placement.

The current study did not reveal any relationships between attention and red-point climbing ability. This finding is likely explained by the different characteristics between red-point and on-sight types of climbing. While on-sight climbing requires visual inspection of the route to look for the best/next hold to keep ascending, a red-point ascent is defined by a climber's previous knowledge of the route, its holds, and the movement sequences required; thus, the attentional demands of the red-point style are likely lower. The current study supports the idea that on-sight climbing requires greater attentional demand compared to red-point climbing, and this may contribute to the development of better attention. This is an important finding that may indicate that the on-sight climbing style could have a considerable positive learning effect on attention, which could be an important component of competitive climbing performance. However, further research is needed to assess if this learning effect exists and whether it can be trained. As such, coaches and trainers should consider including strategies based on practicing on-sight climbing styles instead of the red-point climbing style.

The findings of the current study may help explain why better climbers are less affected by anxiety during an on-sight ascent as seen in previous studies (e.g., Draper et al., 2011b). Further, greater attention accuracy in better climbers could imply a better climbing efficiency or perceptual motor performance (efficient exploration and decrease in the number of typical exploratory movements) (Orth et al., 2017). This could be very important for competitive climbing, given that international competitions use on-sight climbing and a grade of 0.4 (IRCRA) separated the top four competitors in the 2015 International Federation Sport Climbing World Cup (Fryer et al., 2016). We have reported a larger association than a grade between attention and on-sight climbing ability. This is another key finding that could suggest that attention or attentional demands may be important aspects of competitive rock climbing performance. However, the small R^2 (0.14 and 0.32) still supports the concept that climbing performance is a multifactorial sport. As such, there are likely to be other cognitive skills (working memory, inhibitory control, cognitive flexibility, reasoning, etc.) or attentional functions (alert, orienting, or executive control) (Roca et al., 2018) that might explain large percentages of variance that we have not measured in the current study. However, our finding is still important given that at the top level in climbing, marginal gains are key to success.

While this research has presented important and unique findings, to fully contextualize the data, several limitations should be acknowledged. We performed power analyses on the multiple regression models presented in this study. For a level of significance of 0.05, with the current sample size, taking into account the R^2 of all the covariates in the model and the number of covariates, we observed a power of 64.9–84.8% for the main models. The experimental design allows us to reveal how the variables are related, but it does not allow us to detect possible cause–effect relationships. In addition, this study does not allow us to determine whether there are any differences between climbers and non-climbers. Given these points, future research should (1) increase the sample size, (2) conduct an intervention to confirm whether improving the ability of a climber actually improves execution in attention or even knowing whether climber with better attention is less affected by anxiety, and finally (3) study possible differences in attention as a consequence of climbing training between climbers and non-climbers.

CONCLUSION

In summary, our results suggest that after controlling for potential confounding factors (sex, age, climbing experience, and CRF), attention measured objectively is positively related to on-sight, but not red-point, climbing ability. This may be explained by the different ascent characteristics; in particular, the greater attentional demands of on-sight lead climbing may be due to the lack of information regarding the route. The lack of association between RT and climbing performance may be due to the self-paced nature of the sport, as little external temporal demand is placed on the athlete. Rock climbers and their coaches should consider attentional training for on-sight climbing performance in order to increase or maintain climbing ability.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/supplementary material.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comité de Ética para la Experimentación Biomédica y de Evaluación de Experimentación con Organismos Modificados Genéticamente (CEED/OMGs) from Cadiz University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

IG-P wrote the first draft of the manuscript. VE-R performed the statistical analyses and together to SF and DG conceived and designed the study and contributed to manuscript development and writing until manuscript was submitted in its final version. JG-R has contributed to the reading and suggestions of the final version.

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Conflict of Interest: DG was employed by Lattice Training Ltd. while working on this manuscript.

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.

frontiers in Sports and Active Living

ORIGINAL RESEARCH
published: 24 July 2020
doi: 10.3389/fspor.2020.00086

Prevalence of Disordered Eating Among International Sport Lead Rock Climbers

Lanae M. Joubert [1*], ***Gina Blunt Gonzalez*** [2] ***and Abigail J. Larson*** [3]

[1] Exercise Science Laboratory, School of Health and Human Performance, Northern Michigan University, Marquette, MI, United States, [2] Exercise Science Laboratory, Department of Kinesiology, Health and Imaging Sciences, Morehead State University, Morehead, KY, United States, [3] Exercise Science Laboratory, Department of Kinesiology and Outdoor Recreation, Southern Utah University, Cedar City, UT, United States

OPEN ACCESS

Edited by:
Jiri Balas, Charles University, Czechia

Reviewed by:
Jennifer Cumming, University of Birmingham, United Kingdom
Libor Vitek, Charles University, Czechia

***Correspondence:**
Lanae M. Joubert
ljoubert@nmu.edu

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Sports and Active Living

Received: *02 December 2019*
Accepted: *03 June 2020*
Published: *24 July 2020*

Citation:
Joubert LM, Gonzalez GB and Larson AJ (2020) Prevalence of Disordered Eating Among International Sport Lead Rock Climbers. Front. Sports Act. Living 2:86. doi: 10.3389/fspor.2020.00086

Disordered eating (DE) is characterized as a range of irregular eating patterns or behaviors, which may lead to pathological eating or a clinical eating disorder diagnosis. DE patterns are associated with a variety of negative health outcomes. The prevalence of DE is highest in female athletes who participate in aesthetic or weight dependent sports. Elite rock climbers tend to be strong, small and lean, but the prevalence of DE in rock climbers is unknown. The purpose of the present study was to assess DE prevalence in a large group of international rock climbers and to explore the relationship between sport rock climbing ability and DE. A web-based survey assessed both DE (Eating Attitudes Test-26) and climbing ability based on the International Rock Climbing Research Association's position statement on comparative grading scales. The survey was distributed to international climbing communities; 810 individuals attempted the survey; 604 completed all questions; 498 identified as sport lead climbers. The majority of sport lead climbers were lower grade/intermediate (57.8%), compared to advanced (30.7%) and elite/higher elite (11.4%), and male (76.9%). Forty-three sport lead climbers reported a score of 20 or above on the EAT-26 indicating an 8.6% prevalence of DE in this sample. Male climbers had a DE prevalence of 6.3% (24 of 383) and female climbers more than doubled that with 16.5% (19 of 115). Chi-square analysis revealed that DE was associated with climbing ability level [$\chi 2$ (2, $n = 498$, 8.076, $p = 0.02$)], and when analyzed by sex, only the female climbers had a significant relationship of DE with climbing ability [$\chi 2$ (2, $n = 115$, 15.640, $p = 0.00$)]. These findings suggest sport lead rock climbers are not immune to DE and that the risk is elevated in female climbers, particularly at the elite/high elite climbing ability level. Our research indicates further investigations are warranted to determine if and how disordered eating behaviors affect health and performance of adult rock climbers.

Keywords: rock climbing, eating attitudes, eating behavior, sport performance, sex differences, nutrition

INTRODUCTION

Early research by Black and Burckes-Miller (1988) postulated that, due to the unique pressures associated with sport participation (e.g., athletic performances, coaches' expectations, sporting environment, and subculture), athletes may be more prone to engage in disordered eating (DE) and unwise weight management techniques, which may lead to eating disorders (EDs). Nearly 15 years later, research by Sundgot-Borgen and Torstveit (2004) provided evidence supporting these hypotheses. In their large, well-conducted study among Norwegian elite athletes ($n = 1,259$) and controls ($n = 1,203$), they concluded that the prevalence of EDs was higher in elite athletes (13.5%) compared to controls (4.6%). In addition, EDs were higher in female athletes (20.1%) than in male athletes (7.7%). Incidence of EDs was also found to vary between sporting categories; among female athletes, those who competed in aesthetic sports (e.g., gymnastics) had the highest incidence (42%), while among male athletes those who competed in antigravitational sports (e.g., high jump, long jump, and triple jump) had the highest incidence (22%). Athletes who competed in technical and ball game sports had a lower incidence of EDs when compared to athletes of the same sex who competed in leanness-dependent and weight-dependent sports; however, incidence was still higher than in the general population. Given these figures and the consequences of DE and EDs on physical and mental health as well as athletic performance (Kärkkäinen et al., 2018), quantifying ED risk in less-studied athletic populations is necessary in order to identify individuals at high risk and implement appropriate prevention and intervention strategies.

Rock, or sport, climbers represent a population of athletes who may be at increased risk of developing EDs, albeit little research has examined ED risk in climbers. Competitive rock climbing requires intense kinesthetic awareness of the body and its movement as well as an exceptional strength to bodyweight ratio. As such, good climbers tend to have a lean build and low body mass (Watts et al., 1993, 2003; Novoa-Vignau et al., 2017). Climbing can be considered an antigravitational sport and success is supported by a high strength-to-mass ratio, which diet may strongly influence (Tayne et al., 2019). Although research regarding the dietary intake patterns of climbers is scarce (Zapf et al., 2001; Merrells et al., 2008; Krzysztof and Judyta, 2019), there is anecdotal evidence and published personal testimony of climbers practicing DE behaviors in order to minimize body weight and thus potentially enhance performance (Taylor and Geldard, 2008; Samet, 2013). Because of the myriad of physical and mental consequences associated with long term energy deficiency, and the prevalence of "the lighter the better" mentality among some climbers, the medical community has shared concerns regarding the likely inadequate macronutrient intake and potential for EDs among many climbers (Lutter et al., 2017). On this basis, the Austrian Climbing Organization uses Body Mass Index (BMI) values to help determine eligibility for competing in an effort to prevent disordered eating, and concern has been raised regarding the risk of adolescent climbers developing anorexia athletica.

Despite these worrisome ED indicators, to date, only one peer reviewed study has assessed ED prevalence among rock climbers (Michael et al., 2019). This study examined the dietary habits and eating attitudes of a small sample (13 males, 9 females), of adolescent (14.2 ± 1.9 years) competitive climbers who ranged from intermediate to advanced climbing ability. Results from the 3-day dietary recall and Eating Attitudes Test-26 (EAT-26) indicated the majority (82%) of climbers did not meet their target energy intake (target = 2,471 ± 493 kcal·day−1; actual = 1,963 ± 581 kcal·day−1) ($p = 0.01$) but average EAT-26 scores were 5.3 ± 4.1, indicating minimal risk of DE attitudes/behaviors. Additionally, there were no associations between energy intake and EAT-26 score ($R^2 = 0.245$, $p = 0.27$) or climbing ability and EAT-26 score ($R^2 = 0.274$, $p = 0.23$). These data suggest young, adolescent climbers fail to meet energy needs but exhibit minimal risk of DE. However, these findings have not yet been replicated in older adolescents or an adult population of climbers. It is possible that eating attitudes change and risk of developing an ED increases with maturation and typical pubatorial increases in body weight and/or with continued exposure to competitive climbing culture. Therefore, larger studies with more diverse samples are needed to quantify risk in the larger climbing population.

The identification of individuals with DE behaviors can be accomplished via several screening tools. The EAT-26, a 26-item inventory, developed by Garner et al. (1982), has been used to assess a range of attitudes related to eating behavior in athletes and non-athletes. A score of 20 and above is established as a cut-off value to identify individuals with possible DE behavior. The EAT-26 has several advantages when assessing EDs in male and female, athletic populations. Namely the EAT-26 is thought to better predict ED pathology in males compared to other surveys, such as the Eating Disorder Inventory, because it evaluates food preoccupation rather than drive for thinness (Gleaves et al., 2014). Although not specifically developed for use in athletes, the EAT-26 has been frequently used to identify EDs in a variety of athletic populations, thereby making it a useful tool to compare ED prevalence rates between sports, sexes, and ability levels. The EAT-26 has been shown to have an accuracy rate of at least 90% when used to differentially diagnose those with and without ED, according to Mintz and O'Halloran (2000). As such, the EAT-26 was used in the present study in order to evaluate and compare the prevalence of DE in male and female sport lead rock climbers with varying climbing abilities.

PURPOSE

The primary purpose of this study was to assess DE prevalence among a large international, heterogeneous sample of sport lead rock climbers with varying abilities. Secondarily, we wanted to determine if there was a relationship between prevalence of DE and climbing ability and if incidence of DE differed between male and female climbers. Based on previous research, we hypothesized that climbers would have a higher prevalence of disordered eating compared to previously reported values in the general population. We further hypothesized that prevalence of DE would be higher in women than men and similar to those found in aesthetic and antigravitational sport populations, respectively.

MATERIALS AND METHODS

Participants

We aimed to recruit an international sample of 500 adults that were currently actively participating in rock climbing. Participants were recruited via email through the International Rock Climbing Research Association (IRCRA) delegation and were provided a link to the electronic survey. The authors also dispersed the survey within their own rock climbing communities within the U.S. using email and social media. It was open to collect responses for 3 months during late summer and early fall of 2017.

Eight hundred and ten individuals attempted the survey, 604 had complete responses to all questions, and 498 self-identified primarily or secondarily as sport lead climbers. Sport lead climbing was defined as a type of lead climbing where the anchoring system is fixed into the rock (usually a steel bolt) and the climber attaches quickdraws (webbing material with 2 carabiners) to the bolts as the climber ascends. The climbing rope is tied to the climber's harness, threaded through a carabiner on the quick draw that gets clipped to the fixed anchor, and connected to a belayer (partner) or an auto-belay device. These 498 sport lead climbers were analyzed in this study.

Procedures

This study received ethical approval from the Internal Review Board of Northern Michigan University (#HS17-869). After reading the first page explaining the purpose of the research and the types of questions to expect on the survey, participants used a checkbox on the questionnaire to indicate their informed consent in accordance with the Declaration of Helsinki. All surveys were completed anonymously. Only individuals 18 years and older who completed all questions and self-identified as participating in sport lead climbing were included in the present analysis.

Electronic Survey Instrument

The survey instrument was developed and pilot tested by 7 advanced level climbers (IRCRA mean climbing ability level of 18) with ample rock climbing research experience. Their feedback was utilized to reword questions and enhance the electronic questionnaire experience for mobile devices. Qualtrics software (version 2017; Qualtrics, Provo, UT) was used to develop the web-based electronic survey tool and to collect participant responses. There were 42 total questions in 3 main sections.

Section 1 included basic demographics including self-reported age, biological sex, height, weight, body composition, and country of residence. BMI was calculated from height and weight.

Section 2 focused on climbing characteristics. Participants were required to check the types of climbing they had participated in within the past 365 days from the following 6 choices: bouldering, top-roping, traditional lead (placing gear), sport lead (clipping bolts), free solo, and speed climbing. They were asked about the types of climbing they devoted the most time doing in the past 3 months. Those that selected sport lead climbing as a primary or secondary choice were included in the present analysis. Sport lead climbing ability was self-reported based on the IRCRAs recommended standards for reporting a rock climber's ability in a universal format (Draper et al., 2016). Their sport lead climbing ability was selected from a drop down menu of IRCRA climbing ability levels (1–32) that most closely matched their abilities according to their current best redpoint, which was defined as completing a clean ascent (no falls or weighting the rope) after having one or more practice attempts. For example, an IRCRA level of 15 would equate to a 5.11b on the Yosemite Decimal System scale or a 6c in the French Sport scale and be considered an intermediate level for males and advanced level for females.

Section 3 included the EAT-26 with 26 questions and was used with permission (Garner et al., 1982). A tallied score $\geq$ 20 on the EAT-26 was considered indicative of DE behavior (Garner et al., 1982). In addition, the very last question on our survey specifically asked if the participant had been treated for an ED any time in their life with a yes or no response option.

Data Analysis

All data analyses were conducted using the Statistical Package for Social Sciences (SPSS, version 25.0, IBM Corp. Released 2017, Armonk, NY: IBM Corp.) with a significance level set at $p < 0.05$. BMI was calculated from self-reported heights and weights in kg/m^2. The EAT-26 question responses were scored and tallied in accordance with its rating scale (Garner et al., 1982) and grouped as DE (>20 on EAT-26) or NO DE (<20 on EAT-26). Percentages and mean $\pm$ SD are reported for descriptive data. The prevalence of DE was reported in percentages of the total sample, by sex, and by climbing ability level. A Pearson correlation coefficient was used to determine the relationship between BMI and climbing ability in males and females. To discern if DE was associated with climbing ability, we grouped levels 1+2 and levels 4+5 and performed Chi-square analyses with 3 climbing ability groups (low, medium, high) for males and females.

RESULTS

A total of 810 individuals attempted the survey, however only 604 had complete answers for all questions. Of the 604 completed surveys, the highest percentage of responders identified themselves as sport lead climbers either as their primary or secondary form of climbing (82%; $n = 498$) and these participants were included in the present analyses. These rock climbers represented 33 countries, with the top three highest frequencies from the United States (63%), Canada (8%), and Spain (6%) and the majority were male (77%; $n = 383$). Mean age of the sample was 32 $\pm$ 9 years.

Self-reported sport lead climbing abilities ranged from 3 to 31 on the IRCRA scale. Grouped by climbing abilities and sex for the 5 ability levels (lower grade, intermediate, advanced, elite, higher elite), the highest percentage of climbers that completed the survey were considered intermediate for both adult males

TABLE 1 | Sport lead rock climbers' BMI and age by climbing ability level.

	Males ($n = 383$)			Females ($n = 115$)		
	Total sample (%)	BMI (kg/m^2)	Age (yrs)	Total sample (%)	BMI (kg/m^2)	Age (yrs)
Total sample	76.9	22.9±2.6	32 ± 9	23.1	21.9±2.5	33 ± 9
Lower grade	7.8	24.9±2.7	33 ± 11	15.7	23.0±3.0	30 ± 8
Intermediate	51.2	23.0±2.7	30 ± 8	46.1	22.2±2.4	32 ± 10
Advanced	30.7	22.7±2.4	33 ± 10	20.0	21.6±2.4	32 ± 8
Elite	10.0	21.5±1.2	35 ± 7	17.4	20.6±2.0	36 ± 8
Higher elite	1.4	23.3±2.1	37 ± 5	0.8	19.9	44

Data expressed in percentages of total sample for each climbing ability with BMI and age expressed as mean ± SD within sex.
BMI—Body Mass Index.
IRCRA level—International Rock Climbing Research Association's climbing ability scale with 5 levels of climbing abilities; lower grade, intermediate, advanced, elite, higher elite (Draper et al., 2016).

TABLE 2 | Sport lead rock climbers' DE by climbing ability.

Males		Females	
Sport Lead Climb Ability Level (*n*)	Sport Lead Climbers with DE *n* (%)	Sport Lead Climb Ability Level (*n*)	Sport Lead Climbers with DE *n* (%)
Lower grade (21)	3 (14.3)	lower grade (18)	1 (5.5)
Intermediate (196)	10 (5.1)	intermediate (54)	4 (7.4)
Advanced (130)	10 (7.7)	advanced (23)	5 (21.7)
Elite (30)	1 (3.3)	elite (20)	9 (45)
Higher elite (6)	0 (0)	higher elite (1)	0 (0)
Total DE	24 (6.3)	Total DE	19 (16.5)
Total treated for ED	7 (0.2)	Total treated for ED	14 (12.2)

Data expressed in absolute numbers (n) and percentages (%) within each climbing ability level.
International Rock Climbing Research Association's climbing ability scale with 5 levels of climbing abilities; lower grade, intermediate, advanced, elite, higher elite (Draper et al., 2016).
DE—disordered eating determined by scoring 20 or above on EAT-26.
ED—selecting yes to the question "at any time in your life have you been treated for an eating disorder?".

(climb ability of 10–17; $n = 196$; 51.2%) and females (climb ability of 10–14; $n = 54$; 46.1%).

BMI and age for each sex was organized by climbing ability level, see **Table 1**. The overall average BMI was 22.7 ± 2.6 kg/m^2 and average age was 32 ± 9 years. There was a general trend of better climbers having a lower BMI for both the female ($r = -0.329$, $p = 0.00$) and male sport lead climbers ($r = -0.237$, $p = 0.00$).

Table 2 expresses DE prevalence for each climbing ability grouping and between sexes. Using the pre-established cutoff score of >20 on the EAT-26 questionnaire as identifying individuals at risk for or with DE, we found 43 of the 498 sport lead climbers with this score, indicating an 8.6% overall DE prevalence. Additionally, 21 of 498 (4.2%) reported to have been treated for an eating disorder.

Among all of the male sport climbers, DE prevalence was 6.3% (24 of 383). Three of the 21 males with lower grade climbing abilities had DE (14.3%). However, a much higher prevalence was seen in the female climbers with an overall DE prevalence of 16.5% (19 of 115) and nearly half of the females (9 of 21) in the highest two climbing ability levels (elite and high elite) had DE (42.9%).

The final Chi-square analysis reported the overall sample as χ^2 (2, $n = 498$, 8.076, $p = 0.02$), suggesting DE was associated with climbing ability levels. For males, the χ^2 (2, $n = 383$, 1.224, $p = 0.54$) revealed no significant associations between DE and climbing ability. However, for the females, the χ^2 (2, $n = 115$, 15.640, $p = 0.00$) suggested that DE was indeed associated with climbing ability.

DISCUSSION

This study is the first to publish prevalence data of DE in a large, international, sample of adult rock climbers with a variety of climbing abilities. Using the EAT-26, we found an 8.6% prevalence of DE in our sample of 498 sport lead rock climbers, which is similar to what is reported for other athletic groups. For example, in a large Norweigan cohort ($n = 3{,}000$), subclinical or clinical EDs were found, also using the EAT-26, in 13.5% of elite athletes compared to 4.6% of the non-athlete controls ($p < 0.001$) (Sundgot-Borgen and Torstveit, 2004). We acknowledge that the EAT-26 was originally intended to detect DE in the general population and therefore may not accurately represent DE prevalence in athletic populations (Pope et al., 2015). As such, and suggested by some researchers attempting to examine disordered eating behaviors in athletic populations (Beals and Manore, 1994; Smolack et al., 2000; Byrne and McLean, 2001; Sundgot-Borgen and Torstveit, 2004; Reinking and Alexander, 2005; Pope et al., 2015), clinical interviews and validated tools specifically designed for active populations are needed to obtain more accurate DE prevalence data, especially in male athletes.

In the present study, and as expected, the prevalence of DE was higher among female climbers compared to male climbers (16.5 and 6.3%, respectively). Previous research also reports higher incidence of DE among female athletes compared to male athletes with the highest prevalence among elite female athletes competing in aesthetic sports such as gymnastics and figure skating (42%) (Sundgot-Borgen and Torstveit, 2004). We found similar DE outcomes in our sample of elite female climbers (43%). Additionally, our sample of female sport lead rock climbers of all abilities had DE prevalence rates (16.5%) comparable to those reported of female gymnasts and swimmers (16%) (Anderson and Petrie, 2012). Contrary to our hypothesis, our sample of elite male climbers had a lower incidence of DE (2.7%) compared to previously reported values in elite male athletes who participated in antigravitation sports (22%), ball game sports

(5%) and endurance sports (9%) (Sundgot-Borgen and Torstveit, 2004).

As very few high level female sport lead climbers responded to our survey ($n = 21$), it is unclear whether this is a represent ative sample of the number of females climbing at this skill level. Currently there is no known international database of climber demographics and skill level. However, the lack of participants in the elite and higher elite categories is consistent with other survey-based climbing studies and is a limitation of the current study as well as the existing body of research (Gonzalez, 2019; Grønhaug, 2019). Despite the small size of this subsample, the incidence of DE among the elite female climbers who responded to our questionnaire is striking and warrants additional research. Symptoms and potential drivers of EDs in female athletes include body dissatisfaction and exposure to high standards (i.e., appearing very lean), self-imposed expectations of athletic perfection, and a belief in the inverse relationship between body size and performance (Sanborn et al., 2000). Furthermore, constant evaluation of physical appearance by coaches and peers can lead to negative body image if these standards are not met (de Bruin et al., 2011). Although the etiology of EDs in climbers has not yet been explored, evaluating constructs shown to be salient mediators and moderators of EDs in other athletic populations seems to be a reasonable place to start. Hopefully future research will allow us to better understand drivers and risk factors of DE in climbers so appropriate prevention and intervention tools can be made available to the climbing community.

Consequences of DE, even without progression to a diagnosable ED, include long term negative psychological and physiological ramifications (Kärkkäinen et al., 2018). From a performance perspective, DE has been associated with unhealthy physical activity behaviors and Relative Energy Deficiency in Sport (RED-S) (Torstveit et al., 2019), a term used to describe a syndrome in active individuals who display compromised physiological functioning. The main cause is thought to be energy deficiency and may include impairments of metabolic rate, menstrual function in women, bone tissue depredation, a weakened immune system and susceptibility to injury (Mountjoy et al., 2014, 2018). A few recent studies suggest rock climbers may not be consuming adequate energy to support optimal health. These studies recognized low energy availability using 24 h dietary recall in a small group of advanced adolescent climbers (Michael et al., 2019) and 7 day food records in advanced adult climbers (Krzysztof and Judyta, 2019). Although our study did not evaluate dietary energy intake and we did not detect DE in the majority of our participants, it is possible that some of our participants, with or without DE, did not consume enough energy, which may lead to poor bone density, increased risk of injury, and compromised health (Tayne et al., 2019). It is reasonable to suggest that optimal eating behaviors which supply adequate energy and nutrients may offer protection from injury and/or help an athlete to recover from them. Further research is paramount in determining how and what rock climbers should eat to maintain health and to support performance longevity.

CONCLUSION

Our study is the first to assess prevalence of DE among an international heterogeneous sample of sport lead rock climbers. Among our sample, we found a prevalence rate of 8.6%, suggesting sport lead rock climbers are not immune to DE and that the risk is elevated in female climbers (16.5%), particularly at the elite/high elite climbing ability level (42.9%).

The study had several strengths including a large sample size with an international representation of sport climbers from recreational to elite abilities. Both males and females were assessed for DE. However, it is unclear whether the percentage of climbers in each category and sex is representative of the climbing community at large. The majority of our sample was male (76.9%). Other limitations include the self-report cross-sectional nature of the study, sole focus on sport lead climbers, and need for a DE screening tool validated for use in an athletic population.

It is possible that those climbing at the highest levels may be involved in competition or maintaining/acquiring climbing sponsorships. This may lead to additional internal or external pressure to achieve a lower body weight or leanness, which ultimately could negatively affect eating patterns. Future studies should examine how the competitive climbing climate, at all skill levels, affects DE behaviors. Furthermore, studies should explore the relationship between DE and perceived importance of body weight on performance. Finally, future research should examine DE prevalence to include individuals who primarily participate in other types of climbing such as speed climbing, bouldering, traditional, and top-roping.

Our research indicates further investigations are warranted to confirm the present findings as well as how DE behaviors affect psychological and physical health and performance of adult rock climbers. It is our hope that our work will provoke further research, which includes thorough assessment of current as well as appropriate dietary patterns in these athletes. At the very least, proper education surrounding appropriate eating behavior and nutrition to support athletes in this sport is warranted, especially in female climbers.

Climbing federations can be more vocal regarding the health risks, symptoms and prevalence of DE in elite class climbers by educating coaches, trainers and athletes. Recreational and elite athletes alike, should seek professional guidance on establishing and maintaining a healthy diet appropriate to their discipline and climbing performance level.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Northern Michigan University's Internal Review Board #HS17-869. The patients/participants provided their informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LJ designed the study, collected, analyzed and interpreted the data, and drafted the manuscript. AL designed the study and edited the manuscript. GB designed the study, analyzed the data, and edited the manuscript. All authors gave final approval on the accepted manuscript.

ACKNOWLEDGMENTS

The authors wish to thank the IRCRA for their help with disseminating the electronic questionnaire. It reached over 800 individuals in many crevices of the world in a timely and efficient manner. Also, many thanks to those that took the time to complete the survey and their brutal honesty.

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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.

frontiers in Nutrition

ORIGINAL RESEARCH
published: 05 August 2020
doi: 10.3389/fnut.2020.00122

Dietary Intake, Body Composition and Iron Status in Experienced and Elite Climbers

Edward Gibson-Smith[1]*****, *Ryan Storey*[2] *and Mayur Ranchordas*[3]

[1] *Centre for Sport and Exercise Science, College of Health, Wellbeing and Lifestyle, Sheffield Hallam University, Sheffield, United Kingdom,* [2] *Sport Industry Research Centre, College of Health, Wellbeing and Lifestyle, Sheffield Hallam University, Sheffield, United Kingdom,* [3] *Academy of Sport and Physical Activity, College of Health, Wellbeing and Lifestyle, Sheffield Hallam University, Sheffield, United Kingdom*

OPEN ACCESS

Edited by:
Vanesa España-Romero, University of Cádiz, Spain

Reviewed by:
Lanae Marie Joubert, Northern Michigan University, United States
Alba Maria Santaliestra-Pasias, University of Zaragoza, Spain

***Correspondence:**
Edward Gibson-Smith
edward.smith@shu.ac.uk

Specialty section:
This article was submitted to Sport and Exercise Nutrition, a section of the journal Frontiers in Nutrition

Received: *10 March 2020*
Accepted: *30 June 2020*
Published: *05 August 2020*

Citation:
Gibson-Smith E, Storey R and Ranchordas M (2020) Dietary Intake, Body Composition and Iron Status in Experienced and Elite Climbers. Front. Nutr. 7:122. doi: 10.3389/fnut.2020.00122

Climbing has developed into a popular recreational and elite sport, evidenced by a growing number of licenced competition athletes, and the acceptance into the Olympic calendar for Tokyo 2020. A nutritional assessment, including the evaluation of anthropometric and biochemical data, has not been previously reported in climbing athletes. Therefore, the aim of this study was to assess the dietary intake, body composition, and iron status in experienced climbers, across a range of performance levels. Forty climbers ($n = 20$ male, $n = 20$ female; 8.8 ± 6.6 years' experience; BMI 21.6 ± 1.7) aged 18–46 (30.3 ± 6.7 years) participated in the study. Dietary intake was recorded in a 3-days diet diary. Body composition was assessed using a skinfold profile and iron status via blood markers. Mean energy intake was 2154.6 ± 450 kcal·day^{-1}, with 30% of male climbers and 5% of female climbers failing to meet predicted resting metabolic rate. Furthermore, 77.5% of participants failed to meet a predicted energy requirement to support a "moderate" training programme. There were no significant correlations between daily energy intake and exercise volume. Mean intake of carbohydrate, protein and fat was 3.7 ± 0.9 g·kg^{-1}·day^{-1}, 1.6 ± 0.5 g·kg^{-1}·day^{-1}, and 1.4 ± 0.4 g·kg^{-1}·day^{-1}, respectively, with no significant difference between genders. Approximately 17% of males ($n = 3$) and 45% of females ($n = 9$) had a sub-optimal iron status. Thirty percent of females met the classification criteria for iron deficiency. Mean serum ferritin was significantly greater in males, compared to females (102.7 ± 54.9 vs. 51.4 ± 24.2 µg·L^{-1}; $p \leq 0.01$) and significantly lower in vegan/vegetarians vs. omnivores, in female climbers only (33.2 ± 14.8 vs. 57.5 ± 24 µg·L^{-1}; $p = 0.05$). No significant differences were observed between climbing ability groups (intermediate-advanced/elite-higher elite) for body composition, dietary intake, or iron status, for males or females. These findings suggest that experienced climbers are at risk of energy restriction and iron deficiency, therefore, routine assessment of nutritional status is warranted. Future research should consider iron status in relation to energy availability and investigate additional factors which may predispose this population to iron deficiency, as well as the risk of relative energy deficiency in sport (RED-S).

Keywords: climbing, nutrition, bouldering, sport climbing, RED-S, energy availability, weight loss, sport

INTRODUCTION

Climbing was originally devised as a training method for mountaineering and has since developed into a popular recreational and elite sport with an estimated 25 million people participating regularly, and up to 1,500 people trying the sport for the first time every day in the USA alone (1). This is further evidenced by a growing number of licenced competition athletes (2,160) from 65 countries and the acceptance of climbing into the Olympic calendar for Tokyo 2020, with provisional selection for Paris 2024.

In recent decades, an increasing number of studies have been carried out to investigate the anthropometric (2–6), biomechanistic (7, 8), physiological (9–17), and psychological (18) factors contributing to successful climbing performance. Despite the development of climbing into an elite sport, studies investigating the nutritional requirements of climbing are scarce, and no study to date has assessed the dietary intake of adult female climbers, or biochemical markers of iron status.

Reporting on lead rock climbers, Watts et al. (19) published the first large-scale assessment of anthropometric data in elite climbers, presenting findings from 39 athletes who reached the semi-finals of an international competition. The athletes were found to be relatively small in stature (male ∼1.78 m, female ∼1.65 m) with a low body mass (male ∼66.6 kg, female ∼51.1 kg). Since this pioneering work, numerous studies have reported similar findings, with some presenting climbers as excessively lean (6), but more recent work reporting similar results as other weight-sensitive sports (3, 5, 12). Anecdotally, the importance of power to weight ratio is well-recognised by climbers, with many sharing the view that excess fat provides additional resistance during ascent which can harm performance; therefore, a very lean physique is usually favoured. However, research has failed to establish a significant link between body composition and climbing performance thus far (4, 12).

Methods to determine an athlete's nutritional intake from food, fluids and supplement include weighed/measured food records (typically 3–7 days), 24-h dietary recall or food frequency questionnaires (20). Whilst all methods are prone to under-reporting error (21), those that depend on retrospective self-reporting of intake (e.g., 24-h recall) are more susceptible to conscious or sub-conscious exclusion of foods consumed (22), whilst the prospective weighing of foods can increase accuracy (23). It is recommended that a complete nutritional assessment process should also include the evaluation of anthropometric and biochemical data, such as iron status (24).

To date, only three published studies have assessed dietary intake in climbers. Zapf et al. (25) found a mean energy intake of ∼2,650 kcal, with 40% of climbers consuming <2,500 kcal, despite training for more than 2 h per day. Nutritional intake of potatoes and vegetables appeared to be alarmingly low, representing merely 1.8% of total energy intake. Kemmler et al. (26) found similar results, with mean intakes of ∼2,670 kcal·day^{-1}. The energy intake of the climbing athletes was not significantly greater than their BMI matched controls, despite a 9.5 times greater training volume (401 ± 73 min vs. 43 ± 25 min). This pattern also appears to be consistent in adolescent climbers. Michael et al. (27) reported a weak correlation between training volume and energy intake, with 82% of adolescent climbers failing to meet their target daily energy intake. The prevalence of disordered eating and/or eating disorders among athletes in weight-sensitive sports is greater than other sports in which leanness is a not a prioritised performance variable (28), however research in this area within climbing is currently lacking.

These findings (25–27) suggest that climbers are at risk of chronic energy restriction and low energy availability (LEA). Adequate energy intake is important for maintaining health, immunity and injury resilience, as well as growth and repair, and optimising sports performance (29). Furthermore, LEA may contribute to iron deficiency (30) which can attenuate muscle function and capacity, leading to impaired training adaptation and performance, with or without anaemia (31). Despite these negative physiological effects, iron deficiency is commonly reported in athlete populations, affecting ∼15–35% of female and ∼3–11% of male athletes (32). Potential factors proposed to impact an athlete's iron stores include vegetarian diets and endurance exercise (33). However, no study to date has investigated iron status in climbers.

A nutritional assessment, including the evaluation of anthropometric and biochemical data, has not been previously reported in climbing athletes. Furthermore, no previous research has assessed the dietary intake of female climbers. Therefore, the aim of this study was to assess the body composition, dietary intake, iron status and supplement use among experienced climbers, from the recreational to the elite.

METHODS

Participants

Participants were recruited using social media, online climbing forums and posters in local climbing centres (Sheffield, UK). Forty climbers (20 females, 20 males) volunteered to participate. Participants were required to meet the following inclusion criteria: age ≥ 18 years, ≥2 years climbing experience, currently taking part in climbing or climbing specific training ≥2 × per week, in good health with no acute or chronic illness that may influence dietary intake.

Questionnaire

Participants answered a series of questions to identify years of climbing experience, predominant climbing discipline (bouldering/sport), weekly training/climbing volume, dietary preference (vegan/vegetarian or omnivorous) and highest climbing difficulty grade attained in the last 6 months. Self-reported climbing ability has been shown to be a valid representation of actual climbing ability (34). Climbing grades were converted from Font (bouldering) and French/sport (sport climbing) grading systems to the International Rock Climbing Research Association Reporting Scale to support a common approach to the statistical analyses within rock climbing research (35).

Body Composition

Body mass was measured to the nearest 0.1 kg using electronic scales (Tanita, Japan), and height to the nearest 0.1 cm using a wall-mounted stadiometer (Holtain Ltd., UK). Body composition was assessed using the International Society for the Advancement of Kinanthropometry (ISAK) 8-site skinfold profile (36), carried out by an ISAK certified (Level 1) practitioner with an average technical error of measurement of 1%. Skinfold thickness was measured to the nearest 0.2 mm at eight sites (biceps, triceps, subscapular, iliac crest, supraspinal, abdominal, anterior thigh, and medial calf) using research standard calipers (Harpenden, UK). Duplicate measures were taken at each site and, where the technical error of measurement (TEM) was <5%, the mean value was reported. Where the TEM was >5%, a third measure was taken, and the median value reported. Girth measurements (relaxed arm, waist, gluteal and calf) were taken using a Lufkin metallic tape (W606PM, ATG, US). Body fat and fat-free mass (FFM) percentages were calculated using the Durnin and Womersley (37) equation, which has previously been validated against dual-energy X-ray absorptiometry in elite sport climbers (38).

Estimating Energy Needs

Resting metabolic rate (RMR) was calculated using the Cunningham (1980) equation [RMR (kcal·day^{-1}) = 500 + 22 (Fat Free Mass)]. This equation was chosen for its established application in highly active individuals (39). The RMR for each climber was multiplied by a physical activity factor of 1.443 to represent a "moderate" exercise level. Due to the highly variable energy requirements of climbing, and lack of reliable predictive models, this calculation was used as a conservative estimate to allow comparisons to be made between the actual intake of the climbers, and the energy needs to support a "moderately active" training programme. The self-reported data collected suggested that all participants had a training volume that met or exceeded the criteria for a "moderate" exercise level (3 × hard/5 × light sessions per week).

Dietary Assessment

Participants were instructed to weigh (in grams) or measure (in millilitres) all foods, fluids and supplements consumed in a 3-days non-consecutive diary, an accepted method used in previous research to collect this type of data (40). Measurements were taken using self-owned, commercially available digital kitchen scales or by reporting manufacturer weights. An electronic template was provided with guidance notes detailing the requirements for accurate reporting. Participants were instructed to choose three non-consecutive days within a 7-days period to record, and to consider capturing days with a range of training demands (e.g., rest day; indoor climbing training; outdoor climbing session). When consuming pre-packaged products, participants were required to report the brand name, the weight of the product and manufacturer nutritional values. The diet diaries were analysed by a registered sports nutritionist using Nutritics software (Version 5.096). Where exact foods were not listed within the software database, similar foods with matched macronutrient composition were selected. Dietary supplement intake was included within the dietary analysis, therefore, contributing to the energy, macro-, and micro-nutrient content of the log.

Assessment of Iron Status

A random, non-fasted venepuncture blood sample was taken by a trained phlebotomist in line with the World Health Organisation guidelines on drawing blood (41). Blood sampling was not restricted to a specific time of the day in line with diurnal variation data in markers of iron status (42), with fasting conditions recommended only when assessing iron overload (43). Blood was collected in a serum vacutainer (BD, USA) for analysis of serum ferritin and transferrin saturation, and an EDTA vacutainer for follow up haemoglobin analysis. Serum samples were allowed to clot for 30–60 min at room temperature, then processed in a centrifuge for 10 min at ∼2,000 × g (Clinispin Horizon 642E, Drucker Diagnostics, USA) before being securely packaged and posted, as per testing laboratory guidelines. Serum ferritin and transferrin saturation were analysed by an external nationally recognised medical laboratory (TDL, London, UK), using a Roche "Cobas 8000" blood analyser (Roche Diagnostics GmbH, Germany). Serum ferritin was analysed using the sandwich principle; iron using a colorimetric assay; and unsaturated iron binding capacity (UIBC) via direct determination with FerroZine. Transferrin saturation was calculated as; transferrin saturation = [(iron) × 100/(iron+UIBC)]. Haemoglobin was analysed immediately after blood collection using the azide-methemoglobin method (Hb 201 System; HemoCue AB, Sweden) in participants with sub-optimal iron status; serum ferritin (<35 μg·L^{-1}) and/or transferrin saturation (<20%) (44, 45). The sub-optimal iron status cut-off points specified were the same for both genders.

Statistical Analysis

Statistical analysis was performed using SPSS software (version 24, IBM, USA). Data was checked for homogeneity of variance using Levene's test, and normality using Shapiro-Wilk's. Non-conforming data sets were transformed using Log-10. The differences in variables between groups (e.g., males vs. females) was analysed using an independent samples *t*-test, with significance set at $p \leq 0.05$. A Pearson correlation coefficient determined the relationship between data sets (e.g., ability and energy intake). Correlation values (R^2) were set as < 0.2: weak correlation, 0.5: medium correlation, and >0.8: strong correlation (46). Data are presented as means ± standard deviation (SD), unless otherwise stated.

RESULTS

Participant Demographics

Participant demographics are shown in **Table 1**. Forty experienced climbers (n = 20 male, n = 20 female; 8.8 ± 6.6 years' experience) aged 18–46 (mean age 30.3 ± 6.7 years) participated in the study. The average climbing ability of the cohort using the International Rock Climbing Research Association (IRCRA) scale was 22.2 ± 3.7; 47.5% (n = 19) of the climbers were classed as intermediate to advanced level

TABLE 1 | Participant demographics.

	Males	Females
n	20	20
Age (years)	29.1 ± 5.4	31.4 ± 7.7
Height (cm)	177.1 ± 6.9	166.8 ± 4.7
Mass (kg)	69.4 ± 5.8	58.5 ± 5.7
BMI	22.1 ± 1.4	21.1 ± 1.8
Experience (years)	7.8 ± 4.6	9.7 ± 8.2
Climbing Volume (min)	391 ± 181	497 ± 228
Training Volume (min)	214 ± 178	347 ± 193
IRCRA score	23.4 ± 2.9	21.1 ± 4.1
Ability (n)		
Intermediate-Advanced	13	6
Elite-Higher Elite	7	14
Discipline (n)		
Bouldering	17	10
Sport	3	10
Dietary preference (n)		
Vegan/Vegetarian	6	5
Omnivore	14	15

Numbers expressed as means ± SD.
Intermediate-Advanced = IRCRA score; 10–23 males, 10–20 females (35).
Elite-Higher Elite = IRCRA score; 24–32 males, 21–32 females (35).

TABLE 2 | Anthropometric data.

	Males (♂)	Females (♀)	♂ vs. ♀
Height (cm)	177.1 ± 6.9	166.8 ± 4.7	$p = <0.01$*
Mass (kg)	69.4 ± 5.8	58.5 ± 5.7	$p = <0.01$*
BMI	22.1 ± 1.4	21.0 ± 1.8	$p = 0.04$*
Sum of 8 SF	57.0 ± 19.5	83.2 ± 23.0	$p = <0.01$*
Body fat %	12.0 ± 3.8	22.9 ± 3.8	$p = <0.01$*
Arm girth (cm)	30.5 ± 1.8	27.2 ± 1.8	$p = <0.01$*
Waist girth (cm)	76.3 ± 3.5	66.9 ± 3.3	$p = <0.01$*
Gluteal girth (cm)	91.8 ± 3.7	92.62 ± 5.0	$p = 0.58$
Calf girth (cm)	35.5 ± 1.8	34.1 ± 1.8	$p = 0.02$*

*Mean ± SD. Males n = 20; females n = 20. *P ≤ 0.05 is considered significant.*

TABLE 3 | Dietary intake.

	Males (♂)	Females (♀)	♂ vs. ♀
Predicted energy requirements			
RMR (kcal·day^{-1})	1,842 ± 100	1486.3 ± 90	-
'Moderate' Energy Needs (kcal·day^{-1})	2640.1 ± 143.5	2130.2 ± 129.2	-
Energy intake			
Total kcal·day^{-1}	2270.4 ± 562	2038.8 ± 266.7	-
kcal·kgFFM^{-1}·day^{-1}	37.2 ± 9.0	45.6 ± 7.0	$p = <0.01$*
Carbohydrate intake			
Total g·day^{-1}	251.7 ± 61.1	220.5 ± 46.3	-
g·kg^{-1}·day^{-1}	3.7 ± 1.0	3.8 ± 0.9	$p = 0.65$
Protein intake			
Total g·day^{-1}	109.5 ± 34.8	92.6 ± 29.6	-
g·kg^{-1}·day^{-1}	1.6 ± 0.5	1.6 ± 0.5	$p = 0.86$
Fat intake			
Total g·day^{-1}	90.9 ± 29.6	84.0 ± 18.9	-
g·kg^{-1}·day^{-1}	1.3 ± 0.4	1.4 ± 0.3	$p = 0.31$

*Mean ± SD. Males n = 20; females n = 20. *P ≤ 0.05 is considered significant.*

[IRCRA score: 10–23 for males, 10–20 for females; (35)], with 52.5% ($n = 21$) meeting classification criteria for elite or higher elite (IRCRA score: 24–32 for males, 21–32 for females (35). Twenty-seven climbers identified "bouldering" as their primary climbing discipline, with the remaining thirteen climbers reporting "sport climbing." One climber reported a previous case of iron deficiency anaemia. No other known health issues, or the use of medications that could impact dietary intake were reported. Average BMI was 21.6 ± 1.7; a BMI of <18.5, defined as potentially "underweight" (47) was reported in one female participant. Over a quarter (27.5%) of the climbers reported being vegan ($n = 5$) or vegetarian ($n = 6$).

Body Composition

Body composition results are shown in **Table 2.** With the exception of gluteal girth, statistical analysis revealed significant gender differences across all the measured parameters ($p \leq 0.05$). No significant differences were observed between ability groups (intermediate/advanced vs. elite/higher elite) for males or females. However, weak to medium correlations were seen in males between the IRCRA ability score and body mass ($R^2 = 0.506$, $p = 0.02$), and height ($R^2 = 0.478$, $p = 0.03$).

Dietary Intake

Energy Intake and Energy Requirements

Energy intake results are shown in **Table 3**. Mean energy intake was 2154.6 ± 450 kcal·day^{-1} (41.4 ± 9 kcal·kgFFM^{-1}·day^{-1}) for genders combined, with 30% of male climbers ($n = 6$) and 5% of female climbers ($n = 1$) failing to meet predicted RMR values. The 6 males identified consumed energy intakes 8–492 kcal·day^{-1} lower than their respective predicted RMR values (mean energy intake 238.3 ± 171.2 kcal·day^{-1} < RMR), whilst the female participant highlighted consumed 92 kcal·day^{-1} lower than the predicted RMR value (RMR = 1,526 kcal·day^{-1}). Furthermore, 77.5% of climbers failed to meet a predicted energy requirement to support a "moderate" level of physical activity (**Table 3**). Females had a significantly higher energy intake than males when expressed relative to fat-free body mass (45.6 ± 7.0 vs. 37.2 ± 9.0 kcal·kgFFM^{-1}·day^{-1}; $p \leq 0.01$).

There was no significant correlation between the IRCRA ability scale and energy intake (kcal·kgFFM^{-1}·day^{-1}) for males ($R^2 = -0.480$, $p = 0.84$), or females ($R^2 = 0.201$, $p = 0.396$). Furthermore, there were no significant correlations between total daily energy intake (kcal·day^{-1}) and climbing or training volume, with R^2 values of −0.246 ($p = 0.13$) and −0.005 ($p = 0.97$), respectively. **Figure 1** shows energy intake comparisons between climbing discipline, ability, and dietary preference groups.

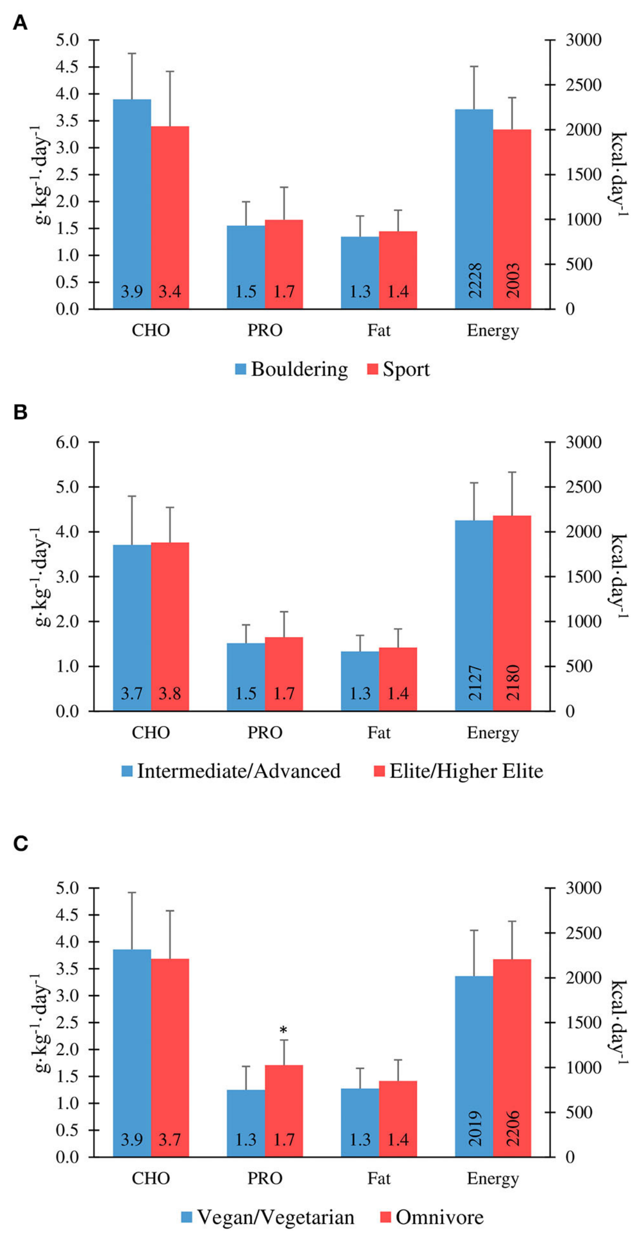

FIGURE 1 | Macronutrient and energy intake in boulderers vs. sport climbers **(A)**, intermediate/advanced vs. elite/higher-elite **(B)**, and vegans/vegetarians vs. omnivores **(C)**. *Protein intake is significantly lower in vegan/vegetarians vs. omnivores ($P \leq 0.05$).

Macronutrient Intake

Macronutrient intake results are shown in **Table 3**. Mean intake of carbohydrate, protein and fat was 3.7 ± 0.9 g·kg^{-1}·day^{-1}, 1.6 ± 0.5 g·kg^{-1}·day^{-1}, and 1.4 ± 0.4 g·kg^{-1}·day^{-1}, respectively; with no significant difference between genders when expressed relative to body mass. One male participant reported a very low protein intake of 0.7 g·kg^{-1}·day^{-1}, failing to meet the dietary reference intake (DRI) for the general population [0.8 g·kg^{-1}; (48)].

TABLE 4 | Iron status.

	Males (♂)	Females (♀)	♂ vs. ♀
Serum ferritin (µg·L^{-1})	102.7 ± 54.9	51.4 ± 24.2	p = <0.01*
Transferrin saturation (%)	30.9 ± 15.9	26.7 ± 11.4	$p = 0.39$
Iron intake (mg)	14.1 ± 7.7	13.4 ± 3.8	$p = 0.72$
Iron intake density (mg·1,000 kcal^{-1})	5.95 ± 2.42	6.58 ± 1.71	$p = 0.35$

*Mean ± SD. Male serum ferritin n = 18, Male iron intake n = 19; females n = 20. *P ≤ 0.05 is considered significant.*

Sub-optimal iron status; serum ferritin (< 35 µg·L^{-1}) and/or transferrin saturation (< 20%) (44, 45).

There were no significant differences between intermediate/advanced and elite/higher-elite level climbers for carbohydrate intake (3.7 ± 1.1 vs. 3.8 ± 0.8 g·kg^{-1}·day^{-1}; $p = 0.86$), protein intake (1.5 ± 0.4 vs. 1.7 ± 0.6 g·kg^{-1}·day^{-1}; $p = 0.40$), or fat intake (1.3 ± 0.4 vs. 1.4 ± 0.4 g·kg^{-1}·day^{-1}; $p = 0.50$) for genders combined (**Figure 1**). However, there was a significant correlation between the IRCRA ability scale and protein intake (g·kg^{-1}·day^{-1}) in female climbers ($R^2 = 0.452$, $p = 0.045$). Only 17.5% of the cohort tested reported alcohol consumption.

Protein intake was significantly lower in vegan/vegetarians when compared to omnivores (1.25 ± 0.43 vs. 1.71 ± 0.47 g·kg^{-1}·day^{-1}; $p = 0.007$). There was no significant difference in protein intake between vegan and vegetarian climbers, when analysed separately (1.35 ± 0.49 vs. 1.17 ± 0.41 g·kg^{-1}·day^{-1}; $p = 0.50$). Overall daily protein intake was significantly higher in participants who used a protein supplement ($n = 11$; 2.0 ± 0.58 vs. 1.46 ± 0.40 g·kg^{-1}·day^{-1}; $p \leq 0.01$). **Figure 1** shows macronutrient intake comparisons between climbing discipline, ability, and dietary preference groups.

Iron Intake

Iron intake results are shown in **Table 4**. Data from one male participant was omitted from the iron intake analysis due to taking a high dose iron supplement. Mean iron intake was 13.7 ± 6 mg·day^{-1}, with no significant difference between gender groups ($p = 0.66$). Four male participants (∼21%) and 16 female participants (80%) failed to meet the DRI for the general population [8 mg for males, 18 mg for females; (49)]. There was no significant correlation between iron intake (mg·day^{-1}) and serum ferritin (µg·L^{-1}) for males or females. There was a significant, medium strength correlation between iron intake (mg·day^{-1}) and daily energy intake ($R^2 = 0.530$, $p = 0.001$). Iron intake comparisons between genders and dietary preference groups are shown in **Figure 2**. There was no significant difference between vegan and vegetarian climbers in daily iron intake (mg·day^{-1}) or iron intake density (mg·1,000 kcal^{-1}·day^{-1}) ($p = 0.13$; $p = 0.09$).

Supplement Use

Forty-five percent of the climbers (males $n = 10$, females $n = 8$) recorded the use of one or more supplements. The most commonly used supplements reported were protein powder

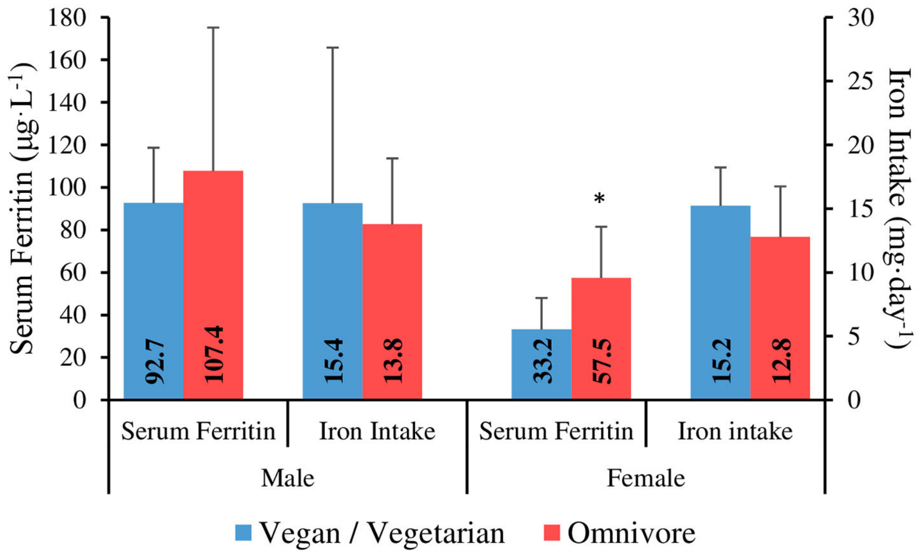

FIGURE 2 | Serum ferritin and iron intake in vegan/vegetarian vs. omnivore climbers. *Serum ferritin is significantly lower in vegan/vegetarians vs. omnivores in females ($P \leq 0.05$).

($n = 11$), vitamin D ($n = 7$), multivitamins ($n = 5$) and fish oil capsules ($n = 3$). Other supplements reported ($n \leq 2$) included creatine, beta-alanine, probiotics, vitamin C, turmeric, calcium, cissus, BCAA, glycine, collagen, vitamin B12, vitamin K, aloe vera, and meal replacements. The prevalence of supplement use was higher in intermediate/advanced level climbers (57.9%) compared to elite/higher-elite level (38.1%), whereas, the prevalence of supplement use amongst vegan/vegetarian climbers was comparable to omnivores (36.4 vs. 35.9%). Overall protein intake was ~31% higher in participants who used a protein powder supplement (124 ± 30.9 vs. 94.4 ± 31.0 g·day^{-1}; $p = 0.016$).

Iron Status

Iron status results are shown in **Table 4**. Data from two male participants was omitted from the iron status analysis. The aforementioned participant was excluded due to taking a high dose iron supplement, while hemochromatosis was incidentally identified in one participant during the study (serum ferritin 515 μg·L^{-1}).

Sub-optimal iron status was found in 16.6% of males ($n = 3$) and 45% of females ($n = 9$). One quarter of females ($n = 5$) met the criteria for stage 1 iron deficiency (ferritin < 35 μg·L^{-1}, Hb > 115 g·L^{-1}, transferrin saturation > 16% (44), and one female was identified with Stage 2 iron-deficient non-anaemia (ferritin < 20 μg·L^{-1}, Hb > 115 g·L^{-1}, transferrin saturation <16%). Follow-up testing revealed only one male participant with anaemia (Hb < 130 g·L^{-1}).

There was no significant correlation between serum ferritin and energy intake (kcal·kgFFM^{-1}·day^{-1}) for males ($R^2 = -0.075$, $p = 0.77$), or females ($R^2 = 0.05$, $p = 0.83$). Furthermore, there were no significant differences between intermediate/advanced and elite/higher-elite level climbers for serum ferritin in males (111.7 ± 59.2 vs. 70.3 ± 25 μg·L^{-1}; $p = 0.08$), or females (46 ± 28.2 vs. 53.7 ± 23.1 μg·L^{-1}; $p = 0.42$). When analysed separately, there was no significant difference between vegan and vegetarian climbers for serum ferritin in females (30.7 ± 11.1 vs. 37.0 ± 24 μg·L^{-1}; $p = 0.82$). However, serum ferritin was significantly lower in vegan/vegetarians combined when compared to omnivores in female climbers (33.2 ± 14.8 vs. 57.5 ± 24 μg·L^{-1}; $p = 0.05$) (**Figure 2**).

DISCUSSION

This is the first study to perform a nutritional assessment, including the evaluation of anthropometric and biochemical data, in experienced male and female climbers across a range of abilities.

Body Composition

Anthropometric and body composition data in the present study were similar to those previously reported in the literature (3, 5, 12, 38), with mean values for height, mass, BMI and body fat % of 177 cm, 69.4 kg, 22.1 (BMI), and 12.0% for males, and 166.8 cm, 58.5 kg, 22 (BMI), and 22.9% for females, respectively. Early research presented climbing athletes as short in stature, with a low body mass (19). Conversely, the present study shows significant weak to medium correlations in males between the IRCRA ability score and body mass, as well as height. However, it is difficult to draw conclusions as the existing anthropometric data in climbing research varies considerably, particularly body fat %, with a range of mean values reported between ~5–13% for males, and ~10–25% for females (3, 5, 12, 19, 38). Explanations for this variation might include the method used to assess body composition

[Skinfold vs. DEXA; (38)], ability level, whether the climbers climb/compete indoors or exclusively climb outdoors, the timing of the measurement in relation to peak conditioning (particularly relevant to competition athletes), and the changing demands of the sport as it has developed over the years. Nevertheless, this study adds further data in climbers, where recent body composition figures are lacking.

There were no significant differences found in any of the anthropometric characteristics between ability groups for males or females, which again supports previous findings (5, 50). Furthermore, Laffaye et al. (2) determined that the only significant anthropometric difference found between novice and elite boulderers was an increased ape index, concluding that anthropometric variables explained only 4% of performance variation. Similarly, Mermier et al. (12) concluded that when anthropometric characteristics are similar, climbing performance is determined to a greater degree by training variables, rather than physique (58.9 vs. 0.3% of total variance). Considering the large variation in the physiological requirements of each climbing route or boulder problem, we have previously proposed that an ideal physique may not exist in climbing (51). Due to the reduced load and friction requirements, a lower mass may be favoured on a route with small holds and where there is more time spent static. Conversely, on routes with higher friction and more explosive, strength reliant moves, an athlete might benefit from greater muscle hypertrophy and consequently, increased force development (51).

Dietary Intake

Energy Intake and Energy Requirements

Mean energy intake was ~2,270 kcal·day^{-1} for males, and ~2,039 kcal·day^{-1} for females, which is lower than the values previously reported (~2,650–2,670 kcal·day^{-1}), however, this research either exclusively studied males (26), or did not clearly state which genders were assessed (abstract only; 26). Therefore, data reported in the present study potentially represents the first of its kind in adult female climbers. Concerningly, seven participants (six males, one female) failed to meet predicted resting metabolic rate (RMR), with 77.5% of climbers overall failing to meet a predicted energy requirement to support a "moderate" level of physical activity, despite a combined mean climbing and training volume of >12 h per week. Furthermore, there were no significant correlations between total daily energy intake (kcal·day^{-1}) and climbing/training volume, in males or females. Under-reporting, either intentionally or unintentionally, is problematic using all methods of dietary assessment (52). Prevalence of underreporting in athletes is high, particularly in those who need to maintain a lean physique, such as gymnasts, with up to 61% classified as under-reporters (53). However, the participants in the present study were coached closely and an electronic template was provided with strict guidance notes detailing the requirements for accurate reporting, in an attempt to negate the effects of underreporting. Moreover, the data presented is consistent with previous research. Zapf et al. (25) reported that 40% of climbers failed to meet a conservative estimate of energy requirements (2,500 kcal·day^{-1}), despite training for more than 2 h per day. Kemmler et al. (26) found similar results, reporting that the energy intake of the climbing athletes was not significantly greater than their BMI matched controls, despite a 9.5 times greater training volume. These findings also appear to be consistent in adolescent climbers, where a high prevalence of sub-optimal energy intake (82%) has been reported, with no significant association between training hours and energy intake (27). Furthermore, no difference was reported in energy intake between climbing ability groups (27), reflecting the data in the present study, where no significant correlation between ability and energy intake was seen in adult climbers. Despite a lower absolute energy intake compared to males (~2,039 vs. ~2,270 kcal·day^{-1}), females had a significantly higher energy intake when expressed relative to fat-free body mass (45.6 vs. 37.2 kcal·kgFFM^{-1}·day^{-1}; $p \leq 0.01$). This finding is likely due to the lower FFM and absolute body mass values reported in the female participants, when compared to the males.

It should be noted that the use of predictive equations to determine RMR values is a limitation of the present study and previous work in this field (27), due to the potential to generate an under or over prediction of energy requirements (39). Although the inclusion of body composition data may improve the accuracy of predictive equations in athletes (39), future research should consider a more precise method, such as indirect calorimetry (54).

A sufficient energy intake supports the optimal functioning of the body, determines the capacity for macronutrient and micronutrient intake, and influences body composition (29). Although gaining a reliable representation of energy intake using self-reporting methods is challenging (55), based on the data currently available it would be reasonable to suggest that climbers are at risk of energy restriction and/or low energy availability, evidenced by sub-optimal energy intakes, and a lack of adjustment of energy intake in relation to exercise volume.

Relative Energy Deficiency in Sport (RED-S) is a term which describes the myriad of consequences of consuming insufficient energy to meet the requirements for optimal physiological function in athletic populations (28). The negative health consequences of RED-S can be long lasting, and can impact menstrual function, bone health, metabolic, cardiovascular, endocrine, gastrointestinal, and immunological systems, as well as psychological well-being (28). Furthermore, RED-S may negatively impact athletic performance by impairing strength, endurance, injury risk, training response, coordination, concentration, and judgement (28). It is important to note that low energy availability and the development of RED-S can occur in the absence of weight loss, therefore it cannot be considered synonymous with energy balance (28).

Macronutrient Intake

There were no between-gender differences found for intake of carbohydrate, protein, or fat when expressed relative to body mass, which is in agreement with previous research (27, 56). No differences in macronutrient intake were found between intermediate/advanced and elite/higher-elite climbers in males or combined genders, in agreement with the findings of Sas-Nowosielski and Judyta (56), who also found no difference between ability levels. However, there was a significant correlation between climbing ability and protein intake in female athletes, supporting the work of Michael et al. (27), who found that elite climbers consumed more protein than intermediate climbers, although reported differences were small (1.8 vs. 1.7 $g{\cdot}kg^{-1}{\cdot}day^{-1}$).

Mean carbohydrate intake of 3.7 $g{\cdot}kg^{-1}{\cdot}day^{-1}$was similar to values previously reported (27, 56) and within the suggested range of 3–7 $g{\cdot}kg^{-1}{\cdot}day^{-1}$for climbers (57), although very much toward the lower end of the scale. Previous research that has attempted to provide guidelines on carbohydrate intake has primarily relied on extrapolations from other sports, so actual requirements are relatively unknown. Indeed, Tipton et al. (58) suggested that an intake of 5 $g{\cdot}kg^{-1}{\cdot}day^{-1}$ was necessary to prevent depletion of glycogen in sports that feature intermittent bouts of high-intensity resistance exercise.

Mean protein intake of 1.6 $g{\cdot}kg^{-1}{\cdot}day^{-1}$ was similar to values previously reported (27, 56) and double the recommendations for the general public [0.8 $g{\cdot}kg^{-1}{\cdot}day^{-1}$; (48)], indicating that climbers have an awareness of the necessity of protein for muscle remodelling and repair. As anticipated, the overall daily protein intake was ∼31% higher in climbers who used a protein powder supplement ($p = 0.016$). Furthermore, when comparing protein intake relative to body mass in protein supplement non-users vs. users, mean values (1.46 ± 0.40 vs. 2.0 ± 0.58 $g{\cdot}kg^{-1}{\cdot}day^{-1}$; $p \leq 0.01$) show a span similar to the proposed recommended range [1.3–2.0 $g{\cdot}kg^{-1}{\cdot}day^{-1}$; (51, 57)], suggesting a role of supplementation in climbers achieving the upper limits of recommended intake. Protein intake of vegan/vegetarian athletes was significantly lower than that of omnivores (1.25 vs. 1.71 $g{\cdot}kg^{-1}{\cdot}day^{-1}$; $p = 0.007$), and falls below the proposed recommendations for the sport [1.3–2.0 $g{\cdot}kg^{-1}{\cdot}day^{-1}$; (51, 57)]. This is in agreement with the findings of Clarys et al. (59) who found vegan/vegetarian diets to be generally lower in protein. Furthermore, plant-based proteins are generally regarded as being of lower quality than animal-based ones, as they are usually lacking one or more essential amino acids (60) and therefore, need to be carefully combined in order to meet the full spectrum of amino acids required. These findings suggest that vegan/vegetarian athletes may be at greater risk of protein insufficiency and may need to adopt targeted strategies to ensure that recovery, body-composition, and performance are not compromised.

Iron Intake

Mean iron intake was ∼14 $mg{\cdot}day^{-1}$, with no significant difference between genders, however, 79% of males met the DRI for the general population, compared to just 20% of the females. This is primarily due to a large difference in proposed iron requirements (8 mg males, 18 mg females; 46), to compensate for menstrual losses (61).

Sim et al. (32) suggested that reducing energy intake may result in proportionally lower dietary iron consumption. The current findings are in agreement, with medium strength correlations found between iron intake and daily energy intake. Furthermore, this may offer some explanation as to why over 50% of climbers did not meet recommended iron intake, considering that 77.5% failed to consume enough energy to support "moderate" levels of exercise.

No correlation between iron intake and serum ferritin was found in the present study. A contributing factor could be the time-frame of data collection, as an athlete's dietary intake data over a 5–8 days period is recommended to provide an accurate assessment of micronutrient intake (24). However, collecting food records for longer than 3–4 days has been shown to reduce compliance and accuracy, as well as contribute toward a high drop-out rate (62). To increase the timeframe and size of data collection, short dietary records repeated several times, 2–3 months apart over different seasons, using non-consecutive random days, could be used in future research (63).

Supplement Use

Only one study to date has investigated supplement use amongst climbers (56), therefore, comparable data is limited. The prevalence of supplement use was relatively low (45%), considering that prevalence in other athletic populations has been reported around 81–100% (64). One contributing factor could be that the supplement data in this study was taken from food diaries alone, as opposed to a specific supplement history survey often used in other studies (65). Furthermore, tea and coffee were not included, despite containing caffeine, as intake was not assessed relative to training or competition. The most commonly used supplement was protein powder, supporting the findings of Sas-Nowosielski and Judyta (56), and appeared to increase the overall daily intake of protein. Supplementation was found to be more prevalent in intermediate/advanced climbers than in elite/higher elite. This was an unexpected finding considering that supplement use is generally higher in elite athletes than in their non-elite counterparts (65). The use of supplements in climbing athletes requires further investigation.

Iron Status

Iron deficiency has been shown to negatively impact aerobic power, with larger deficiencies correlating with greater reductions in oxygen transport to the working muscles (32). Reduced aerobic power is likely to place greater demands on anaerobic metabolism during climbing (66), especially on steeper routes where it is considered the predominant energy source (9, 67), and may exacerbate decrements in performance. Despite resulting in impaired physiological function, iron deficiency is a commonly reported issue in athlete populations, affecting ∼3–11% of male athletes, with a higher prevalence of ∼15–35% seen in females (32). In the present study, 31.6% of participants had a sub-optimal iron status as defined in the literature (44, 45). The prevalence of sub-optimal iron status was greater in females (45%) compared to males (∼17%), with one quarter of females meeting the criteria for stage 1 iron deficiency (ferritin < 35 $\mu g \cdot L^{-1}$, Hb > 115 $g \cdot L^{-1}$, transferrin saturation $> 16\%$) (44).

It has been suggested that low energy availability (LEA) may be partially induced by and result in the development of iron deficiency (30). The proposed mechanism is related to the iron deficiency induced perturbation of thyroid function, leading to decreased appetite and impaired metabolic efficiency; which can result in a reduced energy intake, increased energy expenditure and potentially, further exacerbation of LEA in athletes (30).

Considering the high prevalence of both sub-optimal energy intake and iron status in the climbing population assessed, it would be reasonable to suggest an interaction of this nature, however, statistical analysis revealed that there was no significant correlation between serum ferritin and energy intake for males, or females. Therefore, further research should consider iron status in relation to energy availability, rather than overall intake. Another factor to consider in the incidence of ID in this population is exercise-induced haemolysis, as previous research has suggested that this is exacerbated by muscle damaging exercise (68), and increased blood lactate levels (69); both of which are considered physiological features of climbing and training for climbing (70). Finally, menstrual blood losses of iron in females, may contribute toward the higher prevalence of ID seen within this population group (61). Larsson et al. (71) reported lower menstrual blood loss (~50%) in combined oral contraceptive pill (OCP) users compared to non-users, with OCP administration increasing serum ferritin levels by ~21–29% in subjects with pre-existing low iron stores (ferritin < 10 $\mu g \cdot L^{-1}$), therefore, OCP use offers a therapeutic intervention for women who struggle to maintain iron stores due to heavy menstruation, with the potential additional benefit of protection from soft tissue injury (72). It is crucial to ensure that the dietary intake of the female athlete supports the energy needs of eumenorrhea and includes iron rich foods to attenuate a continued loss via menstruation. Future research may also consider controlling for variables which may affect iron loss in females.

Although there was no significant difference in iron intake between the dietary preference groups, serum ferritin was significantly lower in vegan/vegetarians when compared to omnivores in female climbers (33.2 vs. 57.5 $\mu g \cdot L^{-1}$), with no difference seen between vegan vs. vegetarian climbers when analysed separately. This could be explained by the different mechanism by which heme iron from animal products is absorbed compared to non-heme iron derived from plants, resulting in more efficient absorption which is less affected by accompanying dietary factors, and therefore, significantly greater bioavailability (73, 74). Whilst the presence of vitamin C can enhance the absorption of non-heme iron, chemicals (polyphenols and phytates) and minerals (calcium) that are found in tea, coffee, whole grains, legumes and dairy products, can inhibit the absorption of non-heme iron within a meal (75) and therefore, the overall intake and timings of these foods should be carefully considered by vegan/vegetarian athletes at risk of ID.

Limitations in the assessment of iron status in this study may lead to confounding results. For example, as an acute state reactant, serum ferritin (SF) may be artificially raised in response to intense exercise (20). Although participants were instructed to avoid exercise in the hours preceding the lab visit, exclusion of this variable relies on strict adherence to instruction. In addition, research suggests that SF may be decreased during menstruation in female participants (76), which is affected by variables such as the menstrual cycle phase (61), the use of birth control (71), or amenorrhea; induced by menopause, or LEA (28). Due to a lack of control of these variables, it is not possible to exclude this interaction and therefore, the data should be considered as preliminary at this stage, although the defined cut off values for ID are consistent irrespective of these variables. Furthermore, C-reactive protein, a marker of inflammation, was not measured and therefore it cannot be ensured that SF was not confounded by infection, inflammation, or injury (77), however, all participants reported to be in good health at the time of testing.

CONCLUSIONS

These findings suggest that experienced climbers with intermediate to higher elite abilities practice energy restriction and are at risk of low energy availability, evidenced by sub-optimal energy intakes, and a lack of adjustment of energy intake in relation to exercise volume, supporting previous research. Furthermore, the preliminary data presented suggests that there is a high prevalence of climbing athletes at risk of iron deficiency, particularly females, who through dietary restriction may struggle to meet the higher gender specific iron intake targets. In view of the limitations outlined, future research should consider iron status in relation to energy availability and investigate additional factors which may predispose this population to iron deficiency, as well as the risk of relative energy deficiency in sport. Routine assessment of nutritional status by a qualified sports dietitian or sports medicine doctor is recommended in this population, with subsequent dietary guidance that focuses on increasing dietary iron intake and periodised energy provision in high risk athletes.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Sheffield Hallam University Research Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

EG-S designed the study, collected, analysed and interpreted the data and produced the manuscript. RS assisted with data collection, production of figures, and preparation of the manuscript. MR supervised the study, advising on all elements,

and performed the final editing of the manuscript. All authors gave final approval on the manuscript.

FUNDING

This work was supported by Sheffield Hallam University—Gold Open Access Fund.

ACKNOWLEDGMENTS

We would like to thank The Climbing Works and Lattice Training for facilitating participant recruitment for this study. We would also like to acknowledge his wife, Megan, for her assistance during data collection.

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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.

frontiers in Psychology

ORIGINAL RESEARCH
published: 28 September 2020
doi: 10.3389/fpsyg.2020.02188

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3D Visualization of Body Motion in Speed Climbing

Lionel Reveret[1*], *Sylvain Chapelle*[2], *Franck Quaine*[3] *and Pierre Legreneur*[4]

[1] LJK, University Grenoble Alpes, CNRS, INRIA, Montbonnot-Saint-Martin, France, [2] FFME, Fédération Française d'Escalade et de Montagne, Paris, France, [3] GIPSA, University Grenoble Alpes, CNRS, Saint Martin d'Hères, France, [4] LIBM, University Lyon 1, Lyon, France

Speed climbing involves an optimization of the velocity of the ascent and the trajectory path during performance. Consequently, any amount of energy spent in the two other directions than vertical, namely the lateral direction and the direction perpendicular to the wall plane, is a potential loss of performance. To assess this principle, we present a study on 3D motion analysis and its 3D visualization for a subject during a speed climbing performance. The fundamentals of geometrical measurement in 3D require to integrate multiple 2D cues, at least two, in order to extract 3D information. First results with two drones following an athlete's ascent show that a 3D velocity profile can be provided from the tracking of a marker on the harness, pointing critical phases in the ascent where the vertical speed is not dominant any more. We further investigate 3D motion of full body using markerless video-based tracking. Our approach is based on a full body 3D avatar model of the climber, represented as a 3D mesh. This model and its deformation are learned in a laboratory studio. The learning needs to be done only once. Result is a manifold embedding of the 3D mesh and its deformations, which can be used afterwards to perform registration onto video of performance of speed climbing. The results of the tracking is an inference of the 3D mesh aligned onto videos of speed climbing performance. From this 3D mesh, we deduce an estimation of the center of mass (COM). We show that this estimation from 3D mesh differs from the usual approximation of the COM as a marker on the harness. In particular, the 3D mesh COM takes into account the whole body movement such as the influence of the limbs which is not detected by a marker on the harness.

Keywords: speed climbing, video analysis, biomechanics, motion analysis, 3D visualization, center of mass

OPEN ACCESS

Edited by:
Bernadette Ann Murphy,
Ontario Tech University, Canada

Reviewed by:
Leonard James Smart,
Miami University, United States
Eloisa Limonta,
University of Milan, Italy

****Correspondence:***
Lionel Reveret
lionel.reveret@inria.fr

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *01 February 2020*
Accepted: *04 August 2020*
Published: *28 September 2020*

Citation:
Reveret L, Chapelle S, Quaine F and Legreneur P (2020) 3D Visualization of Body Motion in Speed Climbing. Front. Psychol. 11:2188. doi: 10.3389/fpsyg.2020.02188

1. INTRODUCTION

Video analysis is now regularly used by high-level athletes and coaches to address performance optimization. Sequences are usually acquired through portable devices or fixed environment, allowing to quickly visualize a current trial and providing an instant feedback on the performance. The quantification of benefit of such video feedback in self-control condition has been reported in Basketball shot for example (Aiken et al., 2012) and specifically in climbing (White and Olsen, 2010). While some angle of view are naturally preferred, typically dorsal view in our case of interest about speed climbing, it logically provides a 2D view only of the performance. One might consider this as a limitation since the range of motion of the performance is deeply embedded in 3D. One straight-forward solution is to use additional viewpoints such as a side view to better assess the tri-dimensionality of motion. This raises the problem of presenting the user with several "windows" which may lead to overwhelming information spread over all views. We present here an original approach to automatically visualize a speed climbing performance in 3D through: (i) the geometrical reconstruction of the climbing scene and (ii) markerless video tracking of a 3D avatar of the performance of the athlete. As an end-result, an interactive 3D scene can be manipulated by non-technical user to inspect all aspect of motion within a single window interface.

Previous works on climbing motion rely wether on 2D video analysis only or inertial measurement unit (IMU) as depicted in the literature review by Orth et al. (2017). Among first kinematical studies of climbing, Cordier et al. introduced the concept of entropy in climbing, based on the convex hull span by the trajectory of a marker on the harness (Cordier et al., 1993). For climbing motion, Seifert et al. stressed the importance of addressing motor-control issues in 3D (Seifert et al., 2014, 2015). From jerk data, calculated using 3D linear accelerations and body orientation, they defined the concept of fluency which can account for the performance of climbers. For 3D position, it is well-known that it is not reliable to deduce this quantity from 3D acceleration due to the propagation of noise in the double numerical integration of the signal. Our goal is to tackle a biomechanical quantity such as COM (Sibella et al., 2008; Zampagni et al., 2011), motivating our focus on the body as a 3D volume. Assessment of the 3D location of COM in climbing has been reported by Sibella et al. (2008). The data were collected from a markers-based system and limited to a 3 m high wall. Such an experimental approach is difficult to adapt for speed climbing, motivating a markerless video-based technique. With the recent advances of Machine Learning approaches, numerous techniques exist now for video-based 3D motion analysis. All of them target a general purpose application with huge learning sets. We focus on a specific athlete for which we built a dedicated 3D biomechanical twin, or avatar. Using this model, we adapted one of our previous work on manifold learning of 3D body shapes in motion (Duveau et al., 2012) to speed climbing gesture.

We describe here a method to capture 3D information about the motion of a speed climbing athlete from video acquired by several points of view, fixed, or possibly moving such as drones. The key aspect of our method is to be based on a 3D avatar of the athlete. This avatar is first learned in a laboratory studio. Granting the morphology of the athlete is not significantly changing, this learning needs to be done only once. Afterwards, the learned 3D avatar is automatically registered onto any video of the performance of the athlete, without the need for any markers. The end result of the approach is an animated 3D representation of the performance which can be interactively explored by changing viewpoint. In addition, we show that a prediction of the 3D trajectory of the COM can be derived from this 3D representation, providing an estimation more reliable than a marker on the harness.

2. METHODS

2.1. Calibration of Viewpoints

In video recording of climbing performance, viewpoints from the ground classically introduce artifacts such as bottom view distortion which impedes the efficiency of visual inspection and automatic processing. For this experiment, we have thus used two drones as they provide high-quality video capabilities and can be easily monitored to follow the ascent of the athlete. As each drone is moving with respect to the environment, motion recorded in the video mixes both the motion of the athlete and the motion of the drone. This is resolved by performing an auto-calibration of the drones 3D position and orientation at each frame with respect to reference frame linked to the wall. Drones usually embed inertial and GPS sensor to monitor their position. Such sensors turned out to be not precise enough to compute an accurate estimation of their relative position and orientation—accuracy goal is to be <1 cm and 1 degree per frame). We used instead a geometrical approach, based on a prior 3D scanning of the wall. At each frame, a prior 3D model of the wall is registered onto the video view by aligning salient features of the holds. Registration is performed by optimizing the 3D location and orientation of the drone with respect to a metric on wall features. Like for traditional markers-based system, the quality of such a calibration can be assessed through back projection. Results showed that the required accuracy can be achieved.

2.2. Extraction of the 3D Trajectory of a Marker

As a first result following calibration and as a matter of validation, we implemented a 3D reconstruction of the trajectory of a marker on the harness. While not exactly the COM (as detailed later), such a location is close enough to COM to be worth noticing and to be considered as a good representative of the overall body 3D location. The 2D location of the marker is tracked on each view using normalized cross correlation. As the 3D location and position of each drone is known at each frame, the 3D location of the marker can be derived using Direct Linear Transform approach (DLT). Drones are calibrated with respect to a fixed reference frame related to the wall, hence the extracted 3D location of the marker. By derivating this 3D location using finite difference and knowing the video frame rate, the athlete's speed can be estimated in metric units. This constitutes a first visualization of a motion quantity in 3D, with a possibility to identify key moment where the vertical speed is decreasing or when the climber is getting too much away from the wall, inducing a loss of performance for the goal of reaching the top in minimal time.

2.3. Construction of the 3D Avatar

To go beyond the 3D trajectory of an isolated marker, we focus now on 3D visualization of the body as a whole based on a 3D mesh representation. This 3D representation will be used to implement a markerless video tracking approach (next section). To build this 3D model of the athlete, we used a laboratory facility consisting in a studio equipped with 68 video cameras. This studio allows to compute, for each video frame, a full 3D reconstruction of the body surface in motion using a convex hull approach (Laurentini, 1994). The process consists in, first, calibrating the video camera so that their location and orientation in 3D space are known. During the live performance, the silhouette of the subject is segmented using background substraction. From this silhouette, a 3D generalized cone is computing for each camera view, made of the camera location at the apex and the silhouette at the base. Finally, the geometrical 3D intersection of all the cones provides the resulting 3D surface of the subject. Unlike a range scanner, such an approach does not deliver the exact 3D surface but an approximating tangent hull. However, with as many as 68 cameras, it can be considered that the convex hull is closely approaching the true 3D surface within a sub-millimeter accuracy. Having a 3D surface allows to easily derive an estimation of the COM using geometrical computation, under the assumption of a constant density of 1 kg/dm^3. This experimental data provides the required information to learn the manifold of all the deformations of the athlete's 3D body surface. This learned model can subsequently be used for tracking live motion from video during a performance on the wall.

2.4. Automatic Tracking of Whole Body 3D Motion From Video

It cannot be envisioned to deploy a set-up with 68 fixed cameras or 68 drones at the speed climbing wall for a day-to-day practice. Instead, we use the set of 3D meshes in motion to learn a manifold of 3D shapes of the athlete. The tracking procedure consists in registering the 3D mesh model of the athlete onto the two drones video view by optimizing the manifold parameters with respect to salient body features (Duveau et al., 2012). The manifold allows for a reduction in dimensions which guarantees the convergence of the registration. At the end of this stage, an instance of the 3D surface of the athlete is inferred onto video, providing a 3D encoding in the frame reference of the climbing wall. Using a registration on two views prevents from ambiguities and occlusions and guarantees a better fit between the 3D model and the real pose of the athlete during ascent.

One female climber performed a set of maximal speed ascents on the official route. We selected the best trial (ascent time = 7.9 s) for this analysis. The performance has been filmed with two drones (DJI Mavic pro) with resolution 3,840 x 2,160 pixels at 30 fps. Drones are following a purely vertical ascent, at a distance of about 8 m from the athlete (one pure dorsal view, one apart from 45 degrees angle). The two drones have been temporally synchronized at the frame level with a common light signal triggered at the beginning of the performance. The procedures (data collection and analysis) were approved by the French Federation of Mountaineering and Climbing (FFME), and conformed to the declaration of Helsinki. It has been approved by the University of Lyon ethic committee as not invasive because it is limited to the video recording of a regular practice without any contact with the subject's body. Piloting of the drones was performed under the supervision of a certified pilot (drone certificate MAVIC-53) in a closed non-public environment. Flying was limited to a vertical ascent of <20 m.

2.5. Assembling the 3D Scene

We assemble all the results into a final 3D scene. First, the 3D scan of the wall used for calibration can be directly imported. Dedicated texturing can be added to augment the quality of the rendering. The 3D mesh representation of the athlete in motion is integrated, with also a possible texturing for aesthetics consideration. It is worth noticing that such texturing needs to be done only once off-line as the topology of the mesh remains constant. Only the 3D location of the vertices is updated by the automatic tracking phase. For the sake of validation of the process, the original video of the drones can be first augmented with the projection of the 3D animated scene (**Figure 2**). The 3D animated scene can also be explored from 3D viewpoint, different from the original drone video viewpoint, following a subjective camera principle (**Figure 3**). Lastly, the 3D view can be augmented with information such as the 3D trajectory of the COM or velocity cues. Hints on time of grasping of the holds can also be visualized by computing 3D velocity of mesh vertices at limbs extremities.

3. RESULTS

3.1. Subject Trial

Center of mass of the subject has been first approximated by a marker attached to her harness, close to the middle of the pelvic ilium bones. The 2D trajectory of this marker has been digitized on each video using image normalized correlation. The 3D reference frame is made of the horizontal ground (plane XZ) and the gravity vertical axis (axe Y), with the origin at the bottom of the wall (**Figure 1**). Triangulation provides the 3D trajectory of this marker into this world reference frame. This paper presents the methodology of the 3D visualization and focuses thus on a single trial.

3.2. 3D Trajectory of the Harness Marker

We report on **Figure 1** the three components of the 3D position of the marker (first row). Data have been processed with a low-pass Butterworth filter (order 5, cut-off frequency 5 Hz). X direction is lateral, Y direction is vertical, and Z direction is perpendicular to the wall minus 5 degrees because of the wall inclination. We also report the corresponding velocity component for this marker in m/s (second row) and the overall 3D norm of the velocity (black curve, identical on each plot). As the trajectory is measured in 3D in world reference frame (gravity exactly vertical), the 5 degrees inclination of the wall appears but can be easily canceled out. This is of particular interest for the Z direction, as such a cancelation allows to clearly visualize the distance of the climber with respect to the wall. **Figure 1** shows both the results in the world reference frame (red, green, and blue) and in the wall reference frame after wall inclination correction (magenta, yellow, and cyan). Biggest difference is on the Z-component, with of course no impact on the overall speed norm. Red and magenta curves are exactly overlapping as the two reference frames differs only in X-axis rotation.

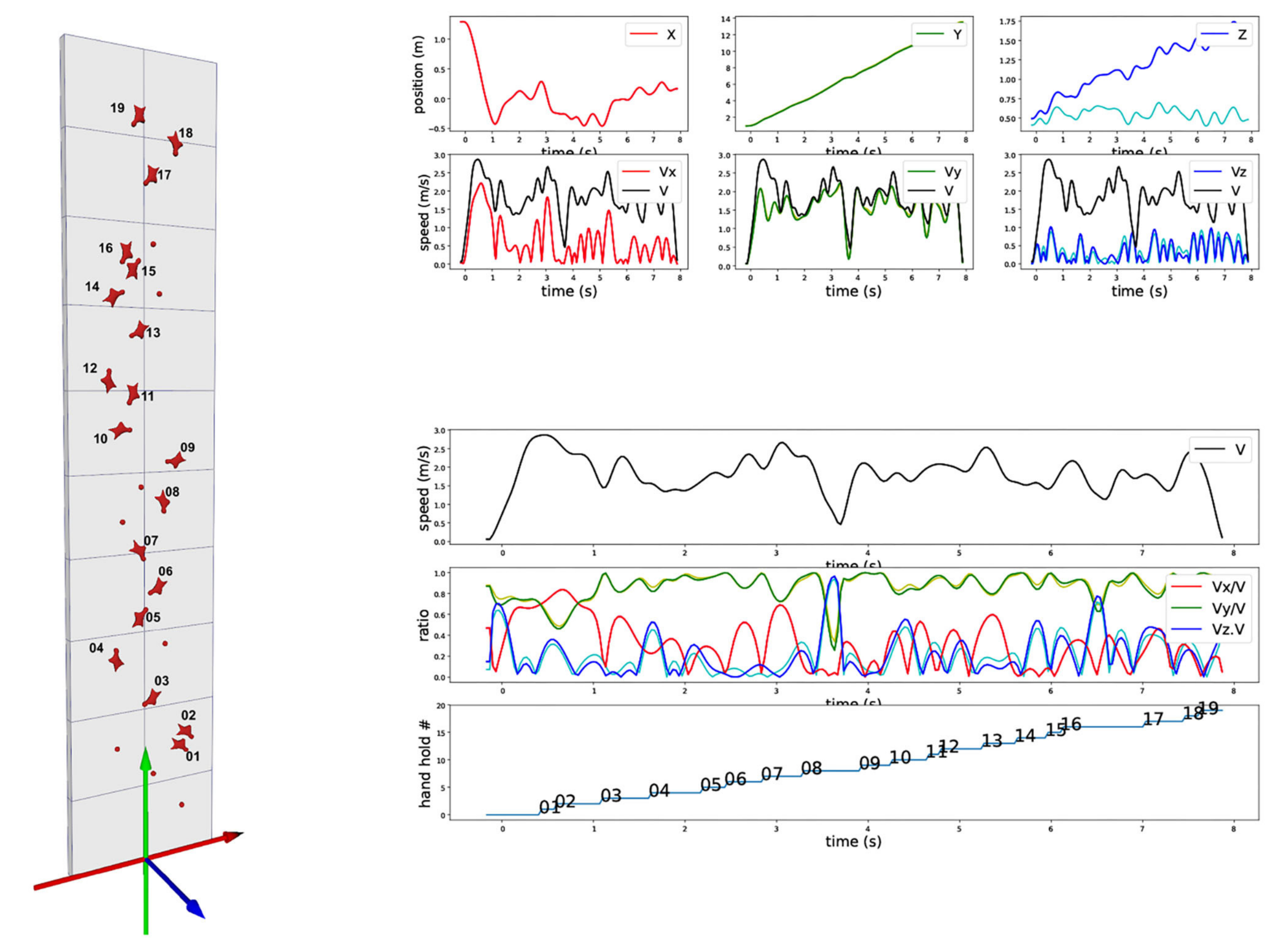

FIGURE 1 | Trajectory and velocity of a marker on the harness. (Left) Standard speed climbing wall with lateral axis (X-red), vertical axis (Y-green), and axis perpendicular to XY plan (Z-blue). (Top right): (upper) 3D trajectory of XYZ components over time of a marker on the harness (dark blue is the world-space Z-trajectory, light blue is the Z-trajectory with the cancelation of the 5 degrees inward inclination of the wall, corresponding to the exact perpendicular distance to the wall); (lower) corresponding XYZ velocity components. (Bottom right): (upper) Velocity euclidian norm across time; (middle) XYZ velocity components ratios with respect to the velocity euclidian norm; (lower) Vertical progression of the marker with respect to the hold numbers as represented on the left.

On bottom of **Figure 1**, we explore the ratio of the velocity components with respect to the total velocity. First row is a recall of the total velocity, second row the three velocity component ratios together, and the last row indicates the evolution of the ascent with respect to "hand" holds number (we omit "feet" holds for clarity). The curve corresponds to the moments when the hips marker vertical position goes above the holds. The different flat areas thus provide an estimate of the time spent between two holds during vertical ascent.

The velocity ratio clearly outline moments when the vertical ascent is less dominant. It typically corresponds to "dyno" transition from hold 8 to 9 and hold 16 to 17. During these periods, the wall-orthogonal Z-axis component becomes dominant, corresponding to a posture which is getting farther from the wall. On hold 7 to 8 and hold 13 to 14, the velocity components ratios profiles show that the lateral X-axis becomes important with respect to the vertical Y-axis. They correspond to a required change of route but also show a drop in the vertical component. The visualization of these 3D cues provide first insights on speed climbing performance.

3.3. 3D Full Body Tracking

The previous steps validated the experimental infrastructure to extract 3D information from video in terms of the trajectory of a single marker. We report here the extension to full body analysis through its 3D visualization. The official 15 m high speed climbing wall can obviously not be replicated into the laboratory as the volume which can be captured at the laboratory facility is limited to 5 × 5 × 3 m. Consequently, the athlete has been asked to perform a mimicry of the speed climbing ascent as the route is standardized and completely memorized. Protocol for the simulation of movement has been left to the expertise of the climber who is a word-level athlete. We used this sequence to learn the manifold of 3D shape variation of the athlete's

3D surface appearance. We used a Gaussian Process Latent Variables Model as described in Duveau et al. (2012). Simulation of motion in laboratory conditions has been used to bootstrap the prediction algorithm through the machine learning phase. It does not impose the real wall condition to exactly replicate the motion in laboratory as some generalization is allowed. Joint angles start from the configuration collected in laboratory but are modified in value and timing to fit the real world case using model alignment. **Figure 2** on the left shows the model learned in the laboratory and the result of the automatic registration onto a video from a drone. It is noticeable that the fit between the learned 3D model and the real silhouette of the athlete on the ascent does not match exactly. For the sake of robustness and prevent from drifting in tracking, we currently constrain the model to stay very closed to the learned manifold in the laboratory. The difference between 3D motion during learning and 3D motion during real ascent at the wall explains the local mismatch. Future works include allowing more degrees of freedom in the model so that local features such as feet and hands orientations can be better recovered. As for now, we focus only on the overall 3D motion of the body. In particular, we explore here the prediction of the COM from the 3D mesh on which local adjustments of feet and hands will not have a significant impact.

3.4. COM Estimation : Marker on the Harness vs. Prediction From 3D Mesh

We examined here the approximation of considering the COM as a fixed marker on the harness near the hips vs. a prediction as the COM of 3D mesh. The prediction from 3D mesh was automatically computed from the 3D mesh as the barycenter of the enclosed 3D volume with the hypothesis of uniform density. We compared this trajectory to the trajectory of the marker on the harness with the result of this prediction. Results show that the mean distance between the marker on the harness and the COM from 3D mesh are, respectively in the three directions: 7.3 ± 5.9 cm for the X direction (lateral), 8.7 ± 4.6 cm for the Y direction (vertical), and 24.1 ± 4.3 cm for the Z direction (perpendicular to wall). The biggest difference is on the Z direction as the marker is attached on the back while the 3D mesh COM is more likely also influenced by limbs projection toward the wall. **Figure 3** illustrates on overall comparison between the trajectory of the marker and the trajectory of the 3D mesh COM. It shows that the actual trajectory of the 3D mesh COM appears smoother than the trajectory of the marker. We also report a situation where the difference in vertical direction has been reported maximal (3D mesh COM is 16.1 cm above the marker). It corresponds to a case where the legs are flexed into an upward position. This explains well why the 3D mesh COM is actually moving upper than the marker on the harness which thus proves not to be always a good approximation of the true COM.

3.5. Visualization of Extra Cues in 3D

The 3D scene can be visualized from different angles and as such represent a valuable enhancement of standard video. In addition, visual cues can be added onto the 3D scene such as velocity. In **Figure 4**, all the position of the COM have been reported during ascent, with a color ramp associated with magnitude of velocity ranging from minimal velocity in red to maximal velocity in green. Other visual cues can be integrated into the 3D view.

4. DISCUSSION

Results show that the trajectories of a marker on the harness and the 3D mesh COM differ. Although no exact measurement of the true COM exists for validation, its estimation from the 3D mesh follows some rational insight and tends to prove it is more reliable. Typically, unlike the marker, the 3D mesh method accounts for the projection of the limbs toward the wall or the flexion of the legs. Therefore, we compared the velocity computed from the marker with the one computed from the COM, following the same scheme as **Figure 1**. Results in **Figure 5** show significant differences, especially around the "dyno" section when body crosses hold 08. Trajectory of the marker is displayed in dashed line and trajectory of 3D mesh COM is in plain line. After a close look at this section, it confirms that the COM from 3D mesh provides a more meaningful interpretation with respect to the true COM, compared to the marker. Indeed, at this section,

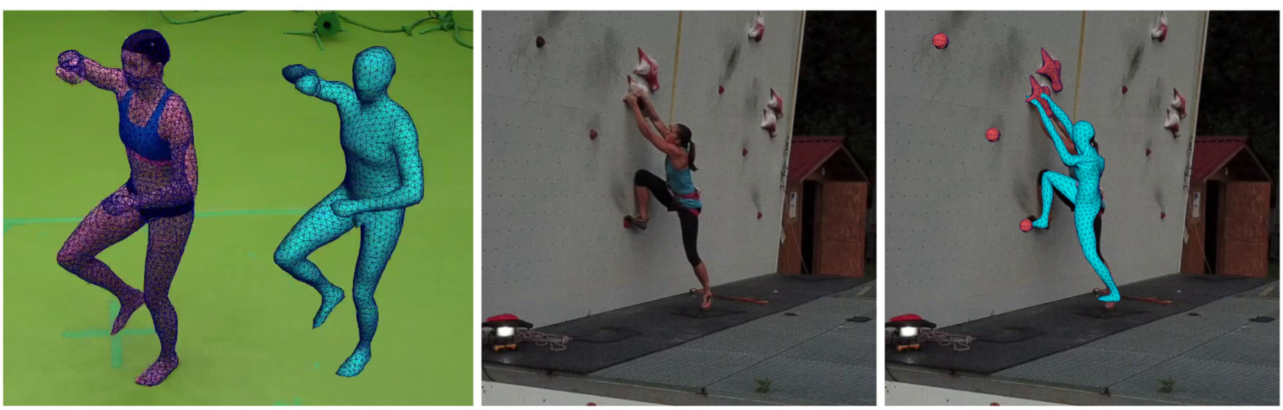

FIGURE 2 | 3D avatar of the athlete and its overlay onto video : during training at the lab (left), original test input condition (middle), tracking result overlay (right).

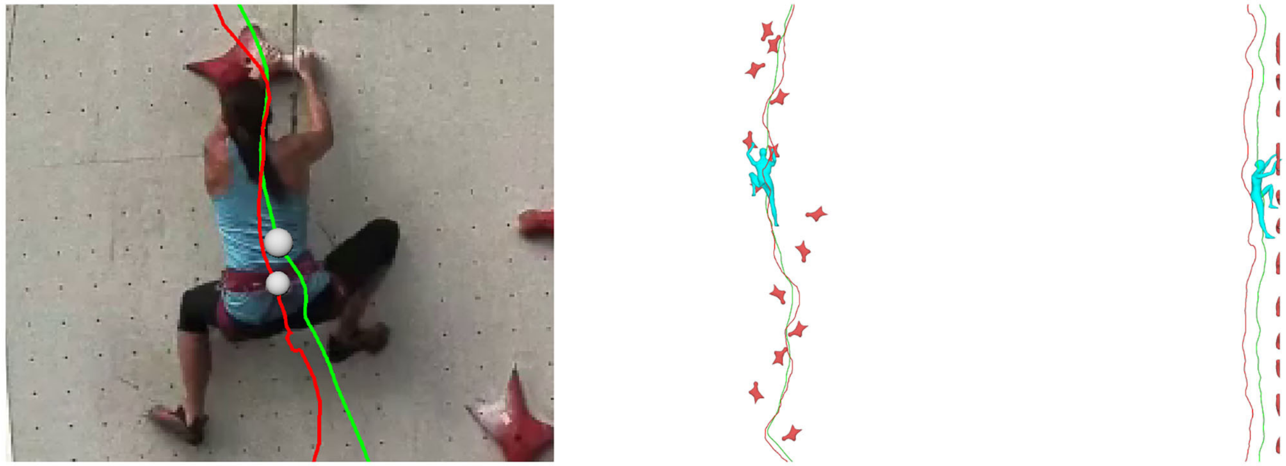

FIGURE 3 | Comparison between trajectories from marker on the harness (red curve) and COM computed from 3D mesh (green curve).

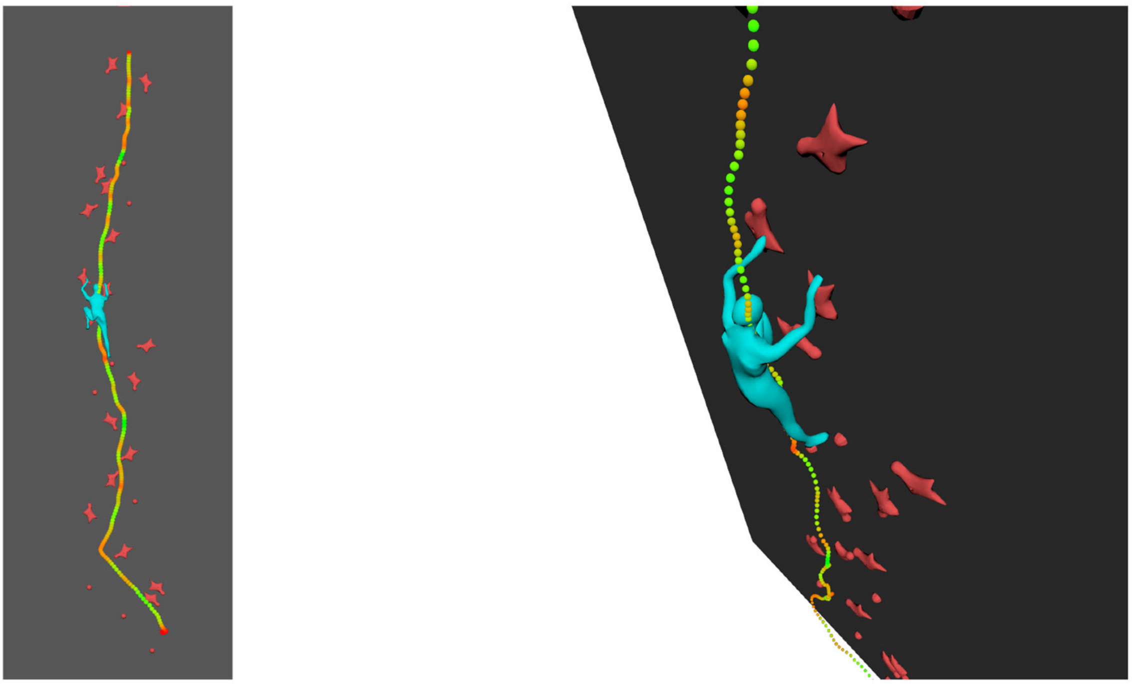

FIGURE 4 | Velocities with color ramp related to velocity magnitude (minimal-red to maximal-green).

even if the pelvis is actually stopping, inducing a loss of vertical speed of the marker, the legs are still moving upward. Similarly to the case reported on **Figure 3**, it suggests why the true COM maintains an upward velocity and why the 3D mesh COM is a better estimate.

Video-based technology is a promising alternative to makers-based system because of its practical use. It is however difficult to exactly evaluate its accuracy against the later approach unless both set-up, with and without markers, are installed at the same location. However, the experiment presented here shows the potential of the approach, first for a qualitative feedback through 3D visualization and also, for quantification of high-level features such as an estimation of the 3D trajectory of the COM. As an example of complementary features extraction and visualization, the 3D tracking allows to measure valuable cues on the timing of holds grasping. Indeed, by inspecting the velocity of the mesh vertices at hands and feet, a duration of the grasping can be deduced. **Figure 6** shows the result for this ascent with a threshold of 1 cm/s to identify grasping from velocity magnitude of limbs extremity vertices (**Figure 6**). In

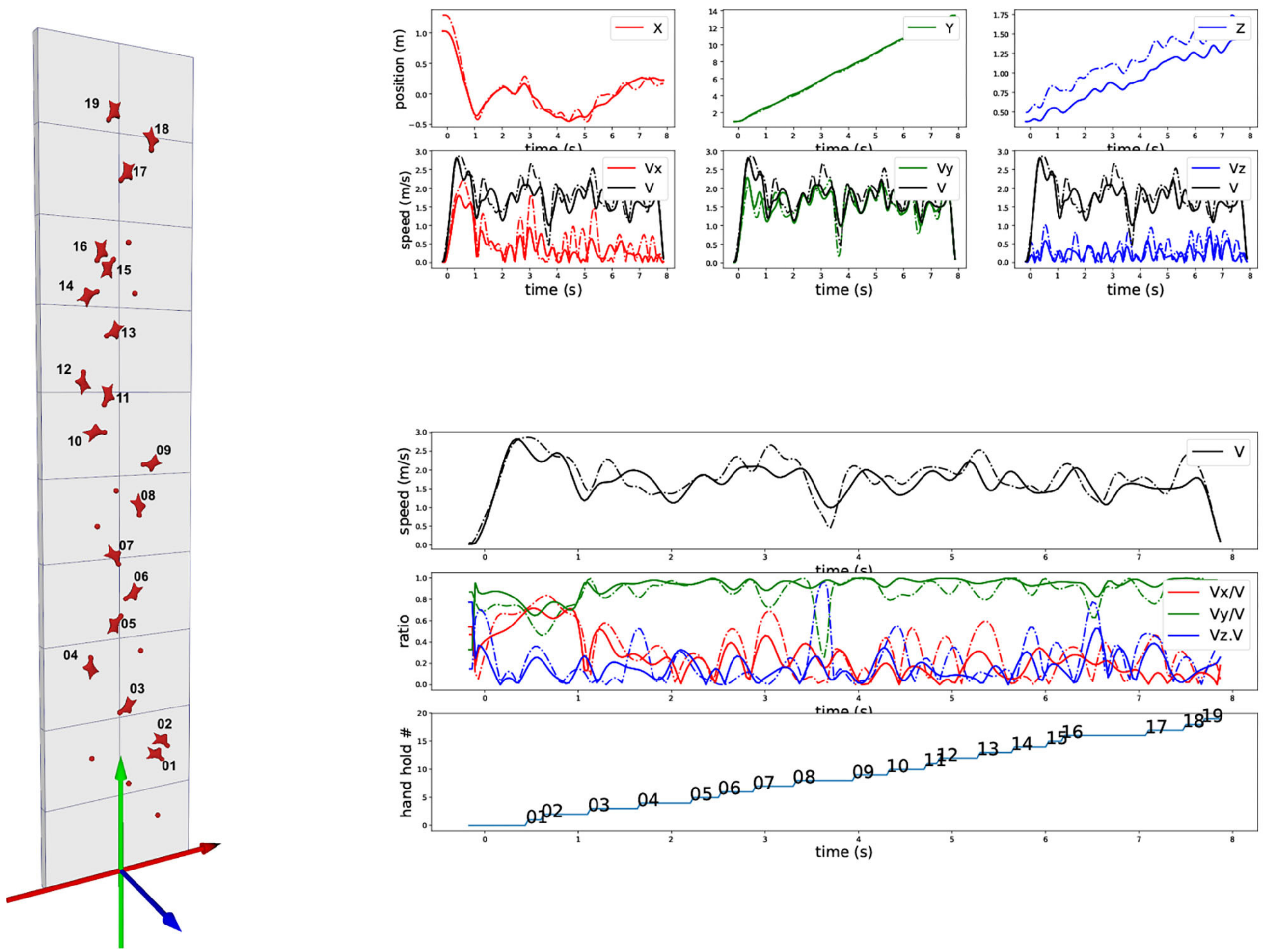

FIGURE 5 | Comparison of trajectories and velocities between marker on the harness (dashed line) and COM computed from 3D mesh (plain line). Curves correspond exactly to the same layout as in **Figure 1**: Top-right are XYZ trajectories and velocities, Bottom-right are velocities and vertical progression (see caption of **Figure 1** for details).

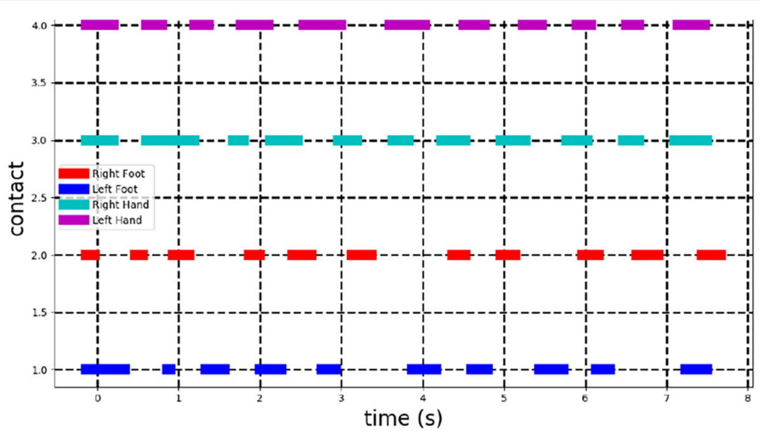

FIGURE 6 | Detection of contacts on the holds and the wall. Each line corresponds to one of the body limb extremity (right foot, left foot, right hand, left hand). It is plain when a contact is detected. A contact is assumed to be hold when velocity of its corresponding vertex on the 3D mesh is below a threshold of 1cm/s.

this case, a user evaluation can be performed as the extracted information is binary, on or off, and is visually identifiable. Results revealed that the identification of grasping duration is perfectly accurate and even include cases when the athlete is using contacts with parts of the wall outside hands and feet holds.

5. CONCLUSION

In the absence of side-by-side experiments with both equipments, it cannot be claimed that a markerless video-based method reaches yet the accuracy of a standard markers-based systems. However, we show that our technique provides reliable cues such as a usable 3D visualization of the whole body in motion and estimation of the 3D trajectory of the center of mass (COM). In particular, our finding is that they are some noticeable discrepancies between the 3D trajectory of a marker on the harness, approximating the COM, and an estimation of the COM of the 3D model of the athlete registered on videos. The estimation of the 3D trajectory of the COM from our video-based 3D mesh tracking tends to follow rational insights that a marker-based approach does not allow.

Future works will explore more precisely dynamics in speed climbing. The goal will be to extend our previous experience in this domain, obtained in a laboratory set-up, to similarly address the context of athletic speed climbing (Quaine and Vigouroux, 2004). In particular, following the markerless objective, we will continue to adapt our previous approaches for prediction of contact forces from kinematical data only (Quaine et al., 2017) through numerical optimization.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available due to ethical concerns regarding confidentiality. Requests to access the datasets should be directed to Lionel Reveret and Sylvain Chapelle.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University Lyon 1—Ethics committee. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

LR developed the techniques, performed the experiment to collect the data to build the athlete's 3D model, performed the 3D video analysis, computed the 3D model kinematics, and wrote the paper. SC provided the sport supervision. PL performed the experiment during the speed climbing tests. FQ and PL participated in the writing of the paper. All authors contributed to the article and approved the submitted version.

FUNDING

For this project, LR and FQ received funding from Region Rhône-Alpes project AIRCAP 2017. SC and PL received funding from INSEP project 17r12-2017.

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