

Physiology of Performance in Competitive Lead, Boulder, and Speed Climbing

Brief Review

Jefferson Brewer^{1,2}, Simon Fyer³, Victor Romano²

¹ University of Utah, Salt Lake City, UT, USA

² Rocky Mountain University of Health Professions, Provo, UT, USA

³ University of Gloucestershire, Cheltenham, GL50 2RH, United Kingdom

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Abstract

Background: Competitive sport climbing has expanded rapidly since its inclusion in the Olympic Games, now comprising three distinct disciplines: lead climbing, bouldering, and speed climbing. Each discipline differs substantially in movement characteristics, duration, and physiological demands. Despite a growing literature base, integrative summaries comparing aerobic and anaerobic demands across disciplines remain limited.

Methods: A brief narrative review of the peer-reviewed literature examined the physiological determinants of performance in competitive sport climbing. Studies published from the late nineteen nineties through January twenty-one, two thousand twenty-six were considered, with emphasis on aerobic capacity, anaerobic metabolism, strength, endurance, and local muscle oxygenation. The review followed the Scale for the Assessment of Narrative Review Articles to promote clarity and methodological transparency, prioritizing discipline-specific findings and climbing relevant testing methodologies.

Results: Lead climbing is characterized by sustained intermittent loading that requires integrating anaerobic energy production during high-intensity sequences with aerobic mechanisms. Bouldering consists of repeated short-duration maximal efforts that rely primarily on anaerobic glycolytic pathways. Speed climbing is a power-dominant discipline that relies almost exclusively on anaerobic lactic metabolism. Across disciplines, climbing-specific assessments of forearm oxygen kinetics and movement economy show stronger associations with performance than traditional whole-body tests.

Conclusion: Sport climbing performance is governed by discipline-specific interactions between aerobic and anaerobic energy systems. Understanding these distinctions is essential for targeted testing and training. Future research should refine sport-specific assessment protocols and clarify how training adaptations influence physiological determinants of performance across climbing disciplines.

Key Words: Muscle Oxygenation, VO₂ max, Energy Systems

Corresponding author: Jefferson Brewer, jefferson.brewer@hsc.utah.edu.

Introduction

Competitive sport climbing has expanded rapidly following its inclusion in the Olympic Games, bringing increased attention to the physiological demands of its three disciplines: lead, bouldering, and speed climbing. Although each of the disciplines differ in duration, movement structure, and intensity, they are often discussed collectively despite placing markedly different demands on the athlete. Early research focused primarily on traditional markers of endurance physiology, including maximal oxygen uptake and blood lactate responses.¹⁻³ While these classic measures remain relevant, advances in measurement technologies⁴ like portable metabolic analyzers⁵ and the advent of near-infrared



spectroscopy (NIRS)⁶⁻¹³, as well as climbing-specific testing protocols¹⁴⁻²¹ have shifted attention toward localized muscular function and discipline-specific demands. These developments have revealed limitations in applying conventional endurance or strength models to climbing, a task which depending on discipline may be characterized by high intensity explosive movement, intermittent isometric contractions, vascular occlusion, and complex movement patterns.

Consequently, a central challenge is not simply identifying which physiological systems contribute to performance, but understanding how these contributions differ across disciplines and interact within the constraints of climbing-specific movement. This review synthesizes current literature to examine the physiological determinants of performance in lead climbing, bouldering, and speed climbing, with particular emphasis on the interaction between aerobic and anaerobic metabolism and the role of local oxygen kinetics and muscular function.

Methods

This brief narrative review synthesizes peer-reviewed literature examining the physiological determinants of performance in competitive sport climbing. Literature searches were conducted using PubMed, Scopus, and SPORTDiscus databases, with combinations of keywords including “sport climbing,” “bouldering,” “lead climbing,” “speed climbing,” “aerobic capacity,” “anaerobic,” “blood lactate,” “strength,” and “muscle oxygenation.” The search included studies published from January 1995 through January 21, 2026. Titles and abstracts were screened for relevance to the physiological determinants of climbing performance. Full-text review was conducted for articles deemed relevant. Reference lists of included studies and relevant reviews were also manually screened to identify additional sources.

Studies were selected based on relevance to competitive climbing and physiological assessment, with priority given to discipline-specific investigations and climbing-specific testing methodologies. The unit of analysis in this review was individual primary research studies. Review articles were used to provide context and identify relevant literature but were not treated as primary evidence sources in the synthesis. Inclusion criteria consisted of: (1) peer-reviewed articles, (2) studies involving human participants, (3) investigations of physiological responses or determinants related to climbing performance, and (4) studies focused on lead, bouldering, or speed climbing or clearly transferable climbing-specific tasks (e.g., finger flexor endurance tests).

Exclusion criteria included: (1) non-peer-reviewed sources, (2) studies unrelated to physiological performance (e.g., purely biomechanical or injury-focused without physiological measures), and (3) studies lacking climbing-specific relevance. The unit of analysis in this review was individual primary research studies. Review articles were used to provide context and identify relevant literature but were not treated as primary evidence sources in the synthesis. Consistent with the Scale for the Assessment of Narrative Review Articles (SANRA), emphasis was placed on clarity of synthesis rather than exhaustive systematic inclusion.²²

Results

Climbing disciplines can be conceptualized along a continuum defined by the interaction between energy system contribution²³⁻²⁶, fatigue^{7,16,19,27-29}, and neuromuscular demand^{16,30}. Lead climbing occupies the longest duration and requires sustained intermittent effort, while bouldering emphasizes repeated high-intensity efforts with incomplete recovery, and speed climbing represents a near-maximal, short-duration task.³¹

Across climbing disciplines, a consistent pattern emerges: systemic physiological measures such as VO_{2max} provide limited explanatory power, while local muscular factors like forearm flexor muscle force production and oxygen kinetics in the forearm demonstrate stronger and more consistent relationships with performance¹⁰⁻¹⁴. This suggests that climbing performance is governed less by systemic aerobic capacity and more by the ability to maintain force production under conditions of intermittent ischemia and incomplete recovery.

Lead Climbing

Lead climbing represents the longest continuous effort among the disciplines, requiring athletes to sustain intermittent contractions over several minutes while managing fatigue and pacing. Modern competitive lead climbing requires athletes to ascend a 15 m wall with varying angles and hold configurations while clipping a rope into fixed protection points for safety. Contemporary lead routes increasingly incorporate dynamic, coordination-based movements alongside traditional static sequences. These changes reflect an integration of acrobatic skill sets that require rapid force generation, precise body positioning, and efficient transitions between movement types. As a result, climbers must



repeatedly alternate between high-intensity efforts and brief opportunities for partial recovery.^{2,7,27} This hybrid movement structure increases the complexity of the physiological demands placed on the athlete. Although early work emphasized aerobic capacity due to the duration of the task¹⁻⁴, subsequent research suggests that its role is primarily supportive rather than determinative.^{5,17,26}

Systemic aerobic capacity consistently demonstrates only moderate associations with performance, particularly when assessed using traditional modalities^{1,5,17}. In contrast, climbing-specific measures such as oxygen cost per movement²³ and forearm oxygen kinetics^{6,10,11,13} more strongly differentiate higher-level climbers. This suggests that efficiency and local oxygen utilization, rather than maximal oxygen transport capacity, are more relevant to performance.

Anaerobic metabolism plays a critical role during high-intensity sequences, particularly in steeper terrain where mechanical demands increase and resting opportunities are limited^{5,19}. Elevated blood lactate responses following lead climbing confirm substantial anaerobic involvement^{2,3,29}, yet performance appears to depend less on absolute anaerobic capacity than on the ability to recover between efforts^{12,19,20,27}. These findings indicate that lead climbing performance is governed by the interaction between anaerobic energy production and aerobic recovery at the local muscular level. Failure occurs not simply due to energy depletion, but when the rate of recovery is insufficient to sustain repeated high-intensity contractions.

Bouldering

Bouldering is characterized by short-duration, high-intensity efforts performed repeatedly within a constrained time frame.³¹ Unlike lead climbing, performance is not determined by sustained effort but by the ability to generate and reproduce maximal force across multiple attempts^{14,16,21,26,32}. Bouldering is consistently identified as an anaerobically dominant discipline²⁵⁻³⁰, relying primarily on the ATP-PCr system and anaerobic glycolysis during repeated efforts. However, physiological measurements during bouldering attempts reveal substantial cardiorespiratory responses despite the short duration of effort,^{5,6} with peak oxygen uptake and heart rate reaching a high percentage of maximal values during attempts. These responses decline rapidly during rest periods, with elite boulderers demonstrating particularly rapid recovery kinetics, highlighting the importance of efficient short-term recovery.⁵

Measures of maximal strength and power demonstrate strong associations with performance, distinguishing bouldering from endurance-oriented climbing tasks.^{14,19,21,32-36} These findings suggest that bouldering performance is limited by the ability to generate force under conditions of incomplete recovery. Accordingly, the interaction between anaerobic output and aerobic recovery capacity becomes critical, particularly in competition formats requiring repeated maximal efforts within short time windows. Training for bouldering, therefore, prioritizes maximal strength, explosive power, and short-duration anaerobic capacity. While aerobic recovery supports repeated efforts, performance is primarily limited by the ability to generate force under fatigue, with failure typically occurring when force production capacity is exhausted.

Speed Climbing

Speed climbing represents the shortest and most distinct discipline, requiring athletes to complete a standardized route in only a few seconds³¹. Because there is minimal route reading or decision making and the efforts are so short, the physiological demands of speed climbing are fundamentally different from those of lead climbing and bouldering, with performance governed primarily by maximal anaerobic power and neuromuscular coordination^{37,38}. The contribution of aerobic metabolism during a single ascent is negligible due to the extremely short duration of the task. Instead, success depends on rapid force production, precise sequencing, and technical efficiency.

While aerobic capacity may contribute to recovery between repeated heats in competition, it does not directly influence performance during an individual climb^{37,38}. This distinguishes speed climbing as a predominantly power-driven task, in which metabolic limitations are secondary to neuromuscular output. As a result, the literature indicates that speed climbing performance is determined by the efficiency of immediate energy systems and the athlete's ability to execute pre-planned movements with high precision and speed.

Discussion

This review highlights a continuum of physiological demands across climbing disciplines. Lead climbing requires sustained interaction between aerobic and anaerobic systems, bouldering emphasizes repeated high-intensity efforts with incomplete recovery, and speed climbing is dominated by maximal power output. A consistent pattern emerged as local physiological factors, in particular those related to forearm muscle function, demonstrate stronger relationships

with performance than traditional whole-body measures. This includes oxygen desaturation capacity, reoxygenation kinetics, and the ability to maintain force production under fatigue.

These findings challenge the applicability of conventional endurance and strength models to climbing and underscore the importance of task-specific assessment. While systemic aerobic capacity contributes to overall performance, particularly in facilitating recovery, it does not appear to be a primary limiting factor in most contexts. Importantly, climbing performance reflects the integration of multiple systems rather than reliance on a single physiological variable. The interaction between metabolic demand, local muscular function, and movement efficiency ultimately determines performance outcomes. This complexity may explain inconsistencies across studies and highlights the need for discipline-specific approaches to both research and training.

Conclusion

Sport climbing performance is governed by discipline-specific physiological demands that exist along a continuum rather than as isolated categories. Lead climbing requires the integration of aerobic and anaerobic metabolism, bouldering emphasizes anaerobic output with repeated recovery demands, and speed climbing is driven by maximal power and neuromuscular coordination. In all climbing disciplines local muscular function is a primary determinant of performance, particularly forearm oxygen kinetics and force production. These findings also highlight the importance of climbing-specific assessment and training approaches that reflect the unique demands of each discipline. Future research should continue to refine task-specific testing methods and further investigate how training interventions influence local and systemic adaptations. By integrating findings across disciplines, a more comprehensive understanding of climbing physiology can inform both athlete development and performance optimization.

Conflict of Interest. The authors declare no conflicts of interest.

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