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

Brief Review

Jefferson Brewer[1,2], Simon Fyer[3], Victor Romano [2]

[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*

Open Access

Dates
Submitted:
April 2, 2026
Accepted:
June 10, 2026
Published:
June 30, 2026

Research in Strength and Performance: *2026, Volume 6 (Issue 1): 19*

ISSN: 3069-0765

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, VO_2 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 technologies[4] like portable metabolic analyzers[5] and the advent of near-infrared spectroscopy (NIRS)[6-13], as well as climbing-specific testing protocols[14-21] 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 contribution[23-26], 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 performance[10-14]. 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 task[1-4], 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 movement[23] 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 discipline[25-30], 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 seconds[31]. 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.

References

1. Mermier CM, Robergs RA, McMinn SM, Heyward VH. Energy expenditure and physiological responses during indoor rock climbing. *Br J Sports Med*. 1997;31(3):224-228. doi:10.1136/bjsm.31.3.224
2. Watts PB, Drobish KM. Physiological responses to simulated rock climbing at different angles. *Med Sci Sports Exerc*. 1998;30(7):1118-1122. doi:10.1097/00005768-199807000-00015
3. Watts PB. Physiology of difficult rock climbing. *Eur J Appl Physiol*. 2004;91(4):361-372. doi:10.1007/s00421-003-1036-7
4. Breen M, Reed T, Nishitani Y, Jones M, Breen HM, Breen MS. Wearable and non-invasive sensors for rock climbing applications: science-based training and performance optimization. *Sensors*. 2023;23(11):5080. doi:10.3390/s23115080
5. Callender NA, Hayes TN, Tiller NB. Cardiorespiratory demands of competitive rock climbing. *Appl Physiol Nutr Me*. 2021;46(2):161-168. doi:10.1139/apnm-2020-0566
6. Fryer SM, Giles D, Palomino IG, de la O Puerta A, España-Romero V. Hemodynamic and cardiorespiratory predictors of sport rock climbing performance. *J Strength Cond Res*. 2018;32(12):3534-3541. doi:10.1519/jsc.0000000000001860
7. Dindorf C, Bartaguiz E, Dully J, Sprenger M, Becker S, Fröhlich M, Ludwig O. In vivo monitoring of acute and intermittent fatigue in sport climbing using near-infrared spectroscopy wearable biosensors. *Sports*. 2023;11(2):37. doi:10.3390/sports11020037
8. Feldmann A, Schmitz R, Erlacher D. Near-infrared spectroscopy-derived muscle oxygen saturation on a 0% to 100% scale: reliability and validity of the Moxy monitor. *J Biomed Opt*. 2019;24(11):1. doi:10.1117/1.jbo.24.11.115001
9. Fryer SM, Stoner L, Dickson TG, Draper SB, McCluskey MJ, Hughes JD, How SC, Draper N. Oxygen recovery kinetics in the forearm flexors of multiple ability groups of rock climbers. *J Strength Cond Res*. 2015;29(6):1633-1639. doi:10.1519/jsc.0000000000000804
10. Winkler M, Künzell S, Augste C. Predictive value of forearm muscle oxygenation parameters for climbing-specific finger endurance and competitive climbing performance. *Sport Sci Health*. 2023;20(1):109-117. doi:10.1007/s11332-023-01072-w
11. Fryer S, Stoner L, Stone K, Giles D, Sveen J, Garrido I, España-Romero V. Forearm muscle oxidative capacity index predicts sport rock-climbing performance. *Eur J Appl Physiol*. 2016;116(8):1479-1484. doi:10.1007/s00421-016-3403-1

12. Fryer S, Stoner L, Scarrott C, Lucero A, Witter T, Love R, Dickson T, Draper N. Forearm oxygenation and blood flow kinetics during a sustained contraction in multiple ability groups of rock climbers. *J Sports Sci.* 2014;33(5):518-526. doi:10.1080/02640414.2014.949828
13. Philippe M, Wegst D, Müller T, Raschner C, Burtscher M. Climbing-specific finger flexor performance and forearm muscle oxygenation in elite male and female sport climbers. *Eur J Appl Physiol.* 2011;112(8):2839-2847. doi:10.1007/s00421-011-2260-1
14. Faggian S, Borasio N, Vecchiato M, Gatterer H, Burtscher M, Battista F, Brunner H, Quinto G, Duregon F, Ermolao A, Neunhaeuserer D. Sport climbing performance determinants and functional testing methods: a systematic review. *J Sport Health Sci.* 2025;14:100974. doi:10.1016/j.jshs.2024.100974
15. Draper N, Giles D, Taylor N, Vigouroux L, España-Romero V, Baláš J, Altamirano IS, Mally F, Beeretz I, Canalejo JC. Josseron G. Performance assessment for rock climbers: the International Rock Climbing Research Association sport-specific test battery. *Int J Sports Physiol Perform.* 2021;16(9):1242-1252. doi:10.1123/ijspp.2020-0672
16. Giles D, Hartley C, Maslen H, Hadley J, Taylor N, Torr O, Chidley J, Randall T, Fryer S. An all-out test to determine finger flexor critical force in rock climbers. *Int J Sports Physiol Perform.* 2021;16(7):942-949. doi:10.1123/ijspp.2020-0637
17. Maciejczyk M, Michailov ML, Wiecek M, Szymura J, Rokowski R, Szygula Z, Beneke R. Climbing-specific exercise tests: energy system contributions and relationships with sport performance. *Front Physiol.* 2022;12. doi:10.3389/fphys.2021.787902
18. Michailov ML, Morrison A, Ketenliev MM, Pentcheva BP. A sport-specific upper-body ergometer test for evaluating submaximal and maximal parameters in elite rock climbers. *Int J Sports Physiol Perform.* 2015;10(3):374-380. doi:10.1123/ijspp.2014-0160
19. Stien N, Saeterbakken AH, Hermans E, Vereide VA, Olsen E, Andersen V. Comparison of climbing-specific strength and endurance between lead and boulder climbers. *PLoS One.* 2019;14(9). doi:10.1371/journal.pone.0222529
20. Baláš J, Gajdošík J, Giles D, Fryer S, Krupková D, Brtník T, Feldmann A. Isolated finger flexor vs. exhaustive whole-body climbing tests? how to assess endurance in sport climbers? *Eur J Appl Physiol.* 2021;121(5):1337-1348. doi:10.1007/s00421-021-04595-7
21. Fanchini M, Violette F, Impellizzeri FM, Maffiuletti NA. Differences in climbing-specific strength between Boulder and lead rock climbers. *J Strength Cond Res.* 2013;27(2):310-314. doi:10.1519/jsc.0b013e3182577026
22. Baethge C, Goldbeck-Wood S, Mertens S. SANRA - a scale for the quality assessment of narrative review articles. *Res Integr Peer Rev.* 2019;4(1). doi:10.1186/s41073-019-0064-8
23. Bertuzzi RC, Franchini E, Kokubun E, Kiss MA. Energy system contributions in indoor rock climbing. *Eur J Appl Physiol.* 2007;101(3):293-300. doi:10.1007/s00421-007-0501-0
24. Giles LV, Rhodes EC, Taunton JE. The physiology of rock climbing. *Sports Med.* 2006;36(6):529-545. doi:10.2165/00007256-200636060-00006
25. Baláš J, Panáčková M, Strejcová B, Martin AJ, Cochrane DJ, Kaláb M, Kodejška J, Draper N. The relationship between climbing ability and physiological responses to rock climbing. *Sci World J.* 2014;2014:1-6. doi:10.1155/2014/678387
26. MacKenzie R, Monaghan L, Masson RA, Werner AK, Caprez TS, Johnston L, Kemi OJ. Physical and physiological determinants of rock climbing. *Int J Sports Physiol Perform.* 2020;15(2):168-179. doi:10.1123/ijspp.2018-0901
27. Valenzuela PL, de la Villa P, Ferragut C. Effect of two types of active recovery on fatigue and climbing performance. *J Sci Med Sport.* 2015;14(4):769.
28. Watts PB, Daggett M, Gallagher P, Wilkins B. Metabolic response during sport rock climbing and the effects of active versus passive recovery. *Int J Sports Med.* 2000;21(3):185-190. doi:10.1055/s-2000-302
29. Gajewski J, Hübner-Woźniak E, Tomaszewski P, Sienkiewicz-Dianzenza E. Changes in handgrip force and blood lactate as response to simulated climbing competition. *Biol Sport.* 2009;26(1):13-21. doi:10.5604/20831862.890171
30. Winkler M, Künzell S, Augste C. Competitive performance predictors in speed climbing, bouldering, and lead climbing. *J Sports Sci.* 2023;41(8):736-746. doi:10.1080/02640414.2023.2239598
31. Winkler M, Künzell S, Augste C. The load structure in international competitive climbing. *Front Sports Act Living.* 2022;4:790336. doi:10.3389/fspor.2022.790336
32. Buraas BF, Brobakken MF, Wang E. Climbing performance in males: the importance of climbing-specific finger strength. *Eur J Appl Physiol.* 2025;125(10):2823-2830. doi:10.1007/s00421-025-05802-5

33. Rokowski R, Michailov M, Maciejczyk M, Więcek M, Szymura J, Draga P, Trendafilov P, Szygula Z. Muscle Strength and endurance in high-level rock climbers. *Sports Biomech*. 2021;23(8):1057-1072. doi:10.1080/14763141.2021.1916577
34. Ozimek M, Krawczyk M, Zadarko E, Barabasz Z, Ambroży T, Stanula A, Mucha DK, Jurczak A, Mucha D. Somatic profile of the elite boulderers in Poland. *J Strength Cond Res*. 2017;31(4):963-970. doi:10.1519/jsc.0000000000001673
35. Deyhle MR, Hsu H-S, Fairfield TJ, Cadez-Schmidt TL, Gurney BA, Mermier CM. Relative importance of four muscle groups for indoor rock climbing performance. *J Strength Cond Res*. 2015;29(7):2006-2014. doi:10.1519/jsc.0000000000000823
36. Langer K, Simon C, Wiemeyer J. Strength training in climbing: a systematic review. *J Strength Cond Res*. 2022;37(3):751-767. doi:10.1519/jsc.0000000000004286
37. Askari Hosseini S, Wolf P. Performance indicators in speed climbing: insights from the literature supplemented by a video analysis and expert interviews. *Front Sports Act Living*. 2023;5. doi:10.3389/fspor.2023.1304403
38. Ozimek M, Krawczyk M, Rokowski R, Draga P, Ambroży T, Mucha D, Omorczyk J, Stanula A, Pociecha M, Görner K. Evaluation of the level of anaerobic power and its effect on speed climbing performance in elite climbers. *Trends Sport Sci*. 2018;3(25): 149-158. doi: 10.23829/TSS2018.25.3-5