14 (3) (2025) 827 - 832

Journal of Physical Education, Sport, Health and Recreations

https://journal.unnes.ac.id/journals/peshr

The Effects of Altitude Training on Blood Components and Performance of Elite Rowing Athletes: Systematic Literature Review

Rifqi Harits Taufiqurahman[1], Dede Rohmat Nurjaya[2]✉, Pipit Pitriani[3], Agus Rusdiana[4]

Sports Education Study Program, Graduate School, Indonesian University of Education, Indonesia[1234]

Article History

Received September 2025
Accepted October 2025
Published Vol.14 No.(3) 2025

Keywords:
Altitude Training; Hematocrit; Hemoglobin; Athlete Performance, Rowing; Systematic Literature

Abstract

Rowing athlete performance is greatly influenced by aerobic capacity, explosive strength, and precise technical coordination. One strategy widely used to support performance improvement is altitude training, namely training in hypoxic conditions through the Live High-Train Low (LHTL), Live High-Train High (LHTH), and Intermittent Hypoxic Training (IHT) methods. Hypoxic exposure is believed to stimulate an increase in erythropoietin (EPO), which in turn increases hemoglobin (Hb), hematocrit (Hct), and total hemoglobin mass (Hbmass), thereby optimizing the body's oxygen transport capacity. This study aims to systematically examine the effect of altitude training on blood components and the performance of elite rowing athletes. The study was conducted using a Systematic Literature Review (SLR) approach based on the PRISMA 2020 guidelines. Data sources were obtained through the Publish or Perish tool with a publication year range of 2015–2025, and inclusion criteria focused on Randomized Controlled Trial (RCT) studies examining the effects of altitude training on elite rowing athletes. The results of the analysis showed that the LHTL method with a duration of 3–4 weeks and hypoxic exposure of ≥12 hours per day provided a significant increase in Hb, Hct, Hbmass, as well as aerobic capacity such as VO_2max and peak power output. However, there are variations in individual responses between "responders" and "non-responders," as well as differences in study design that cause the results to be inconsistent. Factors such as training intensity, initial fitness status, and nutritional support also influence the effectiveness of the intervention. Therefore, it can be concluded that altitude training has the potential to be an effective strategy to improve the performance of rowing athletes through hematological and physiological adaptations, with LHTL as the most promising method. This research is expected to provide theoretical contributions to the development of sports coaching science as well as practical recommendations for coaches and federations in developing evidence-based training programs.

How to Cite

Taufiqurahman, R. H., Nurjaya, D. R., Pitriani, P., & Rusdiana, A. (2025). The Effects of Altitude Training on Blood Components and Performance of Elite Rowing Athletes: Systematic Literature Review. Journal of Physical Education, Sport, Health and Recreation, 14 (3), 827-832.

✉ Correspondence address :
E-mail: dede-rohmat-n@upi.edu

p-ISSN 2460-724X
e-ISSN 2252-6773

INTRODUCTION

Rowing athletes' performance is heavily influenced by aerobic capacity, explosive strength, and precise technical coordination. As a hybrid power-endurance sport, rowing demands simultaneous work of large muscle groups (legs, back, and arms) over a medium competition duration of 5–8 minutes over a distance of 2000 meters. This distinguishes it from other endurance sports such as running or swimming, necessitating a more specific training strategy (Bonato et al., 2023; Volianitis et al., 2020).

One popular strategy for increasing performance capacity is altitude training, or training under hypoxic conditions. This concept utilizes exposure to low-oxygen environments to stimulate beneficial physiological adaptations, particularly in the hematological and cardiovascular systems (Mujika et al., 2024). These adaptations include increases in erythropoietin (EPO), hemoglobin (Hb), hematocrit (Hct), and total hemoglobin mass (Hbmass), all of which play important roles in oxygen transport (Shi & Praphanbundit, 2024).

Altitude training methods have evolved into several models, including Live High–Train Low (LHTL), Live High–Train High (LHTH), and Intermittent Hypoxic Training (IHT). LHTL is considered the most effective because it allows athletes to achieve hematological adaptations from living at high altitudes while maintaining optimal training intensity at low altitudes (Bonetti & Hopkins, 2009; Levine & Stray-Gundersen, 1997). However, the effectiveness of each method still varies depending on the duration, intensity, and characteristics of the athlete (Deng et al., 2025).

Previous studies have focused on athletes running, swimming and cycling, while studies on rowing are still limited (Astorino et al., 2018; Cerda-Kohler et al., 2022). However, rowing demands a unique combination of high aerobic capacity with explosive strength and technical efficiency. This makes generalizing research findings from other disciplines to rowing less accurate, necessitating a systematic review specifically within this sporting context.

Several recent studies have shown that altitude training can have a positive impact on rowing athletes (Meng et al., 2019) found that intermittent hypoxic exposure increased hemoglobin and VO_2Max Chinese elite rowing athletes. Similar findings were reported (Cerda-Kohler et al., 2022) And (Bonato et al., 2023), which emphasized that the LHTL method for three to four weeks can improve metabolic efficiency and rowing performance. However, differences in individual responses between responders and nonresponders remain a challenge (Chapman, 2013).

Debate regarding the dose of hypoxia also continues. Some experts state that exposure to ≥12 hours/day at an altitude of 2000–2500 meters for at least three weeks is the optimal stimulus for increasing Hb mass (Rusko et al., 2004). However, excessive exposure risks reducing sleep quality, triggering acute mountain sickness, and reducing exercise intensity (Saugy et al., 2016). Thus, the balance between benefits and risks needs to be carefully considered.

In addition to hematological factors, altitude training also affects an athlete's neuromuscular, psychological, and hormonal aspects. Hypoxic conditions can accelerate neuromuscular fatigue, which can compromise rowing technique, but can also improve an athlete's mental resilience (Ingham et al., 2002; Turner et al., 2019). This combination of physiological and psychological adaptations makes altitude training a complex, multifaceted intervention.

The novelty of this research lies in its focus, which specifically examines the effects of altitude training on elite rowing athletes through a systematic literature review approach based on PRISMA 2020. This differs from previous meta-analyses which predominantly discussed other endurance athletes (Deng et al., 2025). This study integrates recent findings on training methods, duration, and protocols, as well as hematological and performance adaptations in the context of rowing. In doing so, this study seeks to bridge the existing literature gap.

This study aims to systematically examine the effects of altitude training on blood components and the performance of elite rowing athletes. Using a Systematic Literature Review (SLR) approach guided by the PRISMA 2020 framework, this research seeks to identify the most effective altitude training methods, durations, and models for enhancing hematological parameters (Hb, Hct, Hbmass) and aerobic performance indicators (VO_2max, PPO) among elite rowers.

The novelty of this study lies in its specific focus on the effects of altitude training in elite rowing athletes, which distinguishes it from most previous research that predominantly examined endurance disciplines such as running, swimming, or cycling. Furthermore, this study integrates recent findings from 2015–2025 to analyze the effectiveness of various altitude training models (LHTL, LHTH, IHT, LLTH) in the unique physiological and technical context of rowing. By synthesizing the latest evidence, this review bridges the existing research gap and provides evidence-based recommendations for coaches and sports federations to design more effective altitude training programs for rowing athletes.

METHODS

This study uses a Systematic Literature Review (SLR) design by following the guidelines PRISMA 2020 (Preferred Reporting Items for Systematic Reviews). SLR was chosen to systematically identify, evaluate, and synthesize previous research results to provide a comprehensive picture of the effects of altitude training on blood components and the performance of elite rowing athletes.

The research questions were formulated using the PICO framework. The population was elite rowing athletes; the intervention was altitude training (LHTL, LHTH, IHT, LLTH); the comparators were variations in intervention duration, protocol, and method; while the outcomes included changes in hematological parameters (Hb, Hbmass, EPO) and aerobic performance (VO_2max, PPO, time trial).

A literature search was conducted in PubMed, ScienceDirect, and Google Scholar databases using Publish or Perish (PoP) software. Keywords were compiled using Boolean operators and MeSH terms: ("altitude training" OR "hypoxic training" OR "live high train low") AND ("rowing" OR "rowers") AND ("hemoglobin" OR "Hbmass" OR "blood parameters" OR "performance") AND ("randomized controlled trial" OR "RCT"). The search was limited to peer-reviewed articles published between 2015 and 2025, in English or Indonesian, and available in full-text. PoP was used to extract metadata and citations, and assess the relevance of articles based on the title, abstract, and publication source (Harzing, 2016).

Inclusion criteria included studies of the RCT type or controlled experiments with elite rowing athletes aged ≥18 years, using altitude training interventions, reporting pre- and post-intervention data, and measuring blood parameters (Hb, Hbmass, EPO) and aerobic performance (VO_2max, trial test). Exclusion criteria included non-athlete or non-rowing studies, animal studies, non-experimental or opinion reviews, articles without pre–post data, and publications not available in full text.

Article selection was conducted according to the PRISMA 2020 process: identification, screening, full-text review, and final inclusion. Of the 14,024 articles retrieved, 399 duplicates were removed, and 13,579 were eliminated due to irrelevance. Five studies met the inclusion criteria and were further analyzed.

The research instrument was a data extraction sheet that recorded: author and year of publication, sample characteristics (number, age, gender), altitude training method (model, duration, height), training protocol (frequency, intensity, duration of exposure), and the main results in the form of changes in blood components (Hb, Hbmass, EPO) and physical performance (VO_2max, PPO, time trial test). This instrument is used to maintain consistency and accuracy of recording between studies (Haddaway et al., 2022). Data analysis was performed narratively and tabulated, as protocol heterogeneity across studies precluded quantitative meta-analysis. The methodological quality of the studies was assessed by considering randomization, data completeness, and risk of bias based on quality assessment guidelines for randomized controlled trials (Higgins et al., 2020).

RESULTS AND DISCUSSION

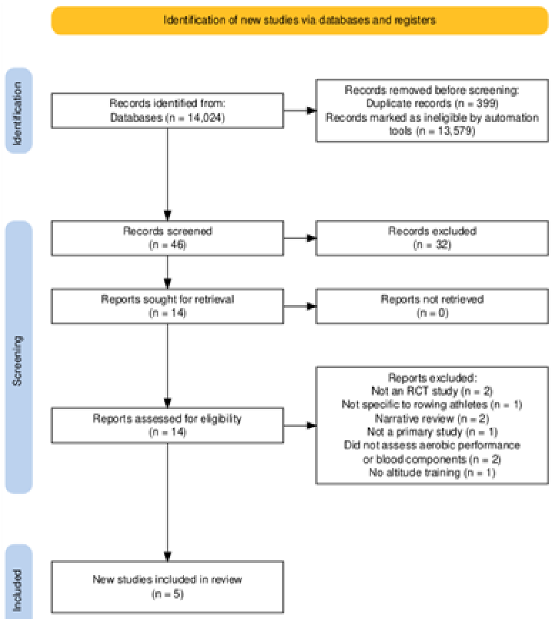

Figure 1. Literature Screening

A literature search using PubMed, ScienceDirect, Google Scholar, and Publish or Perish (PoP) yielded 14,024 articles. After removing 399 duplicate articles and 13,579 irrelevant articles, 46 articles remained for review. Title and abstract screening eliminated 32 articles, leaving 14 articles for full-text review. At this stage, 9 articles were excluded because they were not RCTs, were not rowing athletes, were narrative reviews, did not assess blood components or performance, or did not use altitude training interventions. Ultimately, five articles met the inclusion criteria and were analyzed further.

The five studies involved 16–33 elite rowing athletes with an average age of 17–26 years. The interventions used included Live High–Train High (LHTH), Live High–Train Low (LHTL), Live Low–Train High (LLTH), and natural altitude training, with a duration of 3–8 weeks. Hypoxic exposure varied from simulated altitudes of 1600–3000 m to natural altitudes of 2280 m.

Table 1. Summary of altitude training studies in elite rowing athletes

Author (Year)	Sample	Intervention	Duration	Key Findings
Bachev (2019)	16	LHTH 2100 m	3 weeks	UpHb, Hct, VO_2max
Neykov et al. (2019)	16	LHTL 1600–2800 m	4 weeks	UpHb, VO_2max
Meng et al. (2019)	16	LHTL 2000–3000 m	4 weeks	UpHb, VO_2max, time trial
Meng et al. (2021)	33	Natural 2280 m	8 weeks	UpHb-mass, VO_2peak
Cerda-Kohler (2022)	16	Height 2500 m	4 weeks	UpHb-mass, VO_2max, PPO

Hematological Adaptation

The synthesis results showed that all studies reported increases in hemoglobin (Hb) and hematocrit (Hct) after intervention. This confirms that hypoxic exposure stimulates erythropoiesis, thereby increasing oxygen transport capacity (Gore et al., 2013; Siebenmann et al., 2012). Two studies also assessed hemoglobin mass (Hbmass), which is considered more stable because it is not affected by plasma fluctuations (Schmidt & Prommer, 2005). Increasing Hbmass in rowing athletes is very important because it is directly related to endurance in the 2000 m race. Interestingly, (Meng et al., 2021) found increased microcirculatory perfusion, suggesting that hypoxic adaptation is not only systemic but also improves oxygen distribution in peripheral tissues (Bassett & Howley, 2000). However, variations in the indicators used between studies can affect the consistency of the results. Studies that only measure Hb/Hct may report faster changes than those that assess Hbmass. This may partly explain the differences in findings between studies.

Performance Adaptation

The majority of studies reported increases in VO_2max or VO_2peak, indicating improved aerobic capacity. Two studies found significant improvements in rowing ergometer time trials, which is relevant because it mimics real-world competition conditions. Furthermore, altitude training has also been shown to increase Peak Power Output (PPO) (Cerda-Kohler et al., 2022), showing that adaptations support not only aerobic endurance but also anaerobic capacity and muscle strength. However, the results are not entirely consistent. Some studies report aerobic improvements but find no explicit impact on time trial performance. This discrepancy could be due to decreased rowing technique quality due to neuromuscular fatigue in hypoxia, or variations in training intensity between studies. This underscores the need for training programs that focus not only on hematological aspects but also on maintaining technique quality and explosive power.

Duration and Intervention Model

Intervention duration has been shown to influence adaptation. Studies lasting 3–4 weeks consistently produce initial hematologic improvements, while longer interventions (≥6 weeks) provide additional cardiovascular and metabolic benefits (Gore et al., 2001; Meng et al., 2021). From a model perspective, LHTL appears to be the most effective method because it allows athletes to continue training at high intensity at low altitudes while receiving hypoxic stimuli while resting (Levine & Stray-Gundersen, 1997). In contrast, LLTH is relatively more practical and can be applied with limited facilities, but its effects tend to be limited to short-term VO_2max. Natural altitude training is effective in the long term, but requires significant costs and logistics. The implication for Indonesian rowing is the need to select a model based on the competition calendar and available resources.

Individual Response Variability

Although the general trend is positive, not all athletes respond to altitude training the same way (Chapman, 2013) highlighting the existence of "responder" and "non-responder" groups. Factors such as age, initial fitness status, nutrition, sleep quality, and acclimatization ability contribute to this variation (Saugy et al., 2016). The limited research on genetic factors or other biomarkers such as erythropoietin (EPO) also makes adaptation mechanisms unclear. Consequently, altitude training programs need to be personalized. In the Indonesian context, personalization is crucial given the limited availability of hypoxic facilities. Monitoring hematological parameters, sleep quality, and athlete recovery can help optimize results while minimizing the risk of overtraining or sleep disturbances.

Practical Implications for Rowing in Indonesia

Implementing altitude training in the Indonesian context faces a number of practical challenges that differ from those in countries with easy access to mountainous areas or modern hypoxic facilities. Most national training centers are not yet equipped with hypoxic chambers or specialized dormitories at high altitudes, so the Live High–Train Low (LHTL) model recommended in the literature is often used (including Deng et al., 2025). It is difficult to fully adopt. A more realistic alternative is to utilize Live Low–Train High (LLTH) based on intermittent hypoxia simulation with portable equipment, or to integrate training camps in natural highland areas available in Indonesia, such as Ciwidey (±1800–2000m).

In resource-constrained conditions, personalized program strategies are crucial. Monitoring simple indicators such as hemoglobin (Hb), hematocrit (Hct), sleep quality, and recovery status can help coaches adjust training loads to ensure athletes continue to benefit from hematological adaptations without compromising rowing technique. Furthermore, altitude training scheduling should be aligned with the main competition calendar (PON, SEA Games, or Asian Games), ensuring optimal adaptation and tapering periods. With this adaptive approach, altitude training can still be implemented effectively in Indonesia, although limited facilities and costs remain major challenges.

Thus, the results of this study not only strengthen the scientific evidence on the effectiveness of altitude training but also provide practical guidance for its application in the context of Indonesian rowing, which faces limited facilities and resources. This also provides an important basis for the conclusion that altitude training strategies need to be specifically adapted to be truly applicable and support improved athlete performance at the international level.

CONCLUSION

This systematic review demonstrates that altitude training, particularly the Live High–Train Low (LHTL) method, effectively enhances hematological components (Hb, Hct, Hbmass) and aerobic performance (VO_2max, PPO) in elite rowing athletes. Optimal adaptations are achieved with 3–4 weeks of exposure at 2,000–2,500 m for ≥12 hours per day. Nevertheless, individual variability remains a key factor influencing outcomes. Personalized training design and monitoring of physiological responses are therefore essential. In contexts with limited hypoxic facilities, modified models such as LLTH or intermittent hypoxic exposure can provide practical alternatives. Overall, altitude training is a promising evidence-based strategy to improve rowing performance through hematological and physiological adaptations.

Practically, the findings of this study are expected to provide evidence-based recommendations for coaches, sports federations, and coaching practitioners in designing more effective altitude training programs for rowing athletes. Optimizing this strategy will increase the opportunities for Indonesian athletes to improve their competitiveness at international levels, such as the Asian Games and the Olympics.

By mapping the latest scientific evidence, this study not only contributes to theoretical development in sports coaching science but also provides an applicable empirical basis. The results of this review are expected to help coaches determine the most appropriate altitude training methods, durations, and protocols for elite rowing athletes, while also providing a foundation for further experimental research in the future.

REFERENCES

Astorino, T.A., Edmunds, R.M., Clark, A., King, L., Gallant, R.M., Namm, S., Fischer, A., & Wood, K.A. (2018). Increased cardiac output and maximal oxygen uptake in response to ten sessions of high intensity interval training. Journal of Sports Medicine and Physical Fitness, 58(1–2), 164–171. https://doi.org/10.23736/S0022-4707.16.06606-8

Bassett, D. R., & Howley, E. T. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. Medicine and Science in Sports and Exercise, 32(1), 70–84.

Bonato, G., Goodman, S. P. J., & Tjh, L. (2023). Physiological and performance effects of live high train low altitude training for elite endurance athletes: A narrative review. Current Research in Physiology, 6. https://doi.org/10.1016/j.crphys.2023.100113

Bonetti, D. L., & Hopkins, W. G. (2009). Sea-Level Exercise Performance Following Adaptation to Hypoxia: A Meta-Analysis. Sports Medicine, 39(2), 107–127.

Cerda-Kohler, H., Haichelis, D., Reuquén, P., Miarka, B., Homer, M., Zapata-Gómez, D., & Aedo-

Muñoz, E. (2022). Training at moderate altitude improves submaximal but not maximal performance-related parameters in elite rowers. Frontiers in Physiology, 13. https://doi.org/10.3389/fphys.2022.931325

Chapman, R.F. (2013). The individual response to training and competition at altitude. British Journal of Sports Medicine, 47(Suppl 1), i40--i44. https://doi.org/10.1136/bjsports-2013-092837

Deng, L., Liu, Y., Chen, B., Hou, J., Liu, A., & Yuan, X. (2025). Impact of Altitude Training on Athletes' Aerobic Capacity: A Systematic Review and Meta-Analysis. Life, 15(2). https://doi.org/10.3390/life15020305

Gore, C. J., Clark, S. A., & Saunders, P. U. (2013). Nonhematological mechanisms of improved sea-level performance after hypoxic exposure. Medicine and Science in Sports and Exercise, 39(9), 1600–1609. https://doi.org/10.1249/mss.0b013e3180de49d3

Gore, CJ, Hahn, AG, Aughey, RJ, Martin, DT, Ashenden, MJ, Clark, SA, Garnham, AP, Roberts, AD, Slater, GJ, & McKenna, MJ (2001). Live high: train low increases muscle buffer capacity and submaximal cycling efficiency. Acta Physiologica Scandinavica, 173(3), 275–286.

Haddaway, N. R., Page, M. J., Pritchard, C. C., & McGuinness, L. A. (2022). PRISMA2020: R package and ShinyApp for producing PRISMA 2020 compliant flow diagrams, with interactivity for optimized digital transparency and Open Synthesis. Research Synthesis Methods, 13(4), 533–540. https://doi.org/10.1002/jrsm.1567

Harzing, A. W. (2016). Publish or Perish. Tarma Software Research.

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (2020). Cochrane Handbook for Systematic Reviews of Interventions (2nd ed.). Wiley-Blackwell.

Ingham, S. A., Whyte, G. P., Jones, K., & Nevill, A. M. (2002). Determinants of 2,000 m rowing ergometer performance in elite rowers. European Journal of Applied Physiology, 88(3), 243–246. https://doi.org/10.1007/s00421-002-0699-9

Levine, B.D., & Stray-Gundersen, J. (1997). {'Living high-training low'}: effect of moderate-altitude acclimatization with low-altitude training on performance. Journal of Applied Physiology, 83(1), 102–112.

Meng, Z., Gao, B., Gao, H., Ge, P., Li, T., & Wang, Y. (2019). Four weeks of hypoxia training improves cutaneous microcirculation in trained rowers. Physiological Research, 68(5), 757–766. https://doi.org/10.33549/physiolres.934175

Meng, Z., Gao, H., Li, T., Xu, Y., & Gao, B. (2021). Effects of Eight Weeks Altitude Training on the Aerobic Capacity and Microcirculation Function in Trained Rowers. High Altitude Medicine \& Biology, 22(1), 24–31.

Mujika, I., Bourdillon, N., Zelenkova, I., Vergnoux, F., & Millet, G. P. (2024). Hematological and performance adaptations to altitude training (2,320 m) in elite middle-distance and distance swimmers. Frontiers in Physiology, 15. https://doi.org/10.3389/fphys.2024.1474479

Rusko, H.K., Tikkanen, H.O., & Peltonen, J.E. (2004). Altitude and endurance training. Journal of Sports Sciences, 22(10), 928–945. https://doi.org/10.1080/02640410400005933

Saugy, J.J., Schmitt, L., Hauser, A., Constantin, G., Cejuela, R., Faiss, R., Wehrlin, J.P., Rosset, J., Robinson, N., & Millet, G.P. (2016). Same performance changes after live high-train low in normobaric vs. hypobaric hypoxia. Frontiers in Physiology, 7, 138. https://doi.org/10.3389/fphys.2016.00138

Schmidt, W., & Prommer, N. (2005). The optimized CO-rebreathing method: A new tool to determine total hemoglobin mass regularly. European Journal of Applied Physiology, 95(5–6), 486–495. https://doi.org/10.1007/s00421-005-0050-3

Shi, Y., & Praphanbundit, O. (2024). Effects of Altitude Training and Sea-Level Training Programs on the Physiological and Performance of Elite Chinese Male Marathon Runners. International Journal of Sociologies and Anthropologies Science Reviews, 4(5), 155–166. https://doi.org/10.60027/ijsasr.2024.4575

Siebenmann, C., Robach, P., Jacobs, R.A., Rasmussen, P., Nordsborg, N., Diaz, V., Christ, A., Olsen, N. V, Maggiorini, M., & Lundby, C. (2012). Live high-train low using normobaric hypoxia: A double-blinded, placebo-controlled study. Journal of Applied Physiology, 112(1), 106–117. https://doi.org/10.1152/japplphysiol.00388.2011

Turner, G., Fudge, B.W., Pringle, J.S.M., Maxwell, N.S., & Richardson, A.J. (2019). Altitude training in endurance running: perceptions of elite athletes and support staff. Journal of Sports Sciences, 37(2), 163–172. https://doi.org/10.1080/02640414.2018.1488383

Volianitis, S., Yoshiga, C.C., & Secher, N.H. (2020). The physiology of rowing with a perspective on training and health. European Journal of Applied Physiology, 120(9), 1943–1963. https://doi.org/10.1007/s00421-020-04429-y.