Routledge
Taylor & Francis Group

Journal of Sports Sciences

ISSN: 0264-0414 (Print) 1466-447X (Online) Journal homepage: www.tandfonline.com/journals/rjsp20

Living low-training high: Innovative applications and new perspectives on hypoxic interventions for athletes

Paul S. R. Goods, Louise Deldicque & Brendan R. Scott

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2025.2541434

EDITORIAL

Living low-training high: Innovative applications and new perspectives on hypoxic interventions for athletes

Introduction

The effects of varying degrees of hypoxia on exercise performance have been investigated for many decades (Roskamm et al., 1969). In the late twentieth century, living at sea-level but training under hypoxia (which at the time was being referred to as intermittent hypoxic training: IHT) received relatively modest attention in scientific literature. Despite increased attention in the twenty-first century (which by then had been termed live low, train high: LLTH), a review in 2012 concluded that "*LLTH does not increase exercise performance at sea level in endurance athletes any more than simply training at sea level*" (Lundby et al., 2012). A breakthrough occurred in 2013, when Faiss, Léger, et al. (2013) reported improved repeated-sprint performance at sea-level with associated peripheral adaptations following repeated-sprint training in hypoxia (RSH). A review published by the same group that year summarised that, due to "*strikingly poor benefits for sea-level performance*" following IHT, it was time to turn scientific inquiry towards higher-intensity hypoxic training strategies which are based on "*different fundamental mechanisms*" (Faiss, Girard, et al., 2013). A meta-analysis published only 4 years later vindicated this proposal, demonstrating that RSH induces greater improvement for sea-level repeated sprints than matched training in normoxia (Brocherie et al., 2017).

This differentiation of LLTH modes with distinct mechanisms and resultant performance outcomes has led to a proliferation of research in this area. The first attempts to outline the scope of the LLTH research area identified passive, continuous, interval and repeated-sprint modes (Millet et al., 2013). By 2020, nine distinct LLTH modes had emerged in the literature, including seven systemic hypoxic training strategies and two localised hypoxic strategies involving blood flow restriction (BFR) (Girard et al., 2020). Meanwhile, BFR was also a rapidly developing area of athletic performance research, and soon after, nine distinct BFR modes were identified in a review of the area (Scott et al., 2023). While that review identified only two established and efficacious methods of BFR training in the literature (low-load resistance exercise and low-intensity aerobic exercise), many of the same mechanisms responsible for higher-intensity training adaptations with systemic hypoxia have theoretical potential via localised hypoxia (Mckee et al., 2023).

This special issue

With the increasing use of hypoxic interventions for high-performance athletes across a range of sports, this special issue presents a cutting-edge collection of scientific articles on the topic. Contributions were received on various applications of hypoxic methods to improve physiological qualities or performance outcomes, as well as to optimise the rehabilitation or management of load-compromised athletes. The new developments and perspectives in this fast-evolving field arising from this special issue are summarised in the following sections.

Resistance training under systemic or localised hypoxia

A meta-analysis by Benavente and Feriche (2024) showed a significant, yet trivial, benefit for strength development favouring resistance training in systemic hypoxia *versus* normoxia. Sub-group analyses also indicated that differences in exercise programming variables may impact on the benefits of resistance training in hypoxia (e.g., training to failure vs not, number of weekly sets per muscle group), though these effects were again trivial to small. While the effects of systemic hypoxia during resistance training seem small, the benefits of low-load resistance exercise with BFR on increased muscle strength and size have been consistently reported since the late 1990s (Shinohara et al., 1997; Takarada et al., 2000). In this special issue, Loenneke et al. (2025) provides an update of what we know, and what is not yet known, after 25 years of BFR research. While this field has expanded beyond low-load resistance training to other exercise and passive applications (Scott et al., 2023), numerous mechanistic and practical questions remain. Clarkson et al. (2025) surveyed BFR use in high-performance sport, with 98% of practitioners combining BR with resistance training, primarily for injury rehabilitation (81%), programmes targeting hypertrophy (80%), or to limit muscle mass loss (72%). A novel application of BFR presented by Smith et al. (2025) examined low-load BFR resistance training (25–30% 1RM, 60% arterial occlusion pressure: AOP) during a taper phase in basketball athletes. Compared to a traditional high-load resistance training taper (80% 1RM), BFR improved 5-m sprint, back squat, and bench press performance. Interestingly, the beneficial effects of BFR do not seem to translate to high-load resistance training. Bergamasco et al. (2024) demonstrated that despite greater metabolic stress (determined by near-infrared spectroscopy), muscle hypertrophy was not enhanced by combining BFR (60% AOP) with high-load resistance training (20 sessions, 3–4 sets of 10 repetitions with 80% 1RM). Differences in adaptations to low-load BFR training versus high-load training may also be impacted by differences in acute muscle oxygenation characteristics (Simpson, Moore, et al., 2025), though larger studies with greater statistical power are required to confirm these preliminary results.

Repeated sprint training under systemic or localised hypoxia

Faiss et al. (2024) presented an overview for the field of RSH, concluding that this is an '*efficient (but not magic) training intervention*' to delay fatigue. They report that >75% of controlled studies observed benefits from adding hypoxia to repeated-sprint training, especially for team-, combat-, and racket-sports and when used with high exercise-to-rest ratios at moderate altitude (~3000 m). Solsona et al. (2024) examined research utilising both systemic and localised (i.e., BFR) hypoxia during repeated-sprint training, concluding that these strategies may both be useful for sports with a high glycolytic demand as they can improve repeated-sprint ability within short periods. However, practitioners should be aware that more research is needed to understand the physiological consequences of using a hypoxic stimulus during maximal exercise, and how these responses manifest in adaptations (Solsona et al., 2024). For example, Simpson, Walter, et al. (2025) reported that repeated-sprints in hypoxia (10 × 6-s cycle sprints; fraction of inspired oxygen [F_iO_2] adjusted to target peripheral oxygen saturation of ~80%) temporarily increased central sympathetic nervous system activity, along with increased type II and reduced type I muscle fibre recruitment. Finally, McKee et al. (2025) reported that nine sessions of repeated-sprint training for team sport athletes caused comparable improvements to power output at first and second ventilatory thresholds, irrespective of whether training was performed with or without BFR. However, external training load (total work done) was reduced with BFR training, suggesting the utility of BFR to allow adaptations in athletes who may require reduced external demands such as during late-stage rehabilitation.

Systemic or localised hypoxia as rehabilitation tools

Chambion-Diaz et al. (2025) showed that implementing hypoxia ($F_iO_2 = 0.14$) during high-intensity interval running at 80% of bodyweight (AlterG® antigravity treadmill) allowed for similar physiological stress to sea-level running at 100% bodyweight. Echoing McKee et al. (2025), this reduction in external demands whilst maintaining a physiological stimulus for adaptation seems promising in rehabilitation contexts for athletes. This area was expanded on by Narang et al. (2024) in this special issue, who synthesised potential applications of hypoxia to augment injury rehabilitation for athletes in a narrative review. They present a mechanistic basis for how hypoxia may assist in healing processes, as well as augment adaptations to reduced-load exercise during rehabilitation. Focusing on localised hypoxia, the systematic review by Bommasamudram, Morrell, et al. (2025) emphasised the benefits of aerobic BFR training to increase muscle strength, hypertrophy, aerobic capacity, and physical function, concluding that bodyweight BFR training may "*support rehabilitation or periods where equipment access is limited to improve endurance, strength and hypertrophy*". With follow-up experimental work, the same research group then demonstrated that the acute cardiovascular and metabolic responses to walking and bodyweight lunges increase with BFR (60% AOP) yet still remain within the light-to-moderate intensity range (Bommasamudram, Nayak, et al., 2025). These findings have potential applications for athletes recovering from musculoskeletal injury, though it is also important to note that BFR exaggerates the rating of perceived exertion responses (Bommasamudram, Nayak, et al., 2025), which should be considered in exercise programming.

Methodological considerations for training with systemic or localised hypoxia

This special issue highlights that the approach to implementing BFR should be carefully considered along with traditional exercise programming variables. Kamis et al. (2024) demonstrated that occlusion pressures were higher when measured in a seated position compared to a supine position. Furthermore, when participants performed low-load knee extensions (4 sets at 30% 1RM at 60% AOP), fewer repetitions and higher perceptual responses were observed in a session using the seated, compared to supine, AOP measurement. Rolnick et al. (2024) also demonstrated while elbow flexion exercise to failure caused negligible arterial stiffness or blood pressure changes, applying BFR with autoregulation (i.e., cuff automatically adjusts pressure to provide a consistent restrictive stimulus throughout exercise) versus without autoregulation caused small increases in perceived discomfort. Finally, Burtscher et al. (2025) provided perspectives on using perception of effort to augment responses to LLTH interventions. They propose a psychophysiological framework in which changes in a participants' perception of effort could reflect neurophysiological and psychological adjustments to hypoxia, in addition to the well-established physiological adaptations to LLTH.

Key messages and future directions

This special issue has produced several important advances in understanding of systemic and localised LLTH methods. It is clear that acute exercise variables (Benavente & Feriche, 2024; Bergamasco et al., 2024) and manipulations of the hypoxic stimulus (Kamis et al., 2024; Rolnick et al., 2024) must be carefully considered in planning any LLTH intervention. There also now seems to be potential benefits for BFR during repeated-sprint training (McKee et al., 2025; Solsona et al., 2024), which complements the growing RSH literature (Faiss et al., 2024; Simpson, Walter, et al., 2025). Applications of LLTH for athletes who require reduced loads during a taper (Smith et al., 2025), or who are rehabilitating musculoskeletal injuries (Clarkson et al., 2025, Narang et al., 2024) are becoming more sophisticated, with data supporting both systemic (Chambion-Diaz et al., 2025) and localised (Bommasamudram, Morrell, et al., 2025) hypoxic interventions.

As this field continues to develop, it seems pertinent that under-investigated LLTH methods be examined, including high-intensity training modes with BFR, hypoxic interventions in rehabilitation settings, and mechanistic research to further resolve the physiological underpinnings of effective hypoxic training. Additionally, the standardisation of nomenclature for different LLTH modes has helped reduce noise in the literature by clearly delineating these LLTH modes from one another, ensuring that researchers can easily discover new advances in the field (Girard et al., 2020). However, for some recently developed BFR training strategies (e.g., sport-specific and repeated-sprint training with BFR), there is not yet organically adopted consistent nomenclature. The adoption of subscripted modes after the BFR acronym is one solution that should be considered (e.g., repeated-sprint training with blood flow restriction: BFR_{RST}).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Health and Medical Research Council.

References

Benavente, C., & Feriche, B. (2024). The influence of specific resistance training methodological prescription variables on strength development under hypoxic conditions: A systematic review and meta-analysis. *Journal of Sports Sciences*, 1–10. https://doi.org/10.1080/02640414.2024.2425536

Bergamasco, J. G. A., Bittencourt, D., Silva, D. G., Biazon, T., Soligon, S. D., Oliveira, R. M., & Libardi, C. A. (2024). Individual muscle hypertrophy in high-load resistance training with and without blood flow restriction: A near-infrared spectroscopy approach. *Journal of Sports Sciences*, 1–7. https://doi.org/10.1080/02640414.2024.2437588

Bommasamudram, T., Morrell, Z. G., Clarkson, M. J., Nayak, K. R., Kadavigere, R., Russell, A. P., & Warmington, S. A. (2025). Chronic adaptations to blood flow restriction aerobic or bodyweight resistance training: A systematic review. *Journal of Sports Sciences*, 1–15. https://doi.org/10.1080/02640414.2025.2474346

Bommasamudram, T., Nayak, K. R., Clarkson, M. J., Russell, R., Kadavigere, A. P., Warmington, S. A., & Warmington, S. A. (2025). Acute responses to aerobic and bodyweight exercises with and without blood flow restriction in sedentary individuals - a randomized crossover study. *Journal of Sports Sciences*, 1–10. https://doi.org/10.1080/02640414.2025.2474346

Brocherie, F., Girard, O., Faiss, R., & Millet, G. P. (2017). Effects of repeated-sprint training in hypoxia on sea-level performance: A meta-analysis. *Sports Medicine*, *47*(8), 1651–1660. https://doi.org/10.1007/s40279-017-0685-3

Burtscher, M., Alvarez-Herms, J., Burtscher, J., Strasser, B., Kopp, M., & Pageaux, B. (2025). Could the perception of effort help us unravel the potential of "living low-training high"? A perspective article. *Journal of Sports Sciences*, 1–12. https://doi.org/10.1080/02640414.2025.2474352

Chambion-Diaz, M., Chertin, J., Pialoux, V., & Billaut, F. (2025). Combined effects of weight reduction and hypoxia on physiological and perceptual responses to high-intensity exercise in endurance athletes. *Journal of Sports Sciences*, *43*(8), 1–9. https://doi.org/10.1080/02640414.2025.2474333

Clarkson, M. J., Scott, B. R., Patterson, S. D., & Warmington, S. A. (2025). Blood flow restriction exercise in high-performance sport settings: A practitioner survey. *Journal of Sport Sciences*, 1–12.

Faiss, R., Girard, O., & Millet, G. P. (2013). Advancing hypoxic training in team sports: From intermittent hypoxic training to repeated sprint training in hypoxia. *British Journal of*

Sports Medicine, *47*(Suppl 1), i45–i50. https://doi.org/10.1136/bjsports-2013-092741
Faiss, R., Léger, B., Vesin, J. M., Fournier, P. E., Eggel, Y., Dériaz, O., Millet, G. P., & Vinciguerra, M. (2013). Significant molecular and systemic adaptations after repeated sprint training in hypoxia. *PLOS ONE*, *8*(2), e56522. https://doi.org/10.1371/journal.pone.0056522
Faiss, R., Raberin, A., Brocherie, F., & Millet, G. P. (2024). Repeated-sprint training in hypoxia: A review with 10 years of perspective. *Journal of Sports Sciences*, 1–15. https://doi.org/10.1080/02640414.2024.2416821
Girard, O., Brocherie, F., Goods, P. S., & Millet, G. P. (2020). An updated panorama of "living low-training high" altitude/hypoxic methods. *Frontiers in Sports and Active Living*, *2*, 26. https://doi.org/10.3389/fspor.2020.00026
Kamis, O., Rolnick, N., de Queiros, V. S., Akcay, N., Keskin, K., Yildiz, K. C. . . . Sofuoğlu, C., Werner, T., Hughes, L. (2024). Impact of limb occlusion pressure assessment position on performance, cardiovascular, and perceptual responses in blood flow restricted low-load resistance exercise: A randomized crossover trial. *Journal of Sports Sciences*, 1–9. https://doi.org/10.1080/02640414.2024.2422205
Loenneke, J. P., Hammert, W. B., Kataoka, R., Yamada, Y., & Abe, T. (2025). Twenty-five years of blood flow restriction training: What we know, what we don't, and where to next? *Journal of Sports Sciences*, 1–18. https://doi.org/10.1080/02640414.2025.2474329
Lundby, C., Millet, G. P., Calbet, J. A., Bärtsch, P., & Subudhi, A. W. (2012). Does 'altitude training' increase exercise performance in elite athletes? *British Journal of Sports Medicine*, *46*(11), 792–795. https://doi.org/10.1136/bjsports-2012-091231
McKee, J. R., De Marco, K., Girard, O., Peiffer, J. J., & Scott, B. R. (2025). Effects of blood flow restriction on internal and external training load metrics during acute and chronic short-term repeated-sprint training in team-sport athletes. *Journal of Sports Sciences*, 1–10. https://doi.org/10.1080/02640414.2025.2457863
Mckee, J. R., Girard, O., Peiffer, J. J., & Scott, B. R. (2023). Repeated-sprint training with blood flow restriction: A novel approach to improve repeated-sprint ability? *Strength & Conditioning Journal*, *45*(5), 598–607. https://doi.org/10.1519/SSC.0000000000000771
Millet, G. P., Faiss, R., Brocherie, F., & Girard, O. (2013). Hypoxic training and team sports: A challenge to traditional methods? *British Journal of Sports Medicine*, *47*(Suppl 1), i6–i7. https://doi.org/10.1136/bjsports-2013-092793
Narang, B. J., Drole, K., Barber, J. F. P., Goods, P. S. R., & Debevec, T. (2024). Utility of hypoxic modalities for musculoskeletal injury rehabilitation in athletes: A narrative review of mechanisms and contemporary perspectives. *Journal of Sports Sciences*, 1–14. https://doi.org/10.1080/02640414.2024.2416779
Rolnick, N., De Queiros, V. S., Moghaddam, M., Marquette, L., Taylor, S., Walters, J., Fedorko, B., & Werner, T. (2024). Acute impact of autoregulation of applied blood flow restriction pressures on bilateral single-joint upper limb resistance exercise. *Journal of Sports Sciences*, 1–10. https://doi.org/10.1080/02640414.2024.2416793
Roskamm, H., Landry, F., Samek, L., Schlager, M., Weidemann, H., & Reindell, H. (1969). Effects of a standardized ergometer training program at three different altitudes. *Journal of Applied Physiology*, *27*(6), 840–847. https://doi.org/10.1152/jappl.1969.27.6.840
Scott, B. R., Girard, O., Rolnick, N., McKee, J. R., & Goods, P. S. (2023). An updated panorama of blood-flow-restriction methods. *International Journal of Sports Physiology and Performance*, *18*(12), 1461–1465. https://doi.org/10.1123/ijspp.2023-0135
Shinohara, M., Kouzaki, M., Yoshihisa, T., & Fukunaga, T. (1997). Efficacy of tourniquet ischemia for strength training with low resistance. *European Journal of Applied Physiology and Occupational Physiology*, *77*(1–2), 189–191. https://doi.org/10.1007/s004210050319
Simpson, C. W. C., Moore, K. S., Smith, H. K., Coskun, B., & Hamlin, M. J. (2025). Tissue oxygenation in response to low-load and high-load back squats with continuous blood flow restriction in athletes. *Journal of Sports Sciences*, 1–10. https://doi.org/10.1080/02640414.2025.2457859
Simpson, C. W. C., Walter, J., Gieseg, S. P., Lackner, S., Holasek, S., & Hamlin, M. J. (2025). Central and peripheral nervous system activity and muscle oxygenation in athletes during repeated-sprint exercise in normoxia and normobaric hypoxia. *Journal of Sports Sciences*, 1–13. https://doi.org/10.1080/02640414.2025.2461947
Smith, H. K., Bird, S. P., Coskun, B., Olsen, P. D., Kavanagh, T., & Hamlin, M. J. (2025). Effectiveness of blood flow restriction training during a taper phase in basketball players. *Journal of Sports Sciences*, 1–12. https://doi.org/10.1080/02640414.2025.2454712
Solsona, R., Sabater Pastor, F., Normand-Gravier, T., Borrani, F., & Sanchez, A. M. (2024). Sprint training in hypoxia and with blood flow restriction: Controversies and perspectives. *Journal of Sports Sciences*, 1–15. https://doi.org/10.1080/02640414.2024.2416839
Takarada, Y., Takazawa, H., Sato, Y., Takebayashi, S., Tanaka, Y., & Ishii, N. (2000). Effects of resistance exercise combined with moderate vascular occlusion on muscular function in humans. *Journal of Applied Physiology*, *88*(6), 2097–2106. https://doi.org/10.1152/jappl.2000.88.6.2097

Paul S. R. Goods
PHysical Activity, Sport and Exercise (PHASE) Research Group, School of Allied Health (Exercise Science), Murdoch University, Perth, Australia
The Centre for Healthy Ageing, Health Futures Institute, Murdoch University, Perth, Australia
Paul.Goods@murdoch.edu.au
http://orcid.org/0000-0003-2585-6852

Louise Deldicque
Institute of Neuroscience, UCLouvain, Louvain-la-Neuve, Belgium

Brendan R. Scott
PHysical Activity, Sport and Exercise (PHASE) Research Group, School of Allied Health (Exercise Science), Murdoch University, Perth, Australia
The Centre for Healthy Ageing, Health Futures Institute, Murdoch University, Perth, Australia