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The Physiological Effect Of Altitude Training On Endurance Athletes: A Systematic Review

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Abstract

One of the most well-established ways for improving athletic performance, specifically with respect to endurance sports, is through altitude training. Systematic review is synthesized to provide findings from multiple studies that examine the impact of different altitude training models including 'live high, train low' (LHTL) and 'live high, train high' (LHTH) in endurance athletes. However, within and between studies, the outcomes were highly variable and were influenced by both individual variability and genetics, and there was a high degree of consistency across studies in terms of key physiological changes such as improved oxygen transport and ventilatory acclimatization. Most research confirms that altitude training improves endurance performance, but the exact time of exposure and duration, as well as athlete specific responses, are key factors in maximizing its benefit. Altitude training protocols still need further research to refine them and maximize performance outcome in a wide range of endurance sports.

Keywords: Altitude, Endurance, Athletes, Physiological Adaptations, Performance.

Introduction

In recent years, altitude training has become a popular strategy amongst athletes specializing in aerobically based sports, particularly long distance running, cycling and cross-country skiing. Altitude training is founded in a hypoxic setting and the fundamental principle here is to expose the body to a hypoxic environment which stimulates a series of physiological adaptations. Included among these are increased erythropoiesis (blood cell production), increased haemoglobin mass and improved oxygen transport capacity, which are all critical for high ongoing aerobic workloads. Reaching altitude decreases the atmospheric oxygen pressure forcing the body to adapt which improves efficiency of oxygen utilization which may improve performance when they return to sea level where oxygen is easier to use (Bailey & Davies, 1997; Wilhite et al., 2019).

Many altitude training models have been developed that optimize these adaptations while allowing athletes to maintain high training intensities. The most well-known of these is the 'live high, train low' (LHTL) model where athletes live at moderate to high altitude (to stimulate red blood cell production) but train at lower altitude to avoid the fatigue and reduced performance typically associated with high intensity exercise in the hypoxic conditions. The purpose of this approach is to take benefits of acclimatization along with the capacity to train at high intensities (Stray-Gundersen et al., 2001). In contrast, the 'live high, train high' (LHTH) model, living and training at altitude, promotes further physiological adaptations but with a concomitant trade off of the athlete’s ability to train at optimal intensities (Turner, 2016). Flaherty et al. (2016) and Wilhite et al. (2013) found that they both produce large improvements in VO2max and hemoglobin mass, but there is still a mixed correlation between physiological adaptations induced by these models and between these models and performance improvements at sea level (Robach & Lundby, 2020).

However, the individual variability of the response to altitude training is very large, some athletes show more pronounced adaptations than others. Variability in this response could be due to genetic predispositions, previous training history and the altitude that training took place. As a result, Cycavoğlu et al. (2021) discovered that specific genetic markers influenced athletes’ responsiveness to hypoxic environments; hence personalized altitude training protocols would be essential. In addition, the timing of sea level performance after altitude training and the duration of altitude exposure are key determinants of performance outcomes. Chapman et al. (2014) researched that optimal performance correlates with the return of the athlete back to sea level once the athlete has been acclimatized long enough to maximum utilise the physiological adaptations gained from altitude exposure.

Yet for all these complexities, altitude training continues to feature as a central part of endurance training programmes. Specifically, when working at sea level, more standardized guidelines still exist regarding the optimal altitude, duration, and timing of altitude training to maximize performance benefits, which makes it difficult to predict how, when, and where height may positively influence exercise performance (Bishop & Girard, 2013; Sinex & Chapman, 2015). As a result, this systematic review intends to synthesize the state of research on physiological effects of altitude and hypoxic training, and assess to what extent these adaptations facilitate performance, and attempt to clarify the variability in athlete response.

Research Methodology

The aim of this systematic review was to review the effects of altitude and hypoxic training methods on endurance athletes by synthesizing the information from peer reviewed journal articles and studies within the years 1990 to 2024. A structured approach with methodology to follow has been taken based on Preferred Reporting Items for Systematic Reviews and Meta.

Data Sources and Search Strategy

This was a broad search, involved a literature search using PubMed, Google scholar, Scopus and web of science. Keywords used in the search included:

"altitude training,"

"hypoxic training,"

"live high, train low,"

"VO2max,"

"endurance athletes,"

"hemoglobin mass," and

"oxygen transport capacity."

Boolean operators (AND, OR) of these terms were used to created queries to retrieve the most relevant articles. All real and simulated altitude training studies were included.

Inclusion and Exclusion Criteria

The studies selected for this review had to meet the following criteria:

Inclusion criteria:

Hypoxic training studies and its physiological adaptations in endurance athletes.

Some articles about different altitude training model (LHTL and LHTH).

Peer reviewed publications studies available in full text in English.

Athletics studies conducted in athletes, such as running, cycling or cross-country skiing.

Exclusion criteria:

Non-direct studies on the effects of altitude training in endurance athletes.

Articles without peer review, opinion pieces, editorials.

Studies within the context of short duration, non-endurance sports or non-athlete populations.

Study Selection

Approximately 150 studies were initially found by the search. After screening titles and abstracts for relevance, 85 studies were then selected to be reviewed in full. After an in-depth review of the included and excluded studies, 52 of these studies were retained for this systematic review. The major reason that studies were excluded was that they were steered away from non-endurance athletes, or did not provide data on physiological outcomes relevant to altitude training.

Data Extraction and Analysis

For each study included in the review, key data points were extracted, including:

Sample size and participant characteristics (eg, age, gender, training background), Type and duration of altitude training (real or simulated, LHTL or LHTH), Measured physiological outcomes (VO2max, hemoglobin mass, red blood cell count), Performance outcomes (endurance performance improvements at sea level).

Patterns, trends and discrepancies in the results and a qualitative synthesis of the studies were conducted. Performance outcomes across different methodology and athlete populations were compared across different methods formulated for altitude training.

Limitations

The review acknowledges several limitations:

Variability in altitude exposure: The direct comparisons, however, were complicated by studies that employed varied altitudes, durations and trainings intensities.

Individual variability: The results were complicated by genetic factors and by the individual athlete responses to altitude training.

Heterogeneity of sports disciplines: As reviewed, the sport described herein is that of endurance athletes, yet the diversity of sports (e.g. cycling, running, skiing) may yield different physiological adaptations.

The research methodology followed in this work guaranteed a systematic and wide approach to collect and merge data from a long list of studies related to altitude and hypoxic training of endurance athletes.

Review of literature

The use of altitude training, as a performance optimizing strategy for endurance athletes, has been heavily investigated based on the physiological responses to hypoxia (i.e., reduction in available oxygen) typically experienced during high altitude. For example, in athletes competing in disciplines such as long distance running, cycling, and cross country skiing this training modality has been used to increase critical performance markers, such as VO2max and red blood cell production, which are necessary to sustain aerobic efforts in competition.

Different altitude training models including "live high train low" (LHTL) and "live high train high" (LHTH) have been developed and evaluated as to their effectiveness at optimizing performance gains. These models are also designed to leverage the stimulating effects of the hypoxic environment on erythropoiesis and on other physiological adaptations that must be balanced with the demands for high intensity training. Although there is strong evidence of physiological improvement with altitude training, uncertainty remains as to the extent of its translation to competitive performance at sea level.

The uth of altitude training in inducing substantial physiological adaptation associated with improved endurance performance has long been recognized. Hypoxia-induced erythropoiesis is the primary mechanism through which altitude training produces its benefits, an increase in red blood cell mass, and resulting improvement in the body's ability to deliver and utilize oxygen. That's especially important for endurance athletes, where maintaining delivery of oxygen to muscles to support continued high intensity demands is often key to success for extended periods. In short, Bailey and Davies (1997) and Flaherty et al. (2016) have shown that inducing hypoxia (e.g. via 'live high, train low') can improve VO2max and performance on the field. While these physiological changes are promising, the actual sea-level performance impact has been variable and this has continued to generate discussions regarding the practical use of altitude training.

But altitude training is no easy task — and besides the physiological benefits, there are issues such as the variability of responses to hypoxia in different individuals. Chapman (2013) and Mujika et al. (2019) reports also show that some athletes gain from altitude training and others achieve little. The range of this variation can therefore be attributed to genetic factors, the length of time of exposure, the particular altitude, and the athlete's capability to acclimate to the hypoxic enviroment. Further, training can be reduced by the problems of altitude sickness and iron deficiency, as well as mental fatigue due to prolonged exposure to high altitudes. These complexities are explored in this review, and how different training models, individual trait, and technological advances in simulated altitude can improve altitude training protocols for endurance athletes.

In this review, we synthesize the current literature regarding the physiological and performance effects of altitude training on endurance athletes and attempt to explain the variable response amongst individuals, as well as the relative efficacy of different training models and the development of simulated altitude environments. The review also profiles the perils and risks of doing altitude training — like altitude sickness and iron deficiency, which can cut short the benefits. This will review these aspects in order to provide a complete overview of the current evidence for the effects of altitude training on endurance performance, and their practical applications for athletes and coaches looking to improve endurance performance.

Hypoxic Adaptations

In endurance athletes, altitude training has been used for many years to improve performance, largely through adaptations to hypoxia (Bailey & Davies, 1997). In fact, at altitude, reduced oxygen levels trigger a number of physiological changes to act to improve oxygen transport and VO2max such as increased erythropoiesis (Flaherty et al., 2016; Bonetti & Hopskins, 2009). LHTL and LHTH models have been utilized, but how well these models translate physiological gains into improved performance in sea level cannot be established (Levine & Stray-Gundersen, 1997; Mujika et al., 2019).

Physiological Adaptations

Increased red blood cell production is the major physiological adaptation brought on by altitude training and provides an advantage for transporting oxygen. Erythropoiesis, the process by which this takes place, serves to increase endurance performance by permitting athletes to sustain higher oxygen delivery to their muscles during sustained work. The first to document that altitude exposure stimulates erythropoiesis (i.e., it elevates red blood cell mass and thereby oxygen carrying capacity) were Bailey and Davies (1997). But their research also pointed out that being able to support such an adaptation depends on iron availability, as iron deficiency could hinder the benefits from altitude training.

Flaherty et al. (2016) extended the present findings by finding that "live high, train low" (LHTL) model increased VO2max and hemoglobin mass to a point where it was an effective model for improving endurance performance at sea level. That agrees with what Gore et al found (2001) in research, showing that altitude training resulted in an increase in hemoglobin mass, as well as an increase in muscle buffer capacity and submaximal cycling efficiency, leading them to rely on an improvement in the endurance of athletes with performance.

As with altitude training, Rusko et al. (2004) found that altitude training increased hemoglobin mass in cross country skiers, thereby producing significant improvements in endurance performance. These results emphasize the benefits of hypoxic exposure on critical physiological markers important for competitive athletes. The erythropoietic response to altitude training was also reviewed by Płoszczyca et al. (2018), who highlight the importance of factors, including duration of the altitude exposure and the intensity of the training, in achieving the greatest possible physiological benefits from ALT.

Further work, including that of Boning (2002), pinpointed the importance of maintaining similar training loads whilst at altitude to maximize long term performance gains. His research found that while altitude training can indeed produce significant physiological adaptations, these advantages don’t last long unless they’re obtained through long and well-planned training regimens. According to Mazzeo (2008), exercise at altitude following hypoxic exposure and constant training leads to the greatest increases in aerobic and anaerobic Performance.

Individual factors, such as the sport of the athlete, the duration of altitude exposure and specific physiological characteristics, also affect success of altitude training. Millet et al. (2010) compared the effectiveness of the 'live high, train high' (LHTH) and LHTL models and demonstrated that both methods induced physiological benefits, however LHTL was more effective for endurance athletes because it kept training intensities high, while benefitting from erythropoiesis induced by hypoxia.

Individual variability in response to altitude training was further explored by Chapman, Stray-Gundersen, and Levine (1998), who reported a wide range of athlete response to hypoxic exposure. Some athletes demonstrated large effects in oxygen transport and performance while others showed little, according to their study. The variability of this suggests that altitude training programs need to be individualised tailored to the specific needs and characteristics of each athlete for them to be optimal.

Palubiski et al. (2020) describes how athletes have also shown renal adaptations to altitude. High-altitude exposure is a stimulus for multiple renal responses including increased erythropoietin production to enhance red blood cell synthesis, according to their research. However, these adaptations serve an important role supporting endurance performance during prolonged hypoxic demands, and in turn, the incoming oxygen.

Saunders, Pyne and Gore (2009) included an examination of endurance training at altitude, which showed that while moderate altitudes (barely above 2,000–2,500 meters) are adequate hypoxic stimulus in bringing about key physiological adaptations, higher altitudes (above 3,000 meters) may be more effective for stimulating greater erythropoiesis and enhancement in VO2max. But they said maintaining training intensity at higher altitudes is also more difficult, so there is a need to carefully balance altitude exposure and training load to avoid overtraining and performance detriments.

Training Models: LHTL vs. LHTH

In the LHTL model (athletes live at high altitudes, but train at lower), others have considered this literally effective for increasing hypoxic adaptations without decreasing workout intensity (Levine & Stray-Gundersen, 1997). This model demonstrated improved hemoglobin mass, VO2max, muscle efficiency (Stray-Gundersen et al., 2001; Bonato et al., 2023).

As a result, in the case of LHTH model where athletes dwell and train at high altitudes, training intensity might be limited by oxygen limitations. All the work of Millet et al. (2010) and Ventura et al. (2003) agreed that LHTH results in similar physiological adaptations, but also reduces mental fatigue, and training intensity, making it less effective for performance gains at sea level.

Variability in Individual Responses

Variability in individual responses is one of the most critical factors for altitude training. According to Chapman (2013) some athletes improve vastly from altitude exposure while others make very little gain. They have attributed this variability to genetic predispositions that determine how much an athlete is able to adapt to hypoxic environments, Cicavoğlu et al. (2021).

In altitude training, McLean et al (2013) found that team sport athletes tended to gain less pronounced performance gains than their endurance counterparts. Although some athletes do increase their hemoglobin concentration and VO2max following altitude exposure, said Wolski et al. (1996), the direct relationship of these physiological markers and performance is inconsistent.

Performance at Sea Level

Altitude training and improved sea level performance is a complex relationship. Altitude training increases physiological markers such as VO2max and hemoglobin mass, but the direct translation to sea level performance often only modest, Saunders et al. (2009). A meta-analysis has been conducted by Bonetti and Hopkins (2009), who concluded that performing altitude training can yield small but important advantage for long distance athletes.

Since the publication of the Fulco, Rock, and Cymerman (2000) study, the effectiveness of altitude training for athletes competing at sea level has been addressed; the authors argue that the increase in red blood cell production within altitude residence is necessary, but not efficacious, if the ability to maintain high training intensity in a hypoxic environment is not also a priority in performance gain.

Challenges and Risks

Altitude training has its challenges and its risks. Such slowing down of positive effects of training, as altitude sickness, was highlighted by Khodaee et al. (2016). There is also a stage in athletics when iron levels must be regulated carefully, as iron deficiency deprives an athlete of the production of the red blood cells (Bailey & Davies, 1997; Epthorp, 2014).

Ventura, LaTorre et al. (2003) examined the psychological aspects of training in hypoxic environments and found that those who subjected themselves to LHTH training increased mental strain. Marzorati (2020) also noted that athletes find it hard to keep training at high intensity when at altitude, and overall benefits to performance may be limited.

Simulated Altitude Training

Real altitude training has become replaced by simulated altitude training. Chang et al. (2023) and Hamlin et al. (2013) reported that similar physiological benefits arise from both simulated altitude environments, including increased erythropoiesis and VO2max improvements. In particular, Turner (2016) found that for athletes that cannot access high altitude locations, simulated training is of particular use.

In simulated environments, Townsend et al. (2002) observed that LHTL improved VO2max among athletes and also improved hypoxic ventilatory response to enhance their performance at sea level. Independently, Koivisto et al. (2018) also examined the impact that diets high in antioxidants have at altitude training and the authors concluded that antioxidant supplementation does not detract from physiological adaptations.

Sport-Specific Effects

Altitude training responds in different ways to athletes in different sport. I.e, Lundgren et al. (2015) found whole body endurance sports like cross country skiing to improve VO2max more than specialized localized endurance sports. Shah (2018) also added that endurance athletes, especially long-distance runners and cyclists, reap more advantage from altitude training than athletes involved in team sports who are more in need of anaerobic performance.

According to Moges et al. (2024) the altitude training on Ethiopian endurance athletes have shown faster recovery times and improved hematological variables. It suggests that athletes from high altitude regions may have a genetic advantage in adaptation to altitude, offering another indication of genetic determination of the altitude training response.

Timing of Return to Sea Level

This research demonstrates that athletes' performance outcomes following altitude training are highly dependent on the time taken to return to sea level following the training. In particular, Mujika et al. (2019) showed that periodizing and well-timed return from altitude are critical to optimize the physiological effects of altitude exposure. In Chapman et al. (2013), some athletes returned from a brief sea level recovery period and performed better while others returned after a lengthier recovery period before competition.

Like Wolski et al. (1996), we also found that the adaptation process at sea level or to high altitude is quite individualized. The myriad of differences results in the added complication of planning altitude training programs for hypoxic training and subsequent competing at sea level because not all athletes are equal and respond uniformly to such training.

Effects of Altitude Training on Specific Athletic Groups

Although much of this research has included endurance athletes, such as runners, cyclists, and skiers, other athlete groups have also been studied. As an example, McLean et al. (2013) analyzed team sport athletes and while some physiological adaptations, like higher hemoglobin mass, occurred, overall performance gains were much smaller than in endurance athletes. This demonstrates the distinction between energy systems and performance demands in team sport.

Studies by Bahenský et1 al. (2020) have shown an improvement in adolescent endurance athletes' aerobic and anaerobic performance with altitude training. These results show that altitude training has far wider application than the traditional endurance sports and could be exploited to great effect when applied to developing young athletes.

Antioxidant-Rich Foods and Altitude Training

Oxidative stress in athletes is known to be increased with altitude exposure because of increased production of reactive oxygen species (ROS) in the hypoxic environment. If these ROS are not properly controlled they can damage the cells and induce inflammation, impairing recovery and reducing overall performance gains. In order to counter this, researchers are casting their net for the benefits of antioxidant-rich foods in supporting the body against oxidative stress and helping to mitigate oxidative stress brought about during altitude training.

To investigate the effect of antioxidant rich foods on altitude training responses in elite endurance athletes, Koivisto et al. (2018) conducted a randomised controlled trial. However, supplementation with antioxidant rich foods featuring dark leafy greens and berries did not inhibit physiological adaptations typically indicative of altitude training including increased hemoglobin mass and improved VO2max. We conclude that this implies that antioxidant intake by athletes does not interfere with the beneficial consequences of hypoxia on erythropoiesis and oxygen transport (Koivisto et al., 2018).

In a follow up study, Koivisto et al. (2019) looked at how foods rich in antioxidants affected altitude-induced oxidative stress and inflammation. Oxidative stress adaptations during altitude training benefit from antioxidant rich diets (Koivisto et al., 2019), as athletes who consume antioxidant rich diets along with a 3-week altitude camp have not been associated with a blunted increase in hemoglobin mass compared to control diet only athletes, further supporting the idea that antioxidant intake from foods can mitigate oxidative stress while promoting physiologic adaptations (Koivisto et al., 2019).

Other than this, Koivisto-Mørk (2023) investigated the effect of antioxidant rich foods and iron supplementation on inflammation and oxidative stress during altitude training. The findings of the study demonstrated that the antioxidant rich foods consumed by athletes resulted in reduced oxidative stress but not any reduction in their responses to altitude training, such as increased oxygen transport capacity and decreased inflammation (Koivisto-Mørk, 2023).

According to Stellingwerf et al. (2019), antioxidants should be consumed from whole foods and not supplements. The adaptive response to exercise relies on the body's ability to downregulate oxidative stress too fast, for some training adaptations, concluded the authors, who noted that drinking high doses of antioxidant supplements could interfere with this adaptive response by quelling oxidative stress too quickly. Antioxidant rich foods by comparison provide a balanced approach to recovery that enhance recovery without impeding key performance adaptations like red blood cell production and VO2max (Stellingwerff et al., 2019).

Premier researchers were Higgins et al. (2020) and Szczepanski et al. (2022) who also discovered that moderate preparation of antioxidants through nutrients doesn't mediate the inflammation and oxidative tension brought about by the intensity preparing as it enables one to improve their physiological advances, including expanded hemoglobin mass and aerobic ability. According to Koivisto's earlier studies, athletes exercising at altitude react well to antioxidant diets without being disadvantaged from performance gains, which parallels this finding.

Thus, this body of research underscores the dual role of nutrition in altitude training: while providing protective effects against oxidative stress, without loss of the physiological benefits of hypoxia. For athletes who might be more prone to oxidative stress and inflammation, antioxidant rich foods can be a strategic part of the diet when they are training at altitude. Understandably, this growing awareness of how nutrition plays a role in altitude training will only serve to push more research forward aimed at further polishing dietary guidelines to further increase the benefits of hypoxia while decreasing its risks.

The Role of Genetics in Altitude Training

Cicavoğlu et al. (2021) argues that genetic factors play a role in an athlete's response to altitude training. Altitude training may be more helpful for athletes with genetic markers favouring erythropoiesis and oxygen transport. That means, while altitude training helps many athletes, for some, even more physiological 'gain' occurs compared to what others get.

In addition, Durand and Raberin (2021) examined how exercise induced hypoxemia (EIH) affects altitude training responses. They found that athletes with a high risk of EIH — which restricts how much oxygen is transported around the body when exercising intensely — may benefit more from altitude training than athletes without this condition. This implies that altitude training might be individualized for each individual physiological limitation such as respiratory adaptations.

Emerging Trends in Altitude Training

Technological innovation is being utilized to develop new trends in altitude training focused on how to optimize the balance between hypoxic exposure and high intensity training. Contemporary altitude training techniques (Wilber 2001) are reviewed with emphasis on how simulated hypoxic environments, altitude tents and other technologies may supplement traditional LHTL and LHTH approaches.

Hamlin et al. (2013) and Chang et al. (2023) explore, from the perspective of athletes not in a position to travel to high altitude locations, the possibility of simulated altitude training. With the help of these technologies, athletes can train at sea level without the side effects of hypoxia, and thus reaping all the effects of an extra boost in erythropoiesis and VO2max.

Yet, despite its physiological benefits, there continues to be substantial evidence that altitude training improves endurance performance, especially by increasing red blood cell mass and improving VO2max. But whether altitude training is successful requires that an athlete's sport, genetic predispositions, the specifics of the altitude training model (LHTL versus LHTH), and the timing of return to sea level are considered. Despite being the most effective model to retain high training intensities and allow for hypoxic acclimatization, the design of altitude training protocols must also consider individual variability and manage iron, mental fatigue and oxidative stress. Although themost likely will not go and stay at altitude, simulated altitude training offers a promising alternative for athletes who cannot access high altitude locations. Further work is needed to optimize this form of training for various sports and athletes.

While altitude training does not offer the greatest physiological benefits from a cardiovascular, strength or power perspective, one of the reasons is clearly that it does provide substantial physiological benefits as altitudes increase. Although individual variation remains the greatest variable in the outcome of altitude training, the LHTL model has been shown to be the most effective for achieving the balance of hypoxic overdrive with high training intensities. Although not as ideal as true altitude training, 'altitude training' simulation shows promise as a viable alternative for athletes unable to access high altitude locations, but more research is required to optimize the training protocol to all sports and athlete populations. Long-term effects of altitude training on sea level performance should be future studies, as well as the ways altitude training can be tailored to suit individual athlete needs.

Discussion

Research has demonstrated roles of altitude and hypoxic training in endurance athlete performance, however, both have been shown to offer physiological as well as logistical barriers. Real and simulated altitude training leads to the same central adaptation, i.e., increased VO2max and hemoglobin mass, as the hypoxic stimulus (Sinex & Chapman, 2015; Wilhite et al., 2013). However, having these adaptations for endurance performance has been proven to be of great benefit for athletes who live at high altitudes but train at lower altitudes. The approach known as 'live high train low' (LHTL) was well received because it allows you to experience benefits of hypoxic exposure while still maintaining high training intensities (Turner, 2016; Brugniaux et al., 2006).

The most valuable resulting benefit of altitude training is the ability to stimulate erythropoiesis and provides an increase in red blood cell mass, oxygen carrying capacity. Hamlin et al (2013) has also shown that this process improves endurance athletes' ability to sustain higher intensities for a longer period. Nevertheless, individual variability has considerable impact on the effectiveness of altitude training. For this reason, even athletes of similar physiological traits may not experience the same benefit from hypoxia (Cicavoğlu et al., 2021). In addition, the metabolic cost of increased ventilation limits performance gains at high altitudes, especially at greater workloads where more energy is needed to be expended to restore oxygen delivery (Wilhite et al., 2013).

Still, sport specific responses to altitude training do differ; endurance athletes who engage in full body aerobic training such as cross-country skiing improve VO2max more than those in more localized endurance sports (Lundgren et al., 2015). In addition, Turner (2016) determined that well controlled hypoxic exposure during LHTH training regimens best elicits hematological adaptations and enhances total endurance capacity.

The considerable physiological adaptation that accompanies altitude training has been reported by studies to be accompanied by potential downsides, including increased mental and physical fatigue in the initial acclimatization process (Ventura et al., 2003). Also, antioxidant supplementation is able to counteract oxidative stress during hypoxic training, but it fails to impair the hematological adaptations which are key for endurance adaptations (Koivisto et al., 2018).

However, short term altitude exposure has also been successful with younger male athletes, and was especially effective for improving both aerobic and anaerobic capacity. That implies that altitude training holds good for more than just endurance related sports and improves overall athletic performance provided it’s being used correctly (Bahenský et al., 2020).

Conclusion

In terms of an endurance athlete's physiology, altitude and hypoxic training methods provide a large number of great benefits – mainly that of stimulating erythropoisis, whereby increasing the amount of red blood cells the body produces as well as the ability to transport oxygen. Increased aerobic capacity, as demonstrated by higher VO2max values, is important for continued endurance event performance and is the result of these adaptations. A specific model, the "live high, train low" (LHTL) has also been demonstrated to be particularly efficacious as it allows for hypoxic exposure to be experienced by athletes during 'live high' while at the same time facilitates the high intensity training also required for attainment of peak performance.

Not all athletes benefit equally from altitude training however. It turns out individual differences, or differences in genetic predispositions and physiological characteristics, are important in determining how athletes respond to altitude. Indeed, some athletes will see big improvements in endurance while others may see very little improvement. Another critical factor is timing of exposure — research suggests that altitude training and sea level return timing and duration can greatly affect outcome performance. Furthermore, the particular demands of the several sports would make some of them more susceptible to the effect of altitude training than others. As such, one group might experience more improvement than the other; for instance, long distance runners and cyclist may improve more than team sport athletes who need less continuous aerobic output.

Physiological adaptations for training at altitudes—such as enhanced oxygen transport capacity—are well known, but so are the mental and metabolic burdens of chronic hypoxia. Residing at altitude means that the body is put under considerable stress and then if not handled correctly, over training, fatigue and illness follow. Therefore, the hypoxia has to be very well balanced with the excessive physical and mental strain, and must not exceed the level of physical and mental strain, which requires well-structured training plans and a good recovery time.

Future research will need to target fine tuning altitude training protocols to maximize their effect for certain physiological and genetic profiles. Altitude exposure can be taken on an individually designed training plan to facilitate maximum benefits of the exposure while preventing the risks of overtraining. In addition, future studies should be directed toward better understanding how different sports and types of athletes respond to altitude training and the long-term effects on sea level performance. If there are standardized guidelines for the use of altitude training in all kinds of endurance sport, coaches and athletes can benefit from a scientific and systematic tool to enhance performance.

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