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Effect of altitude training on the aerobic capacity of athletes: A systematic review and meta-analysis

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ABSTRACT

Purpose: With a growing number of athletes and coaches adopting altitude training, the importance for rationalizing and optimizing such training has been emphasized. We conducted a meta-analysis to evaluate the influence of altitude training on athletes' aerobic capacity and to explore the best altitude training method to improve this capacity.
Methods: We searched Web of Science, SpringerLink, Science Direct, EBSCO, and PubMed databases combined with manual search of the references to collect studies indexed from 1979 to September 2020 on the effect of altitude training on athletes' aerobic capacity. Data from experimental studies that reported hemoglobin levels and maximum oxygen uptake in athletes before and after altitude training, or in athletes performing altitude training in comparison with a control group were analyzed. Data of the populations, intervention, comparison, outcomes and study design were extracted. Review Manager software 5.3 was used for bias evaluation.
Results: 17 publications were included. In our meta-analysis, altitude training led to higher maximum oxygen uptake [standardized mean difference (SMD) = 0.67, 95% confidence interval (CI) 0.35–1.00, $P < 0.001$] and hemoglobin level (SMD = 0.50, 95% CI 0.11–0.90, $P = 0.013$) than training at lower altitude. The result of sensitivity analysis showed that results of meta-analysis were relatively stable, and there was no bias or change in the result of effect size according to the bias test. The results of subgroup analysis showed that high-altitude living and low-altitude training ("Hi-Lo" regime), with a training cycle of about three weeks at an altitude around 2500 m, had better effects than other regimes on the athletes' aerobic capacity.
Conclusions: Altitude training can improve athletes' aerobic capacity in terms of maximum oxygen uptake and hemoglobin level. Our results are limited by the number and quality of available studies. Therefore, more high-quality studies are needed to verify and extend these findings. Our study can provide scientific suggestions for the training of athletes.

1. Introduction

The Olympic Games of 1968 were controversial because the host, Mexico City, was located at an altitude of 2300 m [1]. There, the

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oxygen content in the air is 30% lower than on the ground, which was considered a great challenge for the athletes [2]. Although those Games were considered a success, they highlighted the need to rationally optimize training regimes to prepare athletes for performance at high altitudes and ensure fair competition [3].

Altitude training, also known as hypoxic training, means that athletes train in high-altitude areas or are subjected to artificial hypoxia in a planned and purposeful way [4]. The altitude training method has been adopted in many countries. Especially for the endurance sports, athletes have used this training method to improve their aerobic capacity and, as a consequence, to ameliorate their performance in competitions [4]. After half a century, the standard altitude training method has evolved from the traditional high-altitude living and training ("Hi-Hi") strategy toward other training modes [4,5]. This allows the athletes to choose the best training mode according to their own needs, including high-altitude living and low-altitude training ("Hi-Lo") [6], low-altitude living and high-altitude exercise ("Lo-Hi") [7], living high-exercise high-training low (Hi-Hi-Lo) [8], intermittent hypoxic training (IHT), and Living low-Training high-Training Low (Lo-Hi-Lo).

The application of altitude training has led to many good achievements for athletes. For example, Chinese athlete Xing Huina conducted five altitude training cycles from 2003 to 2004, and finally won the women's 10,000-m gold medal at the 2004 Olympic Games in Athens. After 28 days of Hi-Lo training in Deer Valley and Salt Lake City (USA), the average time for athletes to complete the 3000-m race decreased by 5.8 s [9]. In preparation for the Tokyo Olympic Games, the Chinese wrestling team went to Kunming, China for altitude training in early July 2020, and the Chinese middle and long distance running team arrived in Eldoret, Kenya, in January 2020 for training.

As athletes and coaches have shown increasing interest in altitude training, the need for rationalizing and optimizing such training has increased. Several important questions remain unanswered, such as what are the best mode, cycle frequency, and altitude for a given sport, and how long athletes' aerobic capacity lasts after altitude training. Research into these questions is all the more important because improper altitude training can seriously affect the circulation, causing loss of body mass and of skeletal muscle, muscle atrophy, cold, gastrointestinal dysfunction, and even injury, hematuria, and other disorders [10].

There are no unified standards measuring the effects of altitude training. Indexes to evaluate aerobic capacity [11], such as aerobic capacity, are often used. Aerobic capacity refers to the capacity of the human body to aerobically oxidize carbohydrates and lipids. Previous studies have proved that aerobic capacity was positively correlated to the capacity of hemoglobin in red blood cells carrying oxygen in circulation to cardiac and skeletal muscles [12]. Therefore, useful indexes of aerobic capacity are the maximum oxygen uptake, measured as maximum oxygen partial volume (VO^2max) and hemoglobin (Hb) level.

One study confirmed that the exercise ability and VO^2max of athletes were significantly improved after seven days of basic training and five days of intermittent training at 2315 m, and that the improvement was greater than that of subjects who trained at low altitude [13]. In another study, high-performing mid- and long-distance runners who followed a "Hi-Lo" training regime spent 14 h a day under hypoxic conditions (6 nights at 2500 m, 12 nights at 3000 m) [14]. Their VO^2max and maximum aerobic power were significantly higher immediately at the end of hypoxia and 15 days afterward. A recent meta-analysis about the effect of altitude training on athletes' intermittent running performance showed that the performance of intermittent running of the intervention group was better than that of the control group while the intervention group received hypoxia training for more than 4 weeks [15]. Another meta-analysis concluded that altitude training led to higher VO^2max and Hb level in elite Korean athletes than sea-level training [16].

On the other hand, other studies did not find a significant improvement after altitude training compared with training at lower altitude. A study of 12 cyclists found that six-week high-intensity endurance training did not improve aerobic capacity, independently of whether it was conducted in a hypoxic or normoxic environment [17]. Another study found no differences in VO^2max and exercise ability between athletes who trained for four weeks in a simulated 2750-m atmospheric pressure under hypoxic conditions, and a control group who trained at low altitude. Another study suggested that exercise ability is improved by the training, rather than the hypoxic environment per se [18]. Many factors are likely to affect how altitude training impacts athlete performance, including the activity of red blood cells, enzymes, pH, and metabolites such as lactic acid. In addition, the athlete's current state of health may affect the results of altitude training.

Therefore, we conducted a systematic review and meta-analysis to evaluate the effects of altitude training on Hb levels and VO^2max of athletes. We aimed to identify emerging consensus about optimal training modes, cycle frequencies, and altitudes that may help athletes and coaches rationalize and optimize their altitude training regimes.

2. Methods

2.1. Search strategy

Web of Science, SpringerLink, Science Direct, EBSCO, and PubMed databases were searched to identify literature on the effects of altitude training on athletes' aerobic capacity. The search period was from the establishment of each database to September 20, 2020. Search terms included "altitude training", "plateau training", "highland training", "VO^2max ", "hemoglobin", and "athlete". As an example, the search strategy used for PubMed was showed as follow:

#1 altitude training OR plateau training OR highland training.

#2 VO^2max OR hemoglobin.

#3 athlete.

#4 #1 AND #2 AND #3.

In addition, the reference lists of included publications were manually searched to identify further relevant studies.

2.2. Eligibility criteria

Studies that fulfilled the following criteria were included: (1) the research design was a controlled interventional study that compared the aerobic ability of athletes before and after altitude training, or the aerobic ability of athletes undergoing altitude training or sea-level training; (2) data from the intervention group came after altitude training, while control data were from after sea-level training or before altitude training; (3) participants were athletes involved in altitude training without limits of nationality, ethnicity and course of disease; and (4) athletes' Hb levels and VO^2max were reported among the outcomes.

Studies were excluded if they (1) examined participants who were not athletes, such as people with cardiopulmonary function diseases; (2) did not clearly describe changes in study parameters between before and after the intervention; (3) were grey literature in which the intervention had not concluded; or (4) conference summaries and reviews; or (5) articles without full text available.

2.3. Study selection and data extraction

Two reviewers independently screened the literature, extracted the data, and checked them for validity. In case of disagreement, a third reviewer was consulted. If data were lacking, we contacted the corresponding author in an attempt to obtain additional information.

The reviewers first read the titles and abstracts of potentially eligible studies, excluded obviously unrelated literature, and then read the full text of the remaining studies. The following data were extracted from the final set of studies: (1) basic information about the study, including the title, first author, journal, and year of publication; (2) baseline characteristics of the study participants, including the sample size of each group, age, and sex; (3) details on intervention measures, follow-up time, intervention cycle, intervention frequency, intervention duration and intensity; (4) information needed to assess risk of different types of study bias (see below); and (5) outcome indicators and the corresponding values.

2.4. Bias assessment

Two reviewers evaluated the methodological quality of the included studies using Review Manager software version 5.3 from

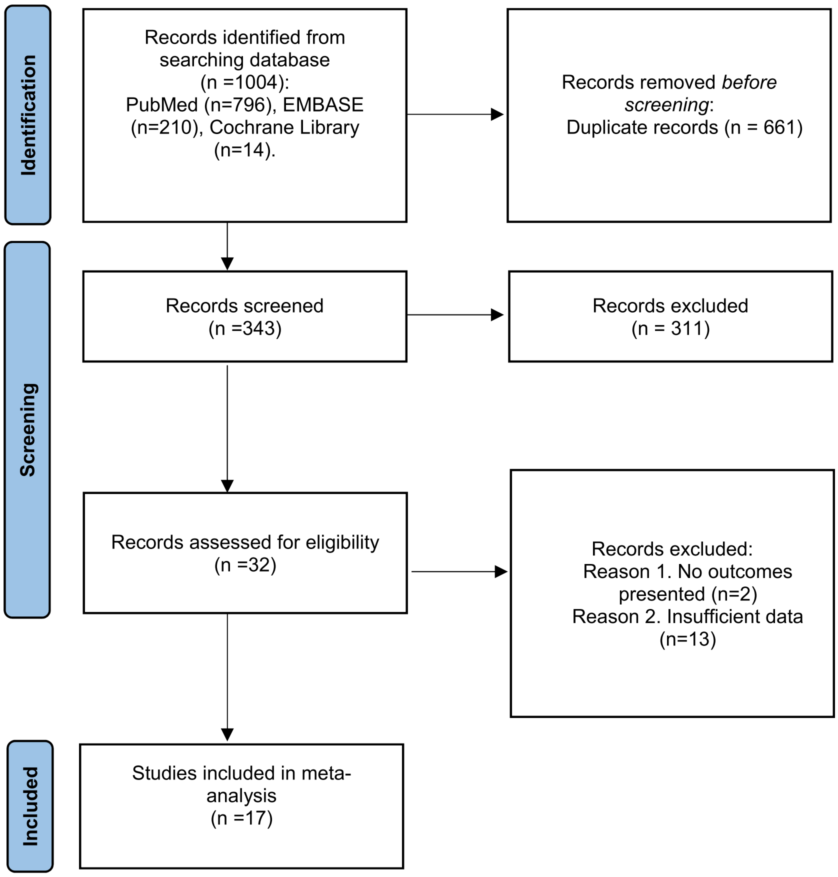

Fig. 1. Literature screening.

Cochrane. The included studies were scored for risk of bias along six dimensions: random sequence generation, allocation consideration, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other bias. For each dimension, risk of bias was assessed as “low”, “high” or “unclear".

2.5. Statistical analysis

Stata 14.0 (StataCorp, College Station, TX, USA) was used for meta-analysis. The standard mean difference (SMD) was used as the effect index, and the point estimation value and 95% confidence intervals (CIs) were calculated. Effect sizes were classified according to Cohen's d index as small ($0.2 \le d < 0.5$), medium ($0.5 \le d < 0.8$) or large ($d \ge 0.8$).

Heterogeneity among included studies was analyzed using the chi-squared test (test level was $\alpha = 0.1$) and the I^2 value. The heterogeneity measured by I^2 was considered negligible (0%–40%), moderate (30%–60%), high (50%–90%) or substantial (75%–100%). If the heterogeneity was negligible across the studies for the given outcome, the pooled data were meta-analyzed using a fixed-effect model. Otherwise, the studies were analyzed for the potential source(s) of heterogeneity. After excluding the influence of obvious clinical heterogeneity, the pooled data were meta-analyzed using a random-effect model.

3. Results

3.1. Literature screening

A total of 1004 articles were retrieved, and 311 articles were selected after reading the titles and abstracts. After reading the full texts and excluding studies with incomplete, duplicate or irrelevant data, we included 17 studies in the meta-analysis (Fig. 1).

Table 1
Characteristics of all studies included.

Authors	Sample size (M/F, A/C)	Age (years, mean ± SD)	Type of athletes	Intervention		Follow-up, weeks	Outcome
				Training mode	Altitude, m		
Roberts et al. (2003) [19]	19(M = 14/F = 5, A = 19/C = 19)	27.7 ± 5.9	Cyclists	Hi-Lo	2650	4	VO^2max
Brugniaux et al. (2006) [14]	11(M = 11/F = 0, A = 5/C = 6)	24 ± 5	Runners	Hi-Lo	3000	3	VO^2max
Pottgiesser et al. (2009) [20]	7(M = 7/F = 0, A = 7/C = 7)	25 ± 1	Cyclists	Hi-Hi	1816	3	Hb
Wilhite et al. (2013) [21]	7(M = 6/F = 1, A = 7/C = 7)	23.6 ± 1	Runners	Hi-Lo	2150	4	VO^2max
Roels et al. (2007) [22]	19(M = 19/F = 0, A = 10/C = 9)	24.4 ± 0.3	Cyclists, Triathletes	Hi-Hi	3000	4	VO^2max
Robach et al. (2006) [23]	18(M = 16/F = 2, A = 9/C = 9)	20 ± 3	Swimmers	Hi-Lo	3000	2	VO^2max
Bonne et al. (2014) [24]	10(M = 5/F = 5, A = 10/C = 10)	27 ± 3	Swimmers	Lo-Hi	2130	6	VO^2max Hb
Hahn et al. (2001) [25]	12(M = 0/F = 12,A = 6/C = 6)	25.5 ± 1.3		Hi-Lo	2100	2	Hb
Wehrlin et al. (2006) [26]	10(M = 5/F = 5, A = 10/C = 10)	23 ± 4	Orienteering	Hi-Lo	2456	6	Hb
Bailey et al. (1998) [10]	14(M/F:NA,A = 14/C = 14)	24 ± 4	Runners	Hi-Hi	2000	4	Hb
Robertson et al. (2010) [5]	17(M = 17/F=0=, A = 8/C = 9)	NA	Runners	Hi-Lo	2200	3	VO^2max
Saugy et al. (2016) [27]	16(M = 16/F = 0, A = 16/C = 16)	24 ± 4	Triathletes	Hi-Lo	1900	3	VO^2max
Czuba et al. (2014) [28]	15(M = 15/F = 0, A = 7/C = 8)	27.1 ± 4.6	Biathletes	Hi-Lo	3000	3	VO^2max
Bahensky et al. (2020) [29]	20(M = 11/F = 9, A = 12/C = 8)	16.7 ± 0.8	Runners	Hi-Hi	1850	2	VO^2max
Sharma et al. (2018) [30]	8(M = 6/F = 2, A = 4/C = 4)	25 ± 6	Runners	Hi-Hi	2100	4	Hb
Diebel et al. (2017) [31]	8(M = 5/F = 3, A = 4/C = 4)	20.50 ± 1.77	Runners	Hi-Hi	1828	2	VO^2max
Park et al. (2019) [16]	24(M = 24/F = 0, A = 12/C = 12)	23.5 ± 2.1	Runners	Hi-Lo	3000	3	VO^2max

M: male; F: female; A: altitude training (intervention group) or after intervention; C: control group or before intervention; SD: standard deviation; NA: data not available.

3.2. Characteristics of the studies and their risk of bias

The basic characteristics of the 17 studies included in the meta-analysis are shown in Table 1.

The studies showed relatively low risk of the various types of bias, suggesting good quality (Fig. 2).

The results of bias assessment suggested that the overall quality of studies included in this meta-analysis was high, which has relatively high reference value and can meet the requirements of secondary research.

3.3. Meta-analysis results

3.3.1. Pooled outcomes

A total of 17 articles were included. Random-effect meta-analysis showed that altitude training was associated with significantly higher VO^2max (SMD = 0.67, 95% CI 0.35–1.00, $P < 0.001$) and Hb content (SMD = 0.50, 95% CI 0.11–0.90, $P < 0.001$) (Fig. 3).

3.3.2. Heterogeneity

Altitude training has a significant effect on the hemoglobin content and maximum oxygen uptake of athletes. Heterogeneity test of hemoglobin showed that $I^2 = 0.0\%$ and heterogeneity test of maximum oxygen uptake showed that $I^2 = 29.8\%$ (Figs. 3 and 4). It is verified that altitude training can improve the aerobic ability of athletes without heterogeneity.

3.3.3. Sensitivity analysis

We performed a sensitivity analysis to test the potential effects of each study on meta-analysis of the outcomes (Fig. 5, Fig. 6).

The results of the sensitivity test of altitude training on the influence of athletes' hemoglobin fluctuates around 0.50; and the result of the sensitivity test of altitude training on the influence of athletes' maximal oxygen uptake fluctuates around 0.67, which showed that our results were stable and of high reference value.

3.3.4. Bias test

Since the outcome indicators were continuous variables, the Egger's test was used to assess risk of bias, which was found to be low. These results suggest that our meta-analyses are likely to be reliable.

3.3.5. Subgroup analyses

Our subgroup analysis showed that more than interventions lasting more than 3 weeks at altitudes over 2500 m led to smaller increases in VO^2max (Table 2). The Hi-Lo training mode increased VO^2max to a greater extent than Hi-Hi training did. We did not separately assess effects of training cycles shorter than 3 weeks on Hb level.

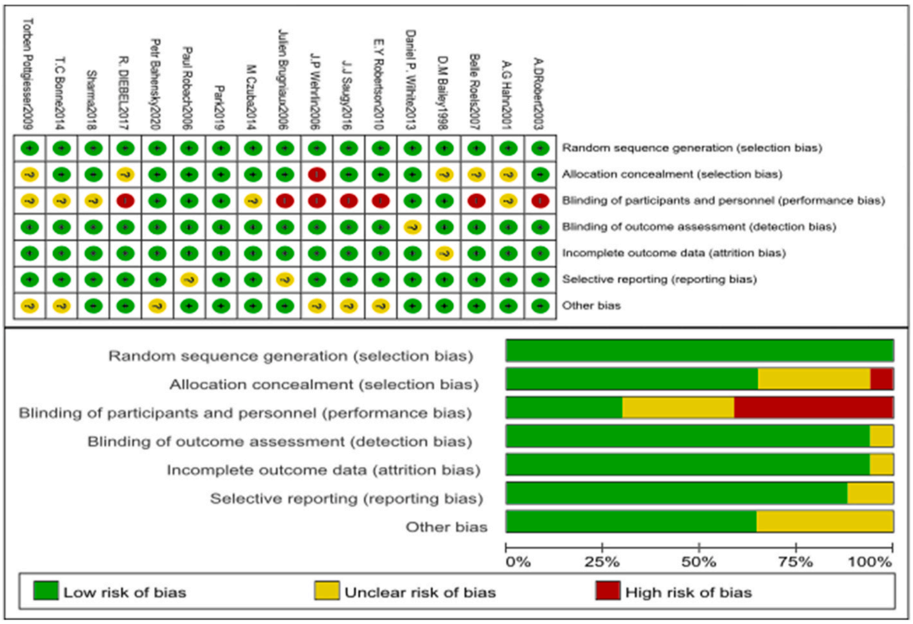

Fig. 2. Risk of bias.

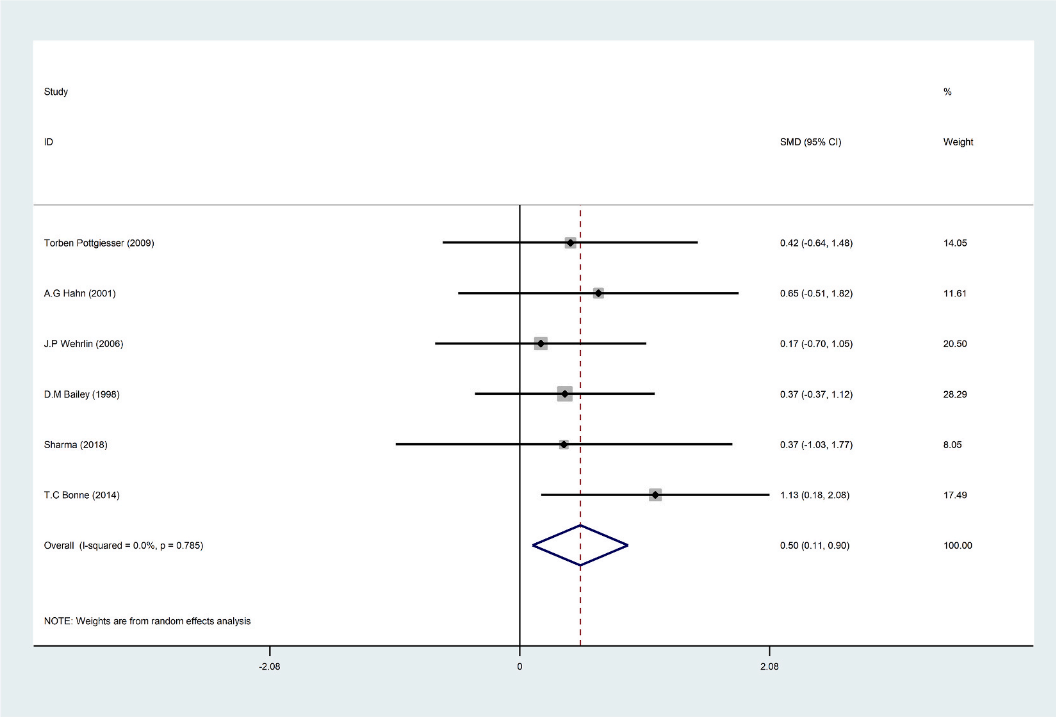

Fig. 3. Forest plot of the effect of altitude training on athletes' hemoglobin.

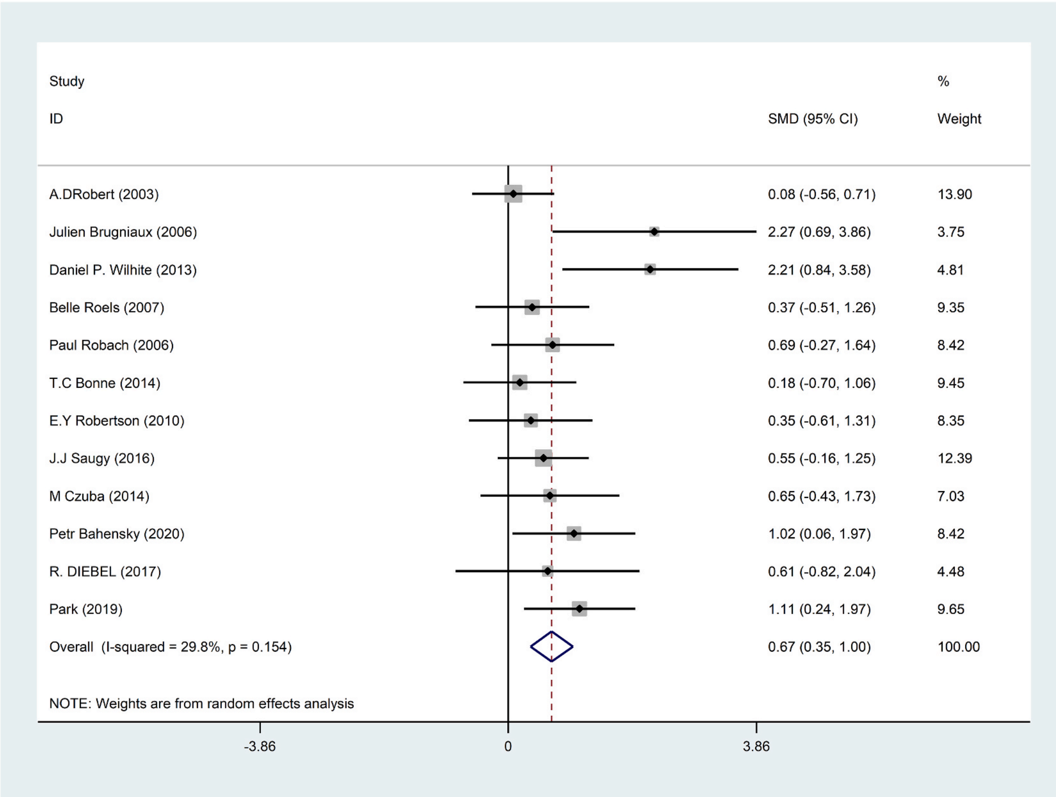

Fig. 4. Forest plot of the effect of altitude training on athletes'VO2 Max.

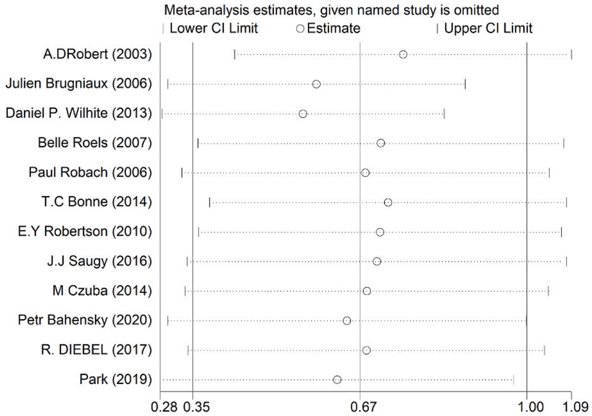

Fig. 5. Sensitivity analysis of the effect of altitude training on athletes'VO2 Max.

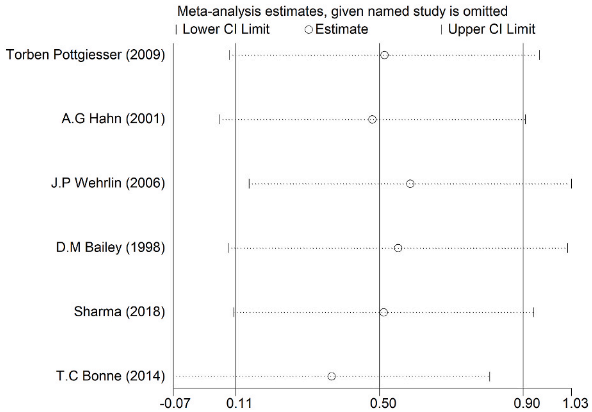

Fig. 6. Sensitivity analysis of the effect of altitude training on athletes' hemoglobin.

Table 2
Subgroup analysis of effects of altitude training on aerobic capacity of athletes.

Subgroup	No. of included studies	Heterogeneity test		Meta-analysis results		
		I^2 (%)	*P* value	SMD (95% CI)	*Z* value	*P* value
Outcome						
VO^2max	12	29.8	0.154	0.67 (0.35–1.00)	4.02	<0.001
Hb	6	0	0.785	0.50 (0.11–0.90)	2.48	0.013
Duration						
<3 weeks	3	0	0.853	0.81 (0.20–1.42)	2.60	0.009
3 weeks	5	23.4	0.266	0.80 (0.31–1.30)	3.20	0.001
>3 weeks	4	62.1	0.048	0.54 (−0.19–1.27)	1.45	0.148
Altitude, m						
<2500	6	29.6	0.213	0.70 (0.22–1.18)	2.84	0.005
≥2500	6	41.1	0.131	0.68 (0.18–1.18)	2.67	0.008
Training mode						
Hi-Lo	8	48.7	0.058	0.79 (0.33–1.26)	3.33	0.001
Hi-Hi	4	0	0.626	0.52 (0.02–1.00)	2.04	0.041

Abbreviations: SMD, standard mean difference; CI, confidence interval; VO^2max, maximal oxygen uptake; Hb, hemoglobin; Hi-Lo, high-altitude living and low-altitude training; Hi-Hi, high-altitude living and high-altitude training.

4. Discussion

The results of our meta-analysis show that altitude training has a significant effect on the improvement of VO^2max and Hb content in athletes, thus improving the aerobic capacity and probably contributing to ameliorate athletes' performance. In our meta-analysis, three weeks of altitude training improved aerobic capacity, particularly at altitudes around 2500 m. Hi-Lo training may increase

VO^2max more than Hi-Hi training.

Altitude training may improve exercise capacity primarily through the "hematology mechanism": such training creates hypoxia that increases the erythropoietin concentration in the body, which in turn increases the number and quality of red blood cells and thereby VO^2max [32]. However, some researchers have also proposed a "non-hematological mechanism" at the gene level, according to which the nuclear transcription factor HIF-1 regulates expression of genes that alter erythropoietin concentration, in turn altering various blood indices [33]. HIF-1 may act as a "bridge" to link the "hematological" and "non-hematological" mechanisms. HIF-1 can regulate erythropoietin and promote angiogenesis to improve the aerobic capacity of athletes. Moreover, the mechanism of action may be related to the changes of cardiac function, the economization of body, the improvement of muscle pH, the increase of training efficiency, the increase of mitochondrial efficiency caused by the coupling of biological energy and energy replacement process in muscle cells, and the enhancement of muscle pH regulation and buffering ability be related to the change of UCP3 content in skeletal muscle [34].

Further work is clearly needed in order to clarify how altitude training affects athletic performance. One study found no correlation between red blood cell numbers and change in VO^2max after altitude training, and the researchers even concluded that 86% of the observed VO^2max change could be attributed simply to individual differences [32]. In addition, one study found that individuals living at similar altitudes in Tibet or the Andes differed significantly in Hb level [34]. There also studies showing improved athletic performance after hypoxia or altitude training, despite the fact that erythropoietin concentration, red blood cell numbers, and VO^2max did not significantly increase [35].

Since being under hypoxic conditions for a long time can cause certain damage to the athletes' cardio cerebrovascular and cardiopulmonary functions, long altitude training cycles are not suitable [36]. Most researchers and coaches agree that 3–4 weeks between 2000 and 2500 m is the best training cycle [37]. Under 2000 m, the hypoxic conditions are insufficient; over 3000 m, the body cannot bear the larger training load, and it is easy to cause irreversible damage to the body. A Chinese study showed that plateau training at 2000–2500 m according to a Hi-Lo regime lasting at least three weeks was better than traditional altitude training according to a Hi-Hi regime [38], and a US study confirmed the positive impact of three-week high-altitude training [39]. A study of 48 athletes who participated in different training cycles at various altitudes concluded that the best aerobic capacity was obtained after a four-week training cycle at 2454 m [40].

Nevertheless, some studies have suggested that altitudes over 2500 m may improve aerobic capacity of athletes. For example, Japan carried out short-term training on 20 long-distance runners at an altitude of 2500–2800 m to prepare for the 1968 Mexico Olympic Games, and 12 athletes improved their aerobic capacity [41]. Through reviewing and summarizing existing literature, the conclusion of this study is similar to the previous research results, which confirms the scientific and authenticity of the results of this meta-analysis.

The Hi-Hi training mode maximizes hypoxic conditions for athletes, while the Hi-Lo training mode can lead athletes to experience hypoxia load and exercise load at different times. As a result, the Hi-Lo mode should be superior for improving the aerobic capacity of the body. The reality, however, may be more complex. Some studies have found that Hi-Hi training led to greater improvement in VO^2max and athletic performance than Hi-Lo training [42,43]. A study of 25 elite Chinese athletes found that a Hi-Hi-Lo mode led to higher aerobic capacity than Lo-Hi [44]. Our meta-analysis suggests that the Hi-Lo mode is more effective than most other modes to improve aerobic performance, but clearly further work is needed.

5. Conclusions

This research evaluated the effects of altitude training on Hb levels and VO^2max of athletes. Although previous meta-analyses were conducted to verify the effect of altitude training on athletes' performance (i.e., 15 and 16), several important questions about altitude training remain unanswered, such as what are the best training mode (i.e., cycle and altitude). To fill these gaps, the current systematic review and meta-analysis concluded more detailed suggestions for altitude training. And more specific indicators (Hb levels and VO^2max) were used as outcome variables. Specifically, we suggest that the altitude of altitude training conducted at about 2500 m and last about 3 weeks is more effective.

Despite the theoretical and practical implications of this study, the current meta-analysis has several limitations. The samples of the included studied were relatively small, and the subgroup analysis results were not significant. Many factors influence the impact of altitude training, including internal and external factors that we were unable to analyze in our meta-analysis. Internal factors include the limitations of athletes themselves, eating habits, work and rest norms, aerobic capacity, exercise intensity and duration, history of injury, and mental health. External factors include the type of sport under consideration, training methods of different coaches, and environmental conditions during training (temperature, humidity, air pressure, UV light). In addition, how athletic performance is defined and measured, and when it is measured relative to the training, can also affect outcomes.

Many aspects of altitude training remain unclear, including whether this method is suitable for athletes of all disciplines; whether the longitude and latitude affect the athlete's improvement; which is the best altitude training mode; and when is the best time to return to lower altitudes after training in altitude. Further work in these areas may help rationalize and optimize altitude training.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data included in article/supplementary material/referenced in article.

Additional information

No additional information is available for this paper.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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