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Haemoglobin mass responses and performance outcomes among high-performance swimmers following a three-week Live-High, Train-High camp at 2,320m

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Original Investigation

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Abstract

Greater quantification and characterisation of training load (TL) throughout Live-High, Train-High (LHTH) altitude (ALT) training is required to identify periodisation strategies that may lead to physiological and performance improvements in swimmers.

Purpose: This study aimed to examine the physiological responses and performance outcomes of fourteen high-performance swimmers (FINA points: 836.0 ± 35.1) following three-weeks of LHTH at 2,320m, while characterising the training load periodisation strategy adopted during the intervention.

Methods: Haemoglobin (Hb) mass was measured pre-, seven- and fourteen-days post-ALT via CO rebreathing. Performance in each athlete's primary event at national standard meets were converted to FINA points and compared from pre-to-post ALT. TL was quantified at sea level (SL) and ALT through session rating of perceived exertion (RPE), where duration of each session was multiplied by its RPE for each athlete, with all sessions totalled to give a weekly TL. Pre-to-post ALT changes were evaluated using repeated-measures ANOVA.

Results: Hb mass increased significantly from 798±182g pre-ALT, to 828±187g at seven-days post (p=0.013) and 833±205g 14-days post-ALT (p=0.026). Weekly TL increased from SL (3179±638 au) during week one (4797±1349 au, p<0.001) and week two (4373±967 au, p<0.001), but not week three (3511±730 au, p=0.149). No evidence of improved SL swimming performance was identified.

Conclusion: A periodisation strategy characterised by a sharp spike in TL followed by a slight de-load towards the end of a LHTH intervention led to improved physiological characteristics but no change in the competitive performance of high-performance swimmers.

Keywords

Altitude, Hypoxia, Terrestrial, Training Load, Athletes

List of Abbreviations

ALT	Altitude
ANOVA	Analysis of Variance
CO	Carbon Monoxide
COHb	Carboxyhaemoglobin
ES	Effect Size
FINA	World Aquatics
Hb	Haemoglobin
LHTH	Live-High, Train-High
RPE	Rate of Perceived Exertion
SD	Standard Deviation
SL	Sea Level
SWC	Smallest Worthwhile Change
TE	Typical Error
TL	Training Load

Statements and Declarations

Competing Interests

The authors have no relevant financial or non-financial competing interests to disclose.

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Ethical Approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Moray House School of Education and Sport Research Ethics Committee at the University of Edinburgh.

Consent to Participate

Written informed consent was collected from all individual participants included in the study.

Consent to Publish

All participants provided informed consent for the publication of their data in a scientific journal.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by DA and MM, under the supervision of AT. The first draft of the manuscript was written by DA and all authors commented on subsequent versions of the manuscript. All authors read and approved the final manuscript.

Introduction

High-performance endurance athletes have made greater use of terrestrial live-high, train-high (LHTH) altitude (ALT) camps in recent decades, aiming to use the hypoxic environment to enhance specific neuromuscular and physiological adaptations to improve subsequent sea level (SL) performance (Sharma, 2022). The primary physiological basis for LHTH is the enhanced oxygen carrying capacity of the blood, resulting from adaptations elicited by acclimation to the hypoxic environment and training under the additional stress of hypoxia (Rodríguez et al., 2015). However, the benefits of hypoxic training for elite athletes are still debated in recent literature (Millet & Brocherie, 2020; Siebenmann & Dempsey, 2020). Despite high-performance swimmers being among the athletes that utilise natural ALT interventions most often (García-Ramos et al., 2016), understanding of the efficacy of LHTH for the enhancement of swimming performance is conflicted (Rodríguez et al., 2015). The success of terrestrial ALT training can be influenced by an extensive range of factors, including injury and illness, iron supplementation and the periodisation of training load (TL) (Mujika et al., 2019).

While most research is in agreement on the ability of LHTH to elicit substantial physiological adaptation in swimmers, with typical increases in haemoglobin mass (Hb mass) ranging from 3.4 to 7.8% (depending on the sojourn duration and altitude)(Bonne et al., 2014; Friedmann et al., 2005; Gough et al., 2012; Rodríguez et al., 2015; Wachsmuth et al., 2013), there is greater discordance in the evidence identifying a translation of these adaptations into improved SL performance. Wachsmuth and colleagues (Wachsmuth et al., 2013) compared pre and post-altitude competitive performances using the point system of the German Swimming Federation, identifying a trend of impaired performance for a period of two-weeks following return to SL, and then no change for the subsequent ten-days. An improvement in performance ($p=0.016$) was not identified until 25-35 days post-ALT. Conversely, Siewierski et al. (Siewierski et al., 2012) identified a 3.1% improvement in competitive swimming performance in international/Olympic swimmers both immediately and three-weeks following 23-days of LHTH at 2,320m. However, Gough et al. (Gough et al., 2012) found that compared to a control group, changes in international performances of 17 Australian swimmers were consistently worse at both day one (1.4±1.3%) and day seven (0.9±1.0%) following ALT. Overall, currently available data demonstrating the value of LHTH for improving SL swimming performance is inconclusive. Studies making use of SL control groups have not convincingly demonstrated greater improvements in performance (Bonne et al., 2014; Gough et al., 2012; Rodríguez et al., 2015; Wachsmuth et al., 2013). In uncontrolled studies that identify performance improvements (Friedmann et al., 2005; Roels et al., 2006; Siewierski et al., 2012) considerable degrees of individual variation are reported. Further, these studies do not highlight which post-ALT race has been targeted for peak performance. This makes it difficult to differentiate the timing of post-ALT training benefits vs. planned timing of peak performance. Given the complexities of translation to performance as a dependent variable, it is perhaps unsurprising that the ergogenic effects of LHTH interventions for high-performance swimmers remain largely unclear.

Translation of many previous LHTH studies into practice can be limited by minimal TL quantification and the reporting of only basic training metrics, such as total volume or duration (Sharma et al., 2018). It is important that coaches and practitioners understand the effects of specific characteristics of endurance training on both physiological adaptations and how these translate into improved performance (Casado et al., 2022). This is especially true during specific interventions, such as LHTH. One of these characteristics is the periodisation of training load, which has been evidenced to influence both physiological and performance adaptations in highly-trained endurance athletes (Bellinger et al., 2020; Ingham et al., 2008; Neal et al., 2013; Stöggl & Sperlich, 2014). In order to establish causal relationships between completed training and subsequent adaptations or performance improvements, it is vital that training is accurately recorded and quantified (Mujika, 2013). More specific and detailed training data from LHTH interventions, alongside related physiological and performance data, will aid in the identification of potential periodisation strategies that could increase the probability of subsequent SL performance improvements.

Therefore, this study sought to determine changes in Hb mass and SL swimming performance before and after a three-week LHTH moderate terrestrial ALT camp, in high-performance swimmers. Furthermore, additional characteristics of the TL completed throughout the camp will be compared with previously completed SL training, to explore potential relationships with changes in performance and Hb mass, taking account of individual differences.

Method

Study Design

This investigation adopted an observational, prospective, multiple case study design to examine changes in Hb mass and swimming performance following an in-season three-week LHTH intervention at 2,320m in high-performance swimmers. The ALT training camp was strategically periodised before the beginning of the national long-course racing season (January). The squad size and ethical considerations of with-holding a potentially beneficial intervention in-season precluded use of a more controlled experimental design. A ten-day lead-in period of reduced TL preceded the camp. A general structure of three-days' training followed by a rest day was adopted throughout the intervention (Table 1). Competitive performance was assessed at national swim meets three-weeks prior, and immediately and three-weeks post ALT. Hb mass testing occurred fourteen-days prior and both seven and fourteen-days post ALT.

Please insert Table 1 near here

Participants

Fourteen (female n=9, male n=5) high-performance swimmers were recruited through convenience sampling. The sample were aged between 18 and 26 years (mean ± SD; 21.8 ± 2.4) and had an average of 12.1 ± 3.4 years of experience in competitive swimming. All were resident near SL (***, average altitude 130m). Seven of the sample targeted primary events of shorter sprint distances (50 or 100m). The remaining seven targeted middle distance (200 or 400m) events. The preferred competitive strokes of the swimmers were freestyle (n=8), breaststroke (n=4), butterfly (n=1) and backstroke (n=1). The participants provided written informed consent before the onset of the study, with ethical approval being granted from the host institution.

The performance level of the sample was assessed through the World Aquatics (FINA)(*Fédération Internationale De Natation, FINA Points*, 2018) point scoring system. Briefly, a point score was attributed to each swimmer based on their pre-study personal best time in their primary event. Scores could range from 0 to 1000 and were based on the 2019 world record times in each event, where a world record equates to 1000 points. A mean of 836.0±35.1 points was held by the sample, falling into 'level 2' of Ruiz-Navarro and colleagues (Ruiz-Navarro et al., 2022) swimming research performance classification model. This level represents the 'B' qualifying standard for FINA international events, highlighting the high-performance nature of the sample.

Haemoglobin Mass

Total Hb mass was assessed pre (double-measure to assess test-retest reliability), seven- and fourteen-days post-ALT using the optimised carbon monoxide (CO) rebreathing method (Schmidt & Prommer, 2005). In brief, a bolus of CO is inhaled (males: 1.0mL CO.kg^{-1}, females: 0.8mL CO.kg^{-1}) and rebreathed for two-minutes in a closed-system spirometer (Bloodtec Gbr, Bayreuth, Germany). Capillary blood, sampled from the fingertip both before, six- and eight-minutes following the rebreathing period, was analysed to determine the percentage of bound carboxyhaemoglobin (COHb) using an ABL80 blood-gas analyser (Radiometer, Copenhagen, Denmark). Ventilatory CO concentration was measured with a Draeger Pac 6500 sensor (Lubek, Germany). Correction factors were added to the calculation of Hb mass, as per Prommer & Schmidt ((Prommer & Schmidt, 2007) with ambient temperature and air pressure being corrected for.

A double baseline was taken pre-ALT, one-day apart, to assess typical error (TE) of measurement. The TE identified was 2.6%, similar to previous research (2.3%) (Sharma et al., 2018). Pre-ALT Hb mass was calculated as the mean of the two baseline measures.

Performance

Performance of each athlete's primary event (both stroke and distance) at national standard meets were compared from pre- to both immediately- and 3-weeks post-ALT. The pools at all locations were indoor, with electronic timing systems (ALGE Timing, Lustenau, Austria). At each meet, athletes followed a consistent, individualised coach-prescribed warm-up, and were instructed to achieve the best time possible within their race. The swimmer's primary event was always the first race completed in each session, with the fastest performance in the competition (i.e., heat or final), taken for subsequent analysis All post-ALT performances were raced in a 50m pool (long-course), with pre-ALT performances completed in a 25m pool (short-course), due to the unavoidable timing of the altitude camp within the season relative to organised national swim meets. This was preferable to ensure ecological validity of the performance, vs. simulated competitions in the same pool. Equal priority was given to each race, with all three targeted for key peak performance in the periodisation of the athlete's season. In order to compare between long- and short-course, all performances were ascribed a FINA point score (*Fédération Internationale De Natation, FINA Points*, 2018) (as described above).

Training

The training of the athletes was monitored for a three-week period of typical SL training preceding the ten-day lead-in phase (with SL load and volume values taken as the average of these three-weeks), and throughout the LHTH intervention. A similar training schedule was followed throughout both the SL and ALT periods, with training days consisting of morning and afternoon pool sessions and a land-based conditioning session (Table 1). Whilst generally adhering to a similar programme and session focus, training was individually prescribed for each swimmer by their coach, based on event specialisation, performance level and physiological characteristics, in attempt to optimise the response from the LHTH intervention. All participants had a reduction in TL in the final week of the camp to de-load slightly for the upcoming meet.

The athletes recorded all training on the 'Smartabase' electronic application (Fusion Sport, Brisbane, Australia). Total distance swam during each pool session was summated to give a total weekly volume in metres. Durations of all sessions (including land-based conditioning) were recorded in minutes, with a rating of perceived exertion (RPE) provided in the electronic application for each session on a modified Borg Scale from 1-10 (Foster, 1998). The sample were very familiar with this scale, using it daily in their normal training environment, and provided ratings within fifteen minutes following the end of each session. TL was quantified for each session as duration multiplied by RPE (session RPE), with this then totalled for all sessions to provide a measure of weekly load. A load:volume ratio (Sharma et al., 2018) was calculated for all pool-based training by dividing weekly pool load by volume, providing a measure of subjective exertion per kilometre swam.

Statistical Analysis

Descriptive data are presented as mean ± SD. Changes in TL, load:volume ratio, Hb mass and performance were evaluated using repeated-measures ANOVA with partial-eta-squared (η_p^2) effect sizes (ES). Least significant difference post-hoc analyses were subsequently applied where significant main effects were found. The non-parametric Friedman test, with Kendall's value ES (W), was used to assess changes in pool volume. Post-hoc analysis with a Wilcoxon signed rank-test (Z), was conducted with a Bonferroni correction applied. Percentage change (%Δ) in the mean, as well as for each athlete, for each of the above parameters were calculated from pre-altitude to each testing point either within or post-ALT. The changes in performance and Hb mass were additionally assessed in relation to the smallest worthwhile change (SWC). This was calculated as one-fifth of the between-subject SD of the pre-ALT measures for each parameter (Hopkins, 2017).

Pearson product-moment correlations were used to assess the associations between the following variables:

- Baseline Hb mass and pre-to-post ALT %Δ in Hb mass
- %Δ in mean weekly TL from SL to ALT and %Δ in pre-to-post ALT Hb mass
- Pre-to-post ALT %Δ in Hb mass and performance.

The magnitude of ES for the above associations were defined as trivial ($r<0.1$), small ($0.1\leq r <0.3$), moderate ($0.3\leq r <0.5$), large ($0.5\leq r < 0.7$), very large ($0.7\leq r <0.9$) or extremely large ($r\geq 0.9$).(Hopkins, 2010)

All analyses were conducted using IBM SPSS (Version 25.0, IBM, Chicago, IL, USA), with the significance level set at $p<0.05$. Cohen's d effect sizes, with 95% confidence intervals, are ascribed to all comparisons where applicable, with the magnitude of these defined as trivial ($d <0.2$), small ($0.2\leq d <0.5$), moderate ($0.5\leq d <0.8$) or large ($d \geq 0.8$), with d representing units of SD (Cohen, 1988).

Results

Haemoglobin Mass

Mean ± SD Hb mass increased significantly ($F_{(2,\ 26)}=5.015$, $p=0.014$, $\eta_p^2=0.278$) from 798±182g pre-ALT, to 828±187g at 7-days post ($p=0.013$, $d=0.89$, 95% CI [0.12, 1.67]) and 833±205g 14-days post-ALT ($p=0.026$, $d=0.92$, 95% CI [0.14, 1.70]). Figure 2 displays %Δ in Hb mass from pre-ALT to both 7-days (range: -3.98% to 12.98%) and 14-days (range: -5.07% to 13.66%) post-ALT, comparing this to the calculated SWC of 4.5%. Six of the 14 athletes reported an increase greater than the SWC at both 7 and 14-days post-ALT, with 1 athlete observing a decrease greater than the SWC at 14-days post-ALT (Figure 2).

Please insert Figure 1 near here

Performance

There were no significant differences ($F_{(2,\ 22)} = 0.214$, $p = 0.809$, $\eta_p^2 = 0.019$) in the mean number of FINA points obtained by the sample either immediately (774.5±42.4; $d = -0.07$, 95% CI [-0.81, 0.67]) or three-weeks (775.4±54.5; $d = -0.04$, 95% CI [-0.79, 0.70]) following the return to SL, when compared to pre-altitude (777.1±53.2). The mean %Δ in FINA points from pre-ALT to both immediately (-0.34%; range: -6.01% to 13.43%) and 3-weeks (0.12%; range: -6.97% to 4.43%) post-ALT were smaller than the calculated SWC of 1.37%. For both post-ALT performances, 5 athletes observed a decrease in FINA points greater than the SWC, whereas 3 and 4 athletes increased FINA points by more than the SWC immediately and three-weeks post-ALT, respectively. When split by event distance, 50-100m swimmers recorded a mean %Δ in FINA points of 1.0±5.9% and 1.3±5.3% respectively at each post-ALT performance compared to baseline. Comparatively, -1.3±2.8% and -3.5±4.1% changes in FINA points were reported for 200-400m swimmers immediately and 3-weeks post-ALT, respectively. There was no difference between groups ($p=0.797$).

Training Load

Total TL increased significantly from SL to ALT ($F_{(3,\ 39)}=14.047$, $p<0.001$, $\eta_p^2=0.519$). It was found, through post-hoc analysis, that weekly TL was greater than SL (3179±638 au) during week 1 (4797±1349 au; $p<0.001$, $d=2.28$, 95% CI [1.34, 3.17]) and week 2 (4373±967 au; $p<0.001$, $d=1.62$, 95% CI [0.77, 2.48]) of ALT, but not week 3 (3511±730 au; $p=0.149$, $d=0.44$, 95% CI [-0.31, 1.20]). Figure 2 displays %Δ in the total TL from SL for each week of ALT. Table 2 presents the descriptive data and %Δ from SL in each of the four components that combine in the calculation of total TL.

Please insert Figure 2 near here

Pool Volume

Pool volume was significantly greater at ALT than at SL ($\chi^2_{(3)} = 30.429$, $p<0.001$, $W=0.724$). Post-hoc analysis identified volume to be greater than SL (33372±2573m) during week 1 (41879±5409 m; $Z= -3.233$, $p=0.001$, $d=2.49$, 95% CI [1.49, 3.46]) and week 2 (46100±6877 m; $Z= -3.296$, $p=0.001$, $d=4.13$, 95% CI [2.83, 5.45]) of ALT, but not throughout week 3 (34543±4057 m; $Z= -0.471$, $p=0.638$, $d=0.39$, 95% CI [-0.36, 1.14]). Mean ± SD %Δ in pool volume from SL were 26.1±18.2%, 38.5±20.9% and 3.8±12.0% for week one, two and three of ALT, respectively.

Please insert Table 2 near here

Pool Load:Volume Ratio

There was no significant difference in the pool load:volume ratio from SL to ALT ($F(_{3,39})=1.492$, $p=0.232$, $\eta_p^2=0.103$). Mean ± SD ratios of 80.3±19.0, 89.0±23.5 (*d*=0.44, 95% CI [-0.31, 1.19]), 81.2±18.6 (*d*=0.05, 95% CI [-0.69, 0.79]) and 79.7±15.9 (*d*= -0.03, 95% CI [-0.77, 0.71]) were calculated for SL training and weeks 1, 2 and 3 of ALT, respectively. Mean and individual %Δ in load:volume ratio is displayed in Figure 3.

Please insert Figure 3 near here

Association Between Variables

Baseline Hb mass and %Δ in Hb mass

No significant association was identified between the baseline Hb mass of the athletes and the mean pre-to-post ALT %Δ in Hb mass (r= -0.326, p=0.128), with the relationship demonstrating a moderate ES.

%Δ in TL and %Δ in Hb mass

No significant association was identified between the mean pre-to-post ALT %Δ in Hb mass and %Δ in total TL from SL to ALT (r= -0.007, p=0.491), with the association displaying a trivial ES.

%Δ in Hb mass and %Δ in Performance

A statistically significant positive association (r=0.476, p=0.043), with a moderate ES (Hopkins, 2010), was identified between the mean pre-to-post ALT %Δ in Hb mass and %Δ in FINA points.

Discussion

This investigation aimed to quantify and characterise the TL periodisation strategy of high-performance swimmers during three-weeks of LHTH ALT training, examining the pre-to-post ALT response in physiological characteristics and SL performance. A significant increase in mean Hb mass (with considerable individual variation; Figure 2) was found post-LHTH, but there was no evidence of an improved squad SL performance either immediately or three-weeks post-ALT. Despite this, there was some evidence of a moderate association between the individual change in Hb mass and change in performance of the sample. Total weekly TL increased significantly from SL during weeks 1 and 2, but not in week 3 (Figure 1), due to a prescribed de-load in preparation for performance immediately post-ALT. Increases in TL were principally influenced by escalation of training duration (Table 2). Changes in TL from SL to ALT were not related to the physiological adaptation observed.

Physiological Adaptation

Compared to baseline, total Hb mass increased significantly both seven (3.9%) and fourteen-days (4.1%) post-ALT. When compared to the model published by Garvican-Lewis and colleagues (Garvican-Lewis et al., 2016), which quantifies the relationship between hypoxic dose (in km.h) and Hb mass response, these findings are slightly below what might be expected (1170km.h = ~4.5% increase). However, the results of the current paper are certainly comparable to those of Gough et al. (Gough et al., 2012), who reported 3.8% and 4.0% increases in total Hb mass following three-weeks of LHTH in elite male and female swimmers, respectively. As displayed in Figure 2, a large degree of inter-individual variability was identified in the Hb mass response across the sample of this study. When compared to baseline, %Δ measures ranged from -4.0% to 13.0% at seven-days and -5.1% to 13.7% fourteen-days post-ALT. Inter-individual Hb mass responses to natural hypoxic interventions are known to be highly variable (Millet et al., 2019). Wachsmuth and colleagues (Wachsmuth et al., 2013) found that the pre-to-post LHTH response in Hb mass in 25 elite German swimmers ranged from -2.5% to 13.0%, similar to the ranges reported here. Possible factors which may influence the response of total Hb mass to a natural hypoxic exposure, beyond the structure and content of the training completed (Rodríguez et al., 2015), include the genetic profile of the athletes, the extent of the erythropoietin response throughout the intervention, fitness levels, iron stores, and any pre-existing injuries or illness (Hauser et al., 2018).

Performance Response

Despite a positive physiological adaptation following the LHTH intervention, no significant change in mean competitive performance was identified either immediately or three-weeks post-ALT. These findings align with those of Gough and colleagues (Gough et al., 2012), who found that LHTH actually led to “possibly slower” competitive performance at one-day post-ALT in 26 elite swimmers (%Δ ± 90% CIs: 0.4±0.4%), with no difference to pre-ALT then identified at seven (-0.2±0.7%), fourteen (-0.3±0.8%) and 28-days (0.2±0.9%) post-intervention. Likewise, a decrease in the performance of elite swimmers for a period of fourteen-days following LHTH was found to approach significance (p=0.06), before showing no change from pre-ALT for the following ten-days (p=0.52) (Wachsmuth et al., 2013). Interestingly, performances then showed a significant improvement from pre-ALT between 25- and 35-days following return to SL (p=0.02) (Wachsmuth et al., 2013). Taken together, these results appear to demonstrate an apparent temporary inhibition of swimming performance immediately following return to SL, with improvements not observed until approximately three- to four-weeks post-intervention. Potential mechanisms for these observations include a possible decrease in buffer capacity through a hypoxia-induced inhibition of both bicarbonate and non-bicarbonate buffer systems (Böning et al., 2001) and a delayed re-adaptation of multiple endocrinological metabolic pathways leading to a reduced synthesis of key performance-related hormones, such as aldosterone (Wachsmuth et al., 2013). Delayed performance improvements may then occur when hormonal status and buffering capacity has returned to normal. In addition, athletes may have then had sufficient time to take advantage of altitude-induced physiological adaptations, allowing a greater volume and intensity of training with improved recovery (Mujika et al., 2019). This may be why, as recently described by Wilber (Wilber, 2022), following a LHTH intervention, USA Swimming first complete a SL training block before competing in major international events.

Despite negligible changes in the group mean of FINA points obtained from pre-to-post ALT, substantial individual variation was identified between athletes. The %Δ in FINA points achieved from pre-ALT ranged from -6.0% to 13.4% and -7.0% to 4.4% immediately and three-weeks post-ALT, respectively. Performance in a competitive environment is influenced by a complex interaction of variables, including tactical strategies, residual fatigue, underlying illness or injury, psychological characteristics and, of course, physiological capacity (Bonne et al., 2014). The significant positive association ($r=0.476$, $p=0.043$), identified between individual pre-to-post-ALT adaptation in Hb mass and individual change in competitive performance suggests those with a greater increase in Hb mass also experienced the largest improvements in performance, and importantly, vice versa. Correspondingly, Wachsmuth and colleagues (Wachsmuth et al., 2013) identified that a 1% increase in Hb mass following LHTH related to a performance improvement of 1.8 points in the German point scoring system. Therefore, their sample mean Hb mass adaptation of 6.5% corresponded with an increase of 11.7 points (translating to a 0.4% performance improvement in male freestyle events). However, the relationship identified in the present study is influenced by an obvious outlier (Figure 3), and only demonstrates a moderate ES, with a variance (R^2) of 23%. Ultimately, the highly variable and unpredictable nature of competitive athletic performance makes it challenging to determine the efficacy of a specific intervention for the development of performance within empirical research (Atkinson & Nevill, 2001).

Training Load Quantification and Periodisation

Total TL increased significantly from pre-ALT SL training during week 1 (54%) and week 2 (41%) but not week 3 (13%) of LHTH. Table 2 demonstrates that these increases in load are primarily due to an increase in training duration, with no change in mean RPE identified across any of the weeks at ALT when compared to SL. This is further evidenced by the lack of a statistically significant change in pool volume:load ratio from SL to ALT, suggesting there was no change in subjective exertion per kilometre swam. Therefore, while load was increased through completion of greater training duration and volume, the hypoxic environment appeared to have little effect in increasing the perceived exertion of the athletes. A possible mechanism for this is that the athlete's self-regulated speed and effort while in hypoxic conditions to match perceived intensity at SL, at the expense of absolute intensity. Sharma and colleagues have previously reported that in elite middle-distance runners, maintenance of absolute intensity (running speed) from SL led to significantly higher perceived exertions at an altitude of 2100m (Sharma et al., 2017). It has been demonstrated that a reduction of absolute intensity during a period of altitude training led to a trend of non-response in 5000m running performance in a sample of collegiate athletes (Chapman et al., 1998). Together, these findings suggest that maintaining absolute training intensity from SL appears necessary to increase the probability of achieving performance improvements following LHTH, despite a possible increase in perceived exertion. However, these findings contrast those found by Rodriguez and colleagues (Rodríguez et al., 2015), where swimmers who completed LHTH reported significantly greater RPE values than those who completed similar LHTL or SL training. These athletes also experienced a certain degree of over-reaching and post-ALT decrease in performance, with a similar mean physiological adaptation (3.8% increase in Hb mass) to the present study (Rodríguez et al., 2015). This suggests that an increased intensity of training at ALT may not necessarily have led to a greater degree of physiological adaptation within the present study's sample. Providing further evidence to this, the current study identified that the association between %Δ in TL from SL to ALT and pre-to-post ALT %Δ in Hb mass was non-significant, with a trivial effect size ($r= -0.007$, $p=0.491$).

Implications, Limitations and Practical Recommendations

A LHTH intervention consisting of a sharp increase in TL, primarily driven by a greater training duration and volume, followed by a slight de-load in the final week, led to a significant mean increase in Hb mass but no change in the mean competitive performance of high-performance swimmers. This TL periodisation strategy is recommended to those aiming for an increase in physiological capacity leading into a subsequent training phase, with those targeting improved SL performance suggested to allow a minimum of 3-4 weeks between return to SL and competition. However, as highlighted previously, it was not possible to employ a randomised control trial design to accurately explore cause-and-effect relationships regarding the interplay of the hypoxic environment and completed training. A further unavoidable limitation of this study is the comparison of short-course and long-course performances from pre-to-post ALT. While this was necessary to retain high ecological validity of the swimming performance in real competition, the change in pool distance may have benefitted some athletes more than others, and so should be considered when comparing the results of the present study to similar research. Nevertheless, the conversion of performance times to FINA points allows the results of the present study to be generalised to swimmers specialising in an event of any recognised stroke and distance, worldwide. Thirdly, it was not possible to track athlete compliance with a general recommendation to supplement their diet with iron, which may have contributed to the high degree of individual changes in Hb mass. Future research should complete pre-intervention assessments of serum ferritin, subsequently prescribing appropriate iron dose supplementation.

Conclusion

This study identified that a three-week LHTH intervention at 2,320m, characterised by a sudden increase in TL followed by a slight de-load in the final week, led to a significant positive physiological adaptation but no improvement in competitive performance in a sample of high-performance swimmers. A statistically significant positive association was identified between the pre-to-post ALT response in Hb mass and change in performance level. However, this relationship demonstrated only a moderate ES. In addition, changes in TL from SL to ALT were not related to the physiological adaptation observed. It is evident that this LHTH approach is not an efficient or effective approach that benefits all swimmers. It is therefore clear that further research is required to characterise the highly individual relationship between the TL periodisation strategy adopted at ALT and the response in Hb mass and competitive swimming performance following the return to SL.

Statements and Declarations

Competing Interests

The authors have no relevant financial or non-financial competing interests to disclose.

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Ethical Approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Moray House School of Education and Sport Research Ethics Committee at the University of Edinburgh.

Consent to Participate

Written informed consent was collected from all individual participants included in the study.

Consent to Publish

All participants provided informed consent for the publication of their data in a scientific journal.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by DA and MM, under the supervision of AT. The first draft of the manuscript was written by DA and all authors commented on subsequent versions of the manuscript. All authors read and approved the final manuscript.

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Tables

Table 1.

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
Session 1 07:00 – 09:00	Travel to altitude.	Swim AEC 1 4000m	REST AM	Swim AEC 1 4000m	REST DAY	Swim AEC 2/3 5000m	Swim AEC 1 5000m
Session 2 14:00 – 16:00		Swim Kick A1 4000m	Swim Pull A1 5000m	Swim ANC 4000m		Swim Speed 3500m	Swim Kick A1 4000m
Session 3 16:30 – 17:30		Land-based S&C	Land-based S&C	Land-based S&C		Land-based S&C	Land-based S&C
	Day 8	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
Session 1 07:00 – 09:00	Swim Pull A1 4000m	REST DAY	Swim AEC 1 5000m	Swim AEC 1 6000m	Swim AEC 1 5600m	REST DAY	Swim Skills A1 5500m
Session 2 14:00 – 16:00	Swim AEC 2/3 6000m		Swim ANC 5000m	Swim Skills A1 5000m	Swim AEC 2/3 5000m		Swim Speed 4000m
Session 3 16:30 – 17:30	Land-based S&C		Land-based S&C	Land-based S&C	Land-based S&C		Land-based S&C
	Day 15	**Day 16**	**Day 17**	**Day 18**	**Day 19**	**Day 20**	**Day 21**
Session 1 07:00 – 09:00	Swim AEC 1 6000m	Swim AEC 1 5000m	REST DAY	Swim AEC 1 5000m	Swim Speed 3000m	Swim AEC 1 3000m	Travel to meet.
Session 2 14:00 – 16:00	Swim Skills A1 4000m	Swim AEC 2/3 5500m		Swim ANC 3500m	Swim AEC 1 4500m	REST PM	
Session 3 16:30 – 17:30	Land-based S&C	Land-based S&C		Land-based S&C	Land-based S&C		

Table 2.

	Sea Level Mean (SD)	**Week 1** Mean (SD)	**Week 2** Mean (SD)	**Week 3** Mean (SD)
Weekly Pool Duration (mins)	823 (142)	1039 (141) +30.5% (32.1%)** $d = 0.99$ 95% CI [0.21, 1.78]	1088 (172) +36.3% (32.4%)** $d = 1.29$ 95% CI [0.47, 2.11]	804 (134) -2.3% (21.78%) $d = -0.1$ 95% CI [-0.84, 0.64]
Pool Session RPE (au)	3.3 (0.6)	3.6 (0.8) +9.9% (18.0%) $d = 0.66$ 95% CI [-0.10, 1.42]	3.4 (0.8) +7.14% (23.5%) $d = 0.17$ 95% CI [-0.57, 0.92]	3.4 (0.6) +6.91% (17.5%) $d = 0.19$ 95% CI [-0.55, 0.93]
Weekly Pool Volume (m)	33372 (2573)	41879 (5409) +26.1% (18.2%)** $d = 2.49$ 95% CI [1.49, 3.46]	46100 (6877) +38.5% (20.9%)** $d = 4.13$ 95% CI [2.83, 5.45]	34543 (4057) +3.8% (12.0%) $d = 0.39$ 95% CI [-0.36, 1.14]
Weekly Land Duration (mins)	131 (29)	241 (32) +90.5% (43.9%)*** $d = 2.82$ 95% CI [1.78, 3.87]	136 (18) +8.74% (27.5%) $d = 0.11$ 95% CI [-0.63, 0.85]	166 (29) +30.8% (30.7%)** $d = 0.99$ 95% CI [0.21, 1.78]
Land Session RPE (au)	3.9 (1.1)	4.3 (1.3) +12.9% (26.6%) $d = 0.49$ 95% CI [-0.26, 1.25]	4.5 (1.1) +20.4% (28.3%) $d = 0.56$ 95% CI [-0.20, 1.31]	4.4 (1.1) +14.1% (16.3%) $d = 0.92$ 95% CI [0.15, 1.71]

Figures

Figure 1.

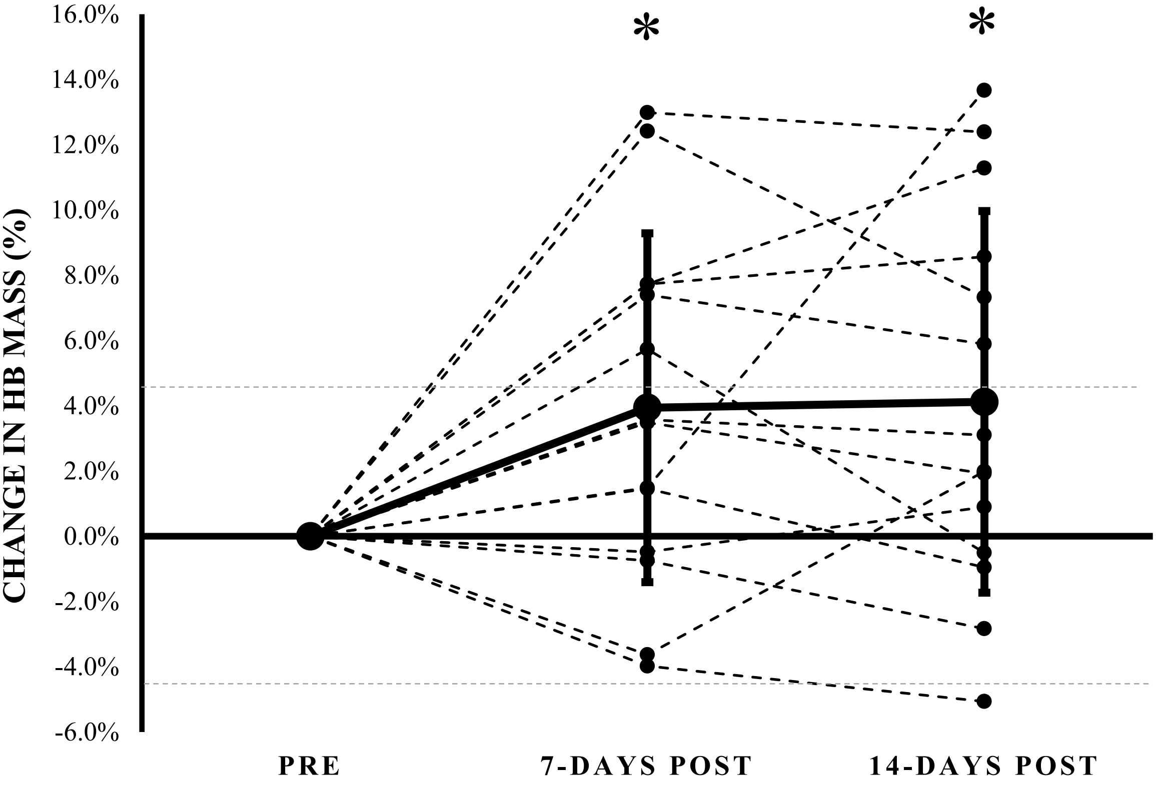

Figure 2.

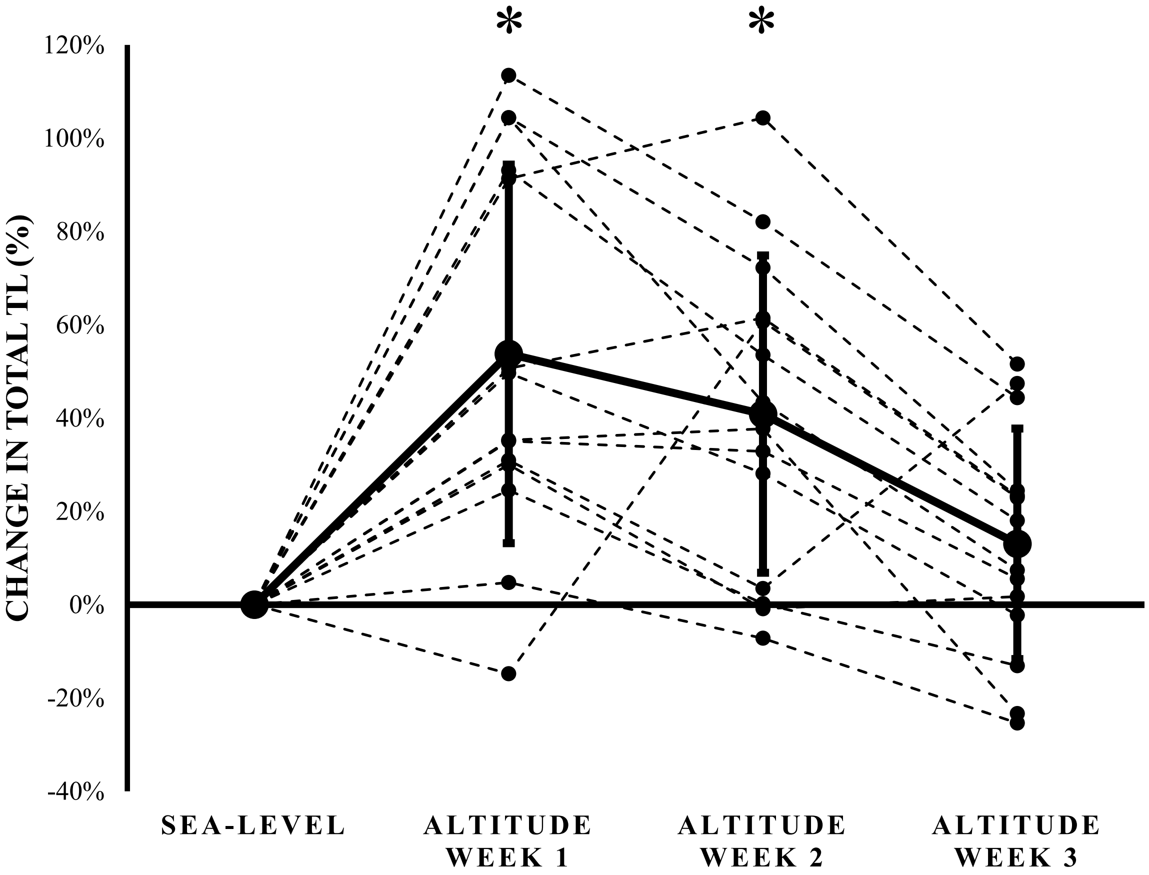
*
*
120%
100%
80%
60%
40%
20%
0%
-20%
-40%
CHANGE IN TOTAL TL (%)
SEA-LEVEL
ALTITUDE WEEK 1
ALTITUDE WEEK 2
ALTITUDE WEEK 3

Figure 3.

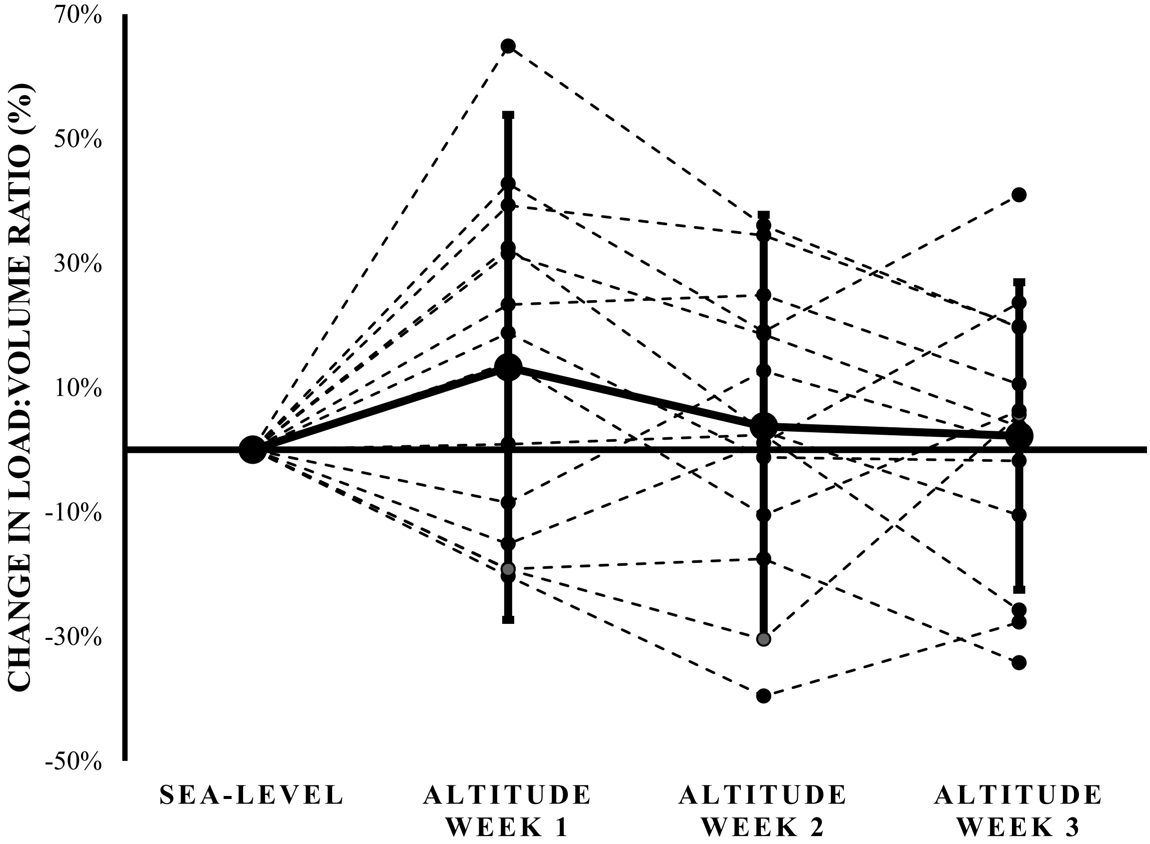
70%
50%
30%
10%
-10%
-30%
-50%
CHANGE IN LOAD:VOLUME RATIO (%)
SEA-LEVEL
ALTITUDE WEEK 1
ALTITUDE WEEK 2
ALTITUDE WEEK 3

Table and Figure Captions

Table 1. Training schedule for the three-week Live-High, Train-High altitude intervention, indicating session type, duration, focus and volume. Skill = session with focus on technical capability, typically comprised of drills completed with accessory equipment. Kick = main set completed using legs only (i.e., holding a kick board). Pull = main set completed using arms only (i.e., with pool buoy between legs). A1 = Regenerative low intensity aerobic training. AEC 1 = Aerobic capacity 1 (long, extensive endurance training). AEC 2/3 = Aerobic capacity 2/3 (aerobic overload (VO_{2max}) training). ANC = Anaerobic capacity (lactate production training). Speed = supramaximal short duration sprint work. S&C = strength and conditioning.

Table 2. Mean (SD) absolute values and percentage change from pre-altitude sea level training for weekly pool session duration (mins), pool session RPE (au), weekly pool volume (m), weekly land session duration (mins) and land session RPE (au), for each week of the altitude training camp. Significant differences are marked with * ($p<0.05$), ** ($p<0.01$) or *** ($p<0.001$). Cohen's *d* effect sizes, with 95% confidence intervals, are displayed for each comparison to sea level.

Figure 1. Percentage change in haemoglobin mass from pre-altitude at seven and fourteen-days post-altitude. Group mean (±SD) displayed in bold. Smallest worthwhile change (SWC) identified with dashed horizontal grey lines. Significant differences ($p<0.05$) in the group mean from pre-altitude identified with an asterisk.

Figure 2. Percentage change in mean weekly total training load from pre-altitude for each week of the altitude training camp. Group mean (±SD) displayed in bold. Significant differences ($p<0.05$) in the group mean from pre-altitude identified with an asterisk.

Figure 3. Percentage change in pool training load:volume ratio from pre-altitude for each week of the altitude training camp. Group mean (±SD) displayed in bold.