

Variability in response to an 8-week low altitude football training camp supplemented with intermittent hypoxic training

APIWAN MANIMMANAKORN¹, NUTTASET MANIMMANAKORN², WORRAWUT THUWAKUM³, CHARLES W.C. SIMPSON⁴, MICHAEL J. HAMLIN^{5*}

¹ Department of Physiology, Faculty of Medicine, Khon Kaen University, Khon Kaen, THAILAND.

² Department of Rehabilitation Medicine, Faculty of Medicine, Khon Kaen University, Khon Kaen, THAILAND.

³ Department of Sport Science and Exercise, Uttaradit Rajabhat University, Uttaradit, THAILAND.

^{4,5} Department of Tourism Sport and Society, Lincoln University, Christchurch, NEW ZEALAND.

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Abstract

Introduction: Living and training at altitude is popular among athletes; however, significant individual differences exist in the improvement of sea-level performance. We investigated potential physiological factors that may explain the difference between responders and non-responders. **Design:** Randomized Controlled Trial. **Methods:** Twenty male football players completed an 8-week training camp at 825 m above sea-level, supplemented with intermittent hypoxic training three times per week at FIO₂ = 0.15. Based on the players 2800 m run performances, players were separated into responders (improved by $10.7 \pm 8.1\%$, mean $\pm$ 95% CI, n=14) and non-responders (decreased by $6.1 \pm 12.8\%$, n = 6). **Results:** Compared to baseline, the responders had a lower resting heart rate (HR_{rest}) at 1 (-4.6 ± 2.7 bpm, Effect Size = 1.2) and 14 days (-6.7 ± 3.3 bpm, ES = 1.7) post-training camp, whereas the non-responders HR_{rest} changed little. Compared to the non-responders, the responders had higher pNN50 at 1 (12.2 ± 11.5 , p = 0.04, ES = 1.6) and 14 days (10.1 ± 11.7 , p = 0.09, ES = 1.4) post-training camp. In addition, the responders decreased their LF/HF ratio at day 1 (-1.1 ± 0.6 , p < 0.01, ES = 1.0) and day 14 post camp (-0.9 ± 0.6 , p < 0.01, ES = 0.8), whereas the non-responders LF/HF ratio increased (0.8 ± 0.9 and 0.9 ± 0.9). **Conclusions:** Reduced HR_{rest} and increased cardiac parasympathetic tone was associated with improved run performance after altitude training and may be used to differentiate altitude responders compared to non-responders.

Keywords: Heart rate variability, Erythropoietin, Haematological changes, Parasympathetic, Soccer

Introduction

Travelling to altitude to train athletes has been popular for many years and has been shown to be an effective means to increase endurance performance, especially if athletes return to lower altitudes to complete high-intensity training. This strategy, often referred to as the "Live High, Train Low" (LHTL) model, has gained traction due to its ability to stimulate erythropoiesis while maintaining training intensity at sea level (Płoszczyca et al., 2018). While some researchers continue to debate the usefulness of altitude training in elite athletes, the current consensus suggests such training produces worthwhile improvements in subsequent sea-level performance (Bonato et al., 2023).

The physiological mechanisms responsible for performance enhancement with altitude training have been widely studied. These include increased red blood cell mass and haemoglobin concentration due to elevated erythropoietin (EPO) production (Płoszczyca et al., 2018), improved capillary density and mitochondrial efficiency (Lemieux & Birot, 2021), and greater muscle oxygen utilization (Vargas Pinilla, 2014). These adaptations collectively improve oxygen delivery and utilization, which are critical for endurance performance.

Heart rate variability (HRV) is indeed a valuable physiological marker that reflects the balance between sympathetic and parasympathetic activity in the autonomic nervous system. It has gained increasing attention as a non-invasive tool to monitor training adaptation, recovery, and overall cardiovascular health in athletes. In the context of altitude training, HRV offers unique insights into how the body responds to hypoxic stress and can help differentiate between positive adaptation and maladaptation (Vandusseldorp & Kravitz, 2015).

Exposure to altitude typically induces a shift toward sympathetic dominance, especially in the early stages, which is reflected by a reduction in HRV and an increase in resting heart rate. Over time, as the body acclimatizes, HRV may gradually return to baseline or even improve, indicating successful adaptation. A study

by Altini (2020) observed that elite triathletes who adapted well to altitude training showed a progressive normalization of HRV and submaximal heart rate, while non-responders maintained elevated heart rates and suppressed HRV throughout the camp (Altini, 2020).

HRV guided training has been shown to enhance performance outcomes during altitude exposure. Bahenský and Grosicki (2021) demonstrated that adolescent runners who adjusted their training based on daily HRV readings experienced significantly greater improvements in $\text{VO}_{2\text{max}}$ and race performance compared to a control group following a fixed training plan (Bahenský & Grosicki, 2021). This suggests that HRV can be a powerful tool for individualizing training loads and optimizing adaptation during altitude camps.

However, altitude training is not without its limitations. Access to natural altitude environments or simulated hypoxic facilities remains limited due to high costs and logistical challenges (Vogt et al., 2022). As a result, athletes and coaches must carefully plan altitude training blocks to maximize physiological adaptations and minimize potential drawbacks such as overtraining or maladaptation.

Moreover, not all athletes benefit equally from altitude exposure. A subset of individuals, termed "non-responders," may experience no improvement or even a decline in performance following altitude training (Hamlin et al., 2015). This variability has been attributed to differences in EPO responsiveness and susceptibility to acute mountain sickness (Burtscher et al., 2008), and other physiological factors such as ventilatory response and arterial oxygen saturation (Hamlin et al., 2015). In addition, HRV metrics such as SDNN, HF, and LF differed significantly, suggesting that autonomic regulation and HRV profiles are closely linked to athletic performance levels (Stepanyan & Lalayan, 2023).

Indeed, Bonetti et al. (2009) found that Live-High Train-High (LHTH) protocols may lead to performance decrements in both elite and sub-elite athletes, whereas LHTL protocols are more consistently associated with performance gains (Bonetti & Hopkins, 2009). These findings underscore the importance of individualized approaches to altitude training and the need for further research into the predictors of training responsiveness.

The aim of this study was to build on previous research by our group (Hamlin et al., 2015) by measuring a different set of physiological variables in a sub-group of athletes undertaking an 8-week altitude training camp situated at 825 m that was supplemented with a short period of intermittent hypoxic training. The goal was to determine whether there were any cardiovascular, heart rate variability, and haematological variables able to differentiate altitude-training responders from non-responders.

Material & methods

Experimental Approach to the Problem

Little information exists on why some athletes respond well to live-high train-high style altitude camps and subsequently improve performance, whereas other athletes fail to show improved performance as a result of altitude training. This study used a subset of participants that were involved in a larger study (Wonnabussapawich et al., 2017) and selected only participants that went to altitude (825 m) for an 8-week training camp. In turn, 20 participants were separated into those that responded well to the training camp ($n = 14$) and those that did not respond well ($n = 6$). To decide which players were classified as responders compared to non-responders, the smallest meaningful change in 2800 m performance was calculated from baseline to 14 days post training camp, using the formula from Hopkins (Hopkins, 2017) which is the baseline between-subject SD multiplied by Cohen's smallest important effect size of 0.2 (Cohen, 2013). The smallest worthwhile change in this study was therefore $1.91 \times 0.2 = 0.4$ min. Any player that improved their 2800 m run time by ≥ 0.4 min was therefore considered a responder, whereas a change in run time of < 0.4 min was considered a non-responder. Performance and blood testing was conducted at sea level and involved 3 tests (baseline, 1-day and 14-days post training). In addition, half of the participants were given an iron supplement (1 capsule/day for first 6 weeks of the 8 weeks, Ferrograd C, Abbott Laboratories, Thailand) that contained 325 mg ferrous sulphate plus 500 mg Vitamin C. The other half received a placebo capsule of plain flour.

Participants

Twenty local university football players (20.6 ± 1.1 years, 173.9 ± 4.8 cm, 67.7 ± 8.3 kg, mean $\pm$ SD) were selected from a larger group of 40 players to travel to an 8-week altitude training camp at Khonsan, Chaiyaphum province, Thailand). Players were well-trained club-level athletes recruited from university football teams. Players were in the pre-season phase of training and completed approximately 5 trainings per week (including skilled-based and conditioning). All players consumed the same meals during the training camp. All players were free from injury and were in their pre-season training block. All players had resided at sea-level for the preceding 6 months. Ethical approval for this research has been obtained by the Khon Kaen University Human Ethics Committee (reference HE571003). Players were informed of the benefits and risks of the investigation before signing an institutionally approved informed consent document to participate in the study.

Procedures

Physiological Measures at Rest

Resting measures of heart rate and arterial blood oxygen saturation (Beurer, PO30, Beurer GmbH, Uttenweiler, Germany) along with heart rate variability (HRV) were taken prior to any of the performance and

blood tests. For the HRV, participants remained in a supine position for a 10-minute period, and the HRV was taken over the last 5-min of this period. HRV was detected using a heart rate monitor set at a sampling frequency of 1000 Hz, providing a temporal resolution of 1ms for each R-R interval (RS800CX, Polar Electro Oy, Kempele, Finland) and belt (Wearlink W.I.N.D, Polar Electro Oy, Kempele, Finland) and analysed using Polar software (Polar ProTrainer 5, Version 5.41.000). To measure HRV, the root mean square of successive differences in the RR interval (rMSSD), along with the proportion of the number of pairs of adjacent NN intervals that are greater than 50 ms from the total number of NN intervals recorded (pNN50) were used to provide an indication of vagal outflow. However, to provide a more complete dataset, and to enable greater comparability with other research, high frequency (HF: 0.15 – 0.4 Hz), Low frequency (LF: 0.04 – 0.15 Hz) and the low frequency to high frequency (LF/HF) ratio were also reported. As HRV can have low repeatability (Tulppo et al., 1998) all data were filtered for ectopic beats using the Polar ProTrainer 5 (PPT5) filters. Data were then visually inspected and any remaining ‘spikes’ in the data were removed and replaced with the next appropriate R-R interval. All data were screened for outliers using the median absolute deviation and participants with greater or less than $3 \times$ the population SD as estimated by the median (Leys et al., 2013) were excluded from the data.

Body composition was measured at baseline and 8 weeks using bioelectrical impedance (Tanita BC-418 MA Segmental Body Composition Analyzer, Tokyo, Japan) in the morning prior to any performance testing with the players in a rested state after emptying their bladders.

2800 m Time Trial; all tests were conducted at sea level at the same venue and at the same time of day and included a warm-up (a slow jog for 5 min and then 5–10 min of dynamic and static stretching). A 2800 m time trial at sea-level was conducted at baseline (1-2 days prior to the camp) and again at 1 and 14 days after the camp on a non-slip hard-surfaced track with verbal encouragement given equally to all players. Only 1 attempt was provided, and times were recorded using a stopwatch with an experienced timekeeper situated at the finish line. Players were asked to refrain from alcohol and caffeine 24 hours before any test and from a heavy meal 1–2 hours before testing.

Blood Parameters

One to 2 days before the 3 main testing sessions, blood samples were taken from the median cubital vein while players were seated and after 5 minutes rest. Bloods were immediately stored in ice and transported to the Srinagarind Hospital, Khon Kaen University laboratory on the same day and analyzed for RBC count, Hb concentration, erythropoietin (EPO), and hematocrit using an automatic hematology analyzer (Mindray BC-5800; Mindray Bio-Medical Electronics Co., Ltd., Shenzhen, China). In addition, blood lactate (Accutrend Plus, Roche Diagnostics, Basel, Switzerland) was sampled before and immediately after a maximal run around the perimeter of a football field (approximately 320 m). Players were encouraged to complete the run in the fastest time possible.

Training Program

The training program for the players has been described in full elsewhere (Wonnabussapawich et al., 2017) and included daily skill sessions along with normal conditioning sessions. All participants at the altitude camp also completed 15 min of stationary cycling (100-120 W, Monark 828E Ergometer, Vansbro Sweden) 3 days per week while breathing hypoxic air (15% oxygen, Altitude Training Systems, Australia). The work intensity of the stationary cycling was deliberately low to reduce any possibility of overreaching. All players have no training program during 1- and 14-days post training camp.

Statistical Analyses

We used a convenience sample of 20 football players for this research and included all participants that completed the altitude camp. Given previous research has found significant differences between responders and non-responders to altitude camps with subject numbers as low as 10 (Hamlin et al., 2015), we are confident that we had sufficient power (numbers) to detect small worthwhile changes. Changes in the 2800 m run from the 3 trials and standard deviations representing the between-and within-subject variability were estimated using a mixed modelling procedure (Proc Mixed) in the Statistical Analysis System (Version 9.3, SAS Institute, Cary, North Carolina, USA).

The differences in 2800 m run times were compared between groups and Cohen’s value of 0.2 of the between-subject standard deviation was used to assess the smallest worthwhile change (Cohen, 2013). Results are displayed as mean $\pm$ SD or raw change $\pm$ 95% confidence interval (CI). P values are given for the within and between-group comparisons with $p \leq 0.05$ used as the alpha level of significance. The effect size (ES) was calculated from the change in the mean between groups divided by the between subject SD. A Pearson correlation was also conducted to investigate the association between changes in the dependent variable (2800m run) and changes in other key variables during the altitude camp. This was done by averaging the post camp data periods (day 1 and day 14) and comparing them to baseline data. The reliability (mean intraclass correlation coefficient) of the dependent measure (2800 m run) over the 3 trials was 0.83.

Results

A clear difference was found between players that responded well to the training camp (responders) compared to those that did not respond positively (non-responders) (Figure 1). Compared to baseline, responders reduced the time it took to cover the 2800 m by $9.0 \pm 8.5\%$ (mean $\pm$ 95%CI, $p = 0.03$, ES = 0.7) 1-day post training camp and improved further at 14-day post training camp ($10.7 \pm 8.1\%$, $p = 0.01$, ES = 0.9). Compared to baseline, the non-responders decreased performance at 1-day post training ($-9.5 \pm 13.0\%$, $p = 0.15$, ES = 0.8) which continued into day-14 post training ($-6.1 \pm 12.8\%$, $p = 0.35$, ES = 0.5). Comparing the two groups, the responders covered the distance significantly faster than the non-responders at 1-day ($18.5 \pm 15.5\%$, $p = 0.02$, ES = 1.5) and 14-day ($16.8 \pm 15.1\%$, $p = 0.03$, ES = 1.4) post training. We found a small correlation ($r = 0.28$) between baseline performance and performance change after the altitude training camp (Figure 2).

Figure 1. Run performance in the two football groups before, 1 and 14 days after the 8-week altitude training camp.

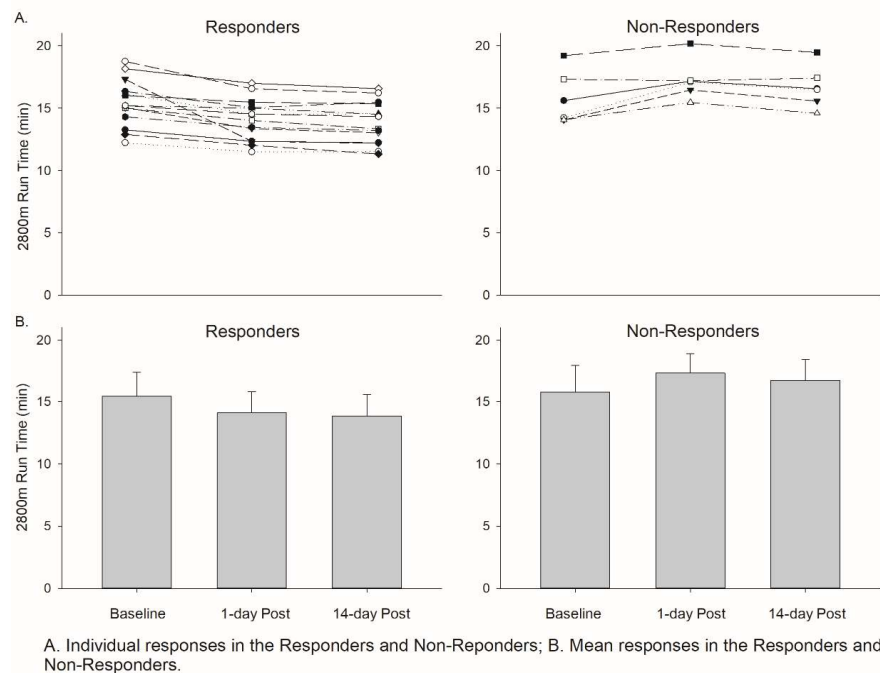
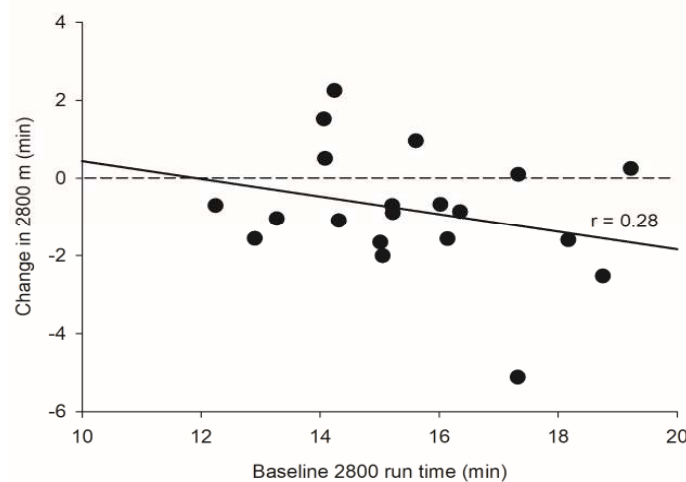


Figure 2. Association between baseline 2800 m run performance and subsequent change in performance at day 14 post training camp.



There was no difference in the body composition between groups at baseline or after the 8-week training period. Players in both groups lost body fat over the 8-week period but maintained skeletal muscle mass resulting in a small decrease in overall body weight for both groups (Table 1).

Table 1. Measurement parameters at baseline, 1 and 14 days after an 8-week low altitude training camp in football players.

	Non-Responders (n = 6)			Responders (n = 14)		
	Baseline	1-day post	14-day post	Baseline	1-day post	14-day post
Body Composition						
Body mass (kg)	70.4 ± 10.7	67.2 ± 9.4		66.6 ± 7.2	65.1 ± 6.3	
SMM (kg)	51.6 ± 5.0	51.9 ± 4.5		51.2 ± 4.4	52.0 ± 4.6	
Body fat (%)	20.3 ± 5.3	16.5 ± 4.8		16.9 ± 4.0	14.1 ± 3.5	
Cardiovascular						
Resting HR (bpm)	76.0 ± 4.2	72.0 ± 4.0	72.3 ± 3.3	74.1 ± 3.9	69.5 ± 3.5 ^b	67.4 ± 4.2 ^b
Resting SpO ₂ (%)	97.5 ± 1.2	98.3 ± 0.8	98.0 ± 0.6	98.4 ± 0.8	98.5 ± 0.5	98.5 ± 0.5
Haematological						
RBC (10 ⁶ /μl)	5.5 ± 0.3	5.6 ± 0.4	5.6 ± 3.3	5.3 ± 0.2	5.3 ± 0.2	5.3 ± 0.3
Serum Iron (ug/dL)	94.3 ± 36.2	92.7 ± 16.1	134.6 ± 24.6 ^b	109.9 ± 44.5	98.5 ± 23.4	154.2 ± 31.6 ^b
TIBC (mg/dL)	211.5 ± 63.0	204.1 ± 38.9	162.8 ± 60.0	180.5 ± 48.4	184.6 ± 37.1	151.1 ± 42.8
EPO (mIU/ml)	14.9 ± 4.0	13.3 ± 2.6	12.7 ± 2.8	11.4 ± 3.3	12.7 ± 5.5	9.9 ± 5.3
Hb (g/dL)	13.9 ± 1.6	13.8 ± 1.3	13.9 ± 1.7	14.4 ± 0.6	14.5 ± 0.8	14.7 ± 0.8
Hct (%)	42.3 ± 3.5	42.5 ± 3.2	44.0 ± 5.2	43.8 ± 1.6	44.5 ± 2.4	46.5 ± 2.7 ^b
Heart Rate Variability						
rMSSD (ms)	75.5 ± 57.1	57.0 ± 23.3	61.2 ± 40.1	68.1 ± 36.6	71.5 ± 33.8	86.2 ± 53.2
pNN50 (%)	12.0 ± 10.1	8.3 ± 7.0	11.0 ± 7.8	11.9 ± 6.3	20.3 ± 9.9 ^{bc}	21.0 ± 9.9 ^{bc}
LF (ms ²)	1508 ± 1579	1729 ± 1856	1465 ± 1605	2420 ± 2126	1676 ± 2334	1922 ± 1643
HF (ms ²)	2613 ± 4179	893 ± 695	1441 ± 1562	1806 ± 2023	2104 ± 1773	3036 ± 3325
LF/HF ratio	0.9 ± 0.4	1.7 ± 0.9	1.8 ± 2.1 ^b	2.0 ± 1.2 ^a	0.8 ± 0.6 ^{bc}	1.0 ± 0.8 ^{bc}
Blood Lactate (mmol/L)						
Pre-exercise	2.4 ± 0.7	1.8 ± 0.5	2.5 ± 0.4	2.9 ± 1.2	2.1 ± 0.9 ^b	2.4 ± 0.6
Post-exercise	19.6 ± 3.7	13.8 ± 2.5 ^b	10.1 ± 3.5 ^b	17.8 ± 4.3	15.2 ± 3.0 ^b	9.8 ± 3.1 ^b
Iron Supplementation	3 supplemented with iron and 3 without			7 supplemented with iron and 7 without		

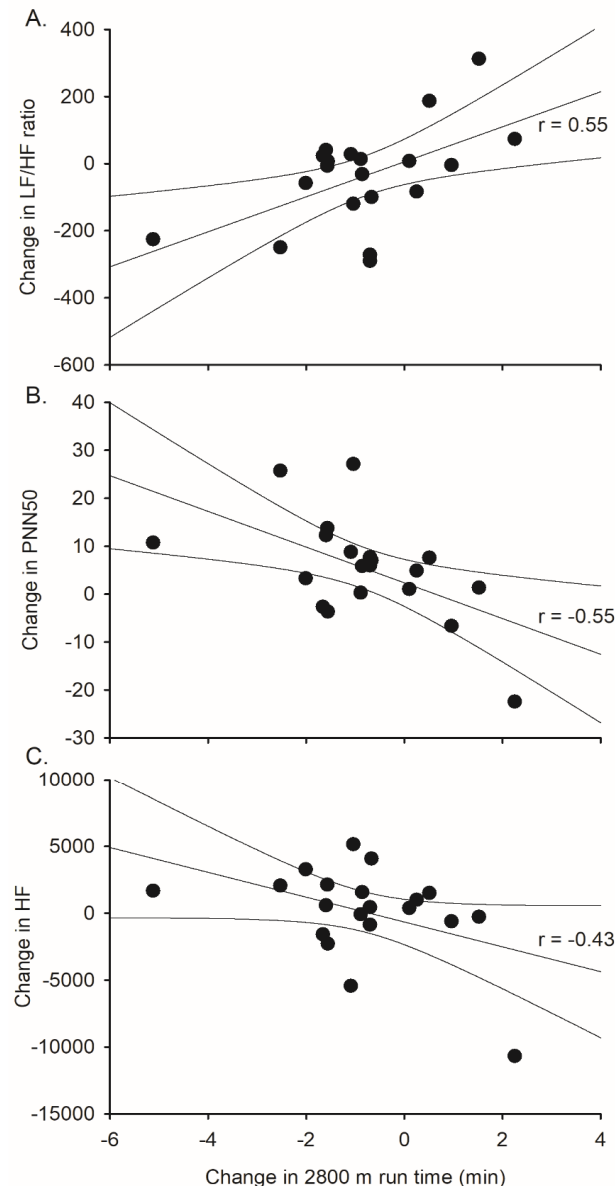
Data are mean ± SD. SMM; Skeletal Muscle Mass, RBC; Red Blood Cell, TIBC; Total Iron Binding Capacity, EPO; Erythropoietin, Hb; Haemoglobin, Hct; Haematocrit, rMSSD; Root Mean Square of Successive Differences in the RR interval, pNN50; Number of successive heartbeat intervals exceeding 50ms, LF; Low Frequency, HF; High Frequency. ^aSignificantly different from baseline, ^bSignificant change from baseline within groups, ^cSignificant change from baseline between groups.

Compared to baseline resting heart rate decreased significantly as a result of the training camp only in players that responded well to training both at 1-day and 14-day post training camp (-4.6 ± 2.7 beats/min, ES = 1.2 and -6.7 ± 3.3 beats/min, ES = 1.7 respectively). Compared to baseline, serum iron changed little at 1 day post training camp, but in both groups increased significantly at 14 days post training camp with no significant difference between groups at any time period. The only other haematological variable to significantly change was an increase in haematocrit in the responder group 14 days after the training camp (43.8% to 46.5%, $p = 0.02$, ES = 1.2).

Notably responders had a significantly higher LF/HF ratio at baseline compared to the non-responders (2.0 compared to 0.9), the ratio moved in opposite directions in the two groups during the duration of the training camp. For the non-responders the LF/HF ratio increased from baseline to day 1 (0.8 ± 0.9 , ES = 0.8) and then again by day 14 post camp (0.9 ± 0.9 , $p = 0.05$, ES = 0.9). Responders by comparison showed a decrease in the LF/HF ratio at day 1 post camp by -1.1 ± 0.6 , ($p < 0.01$, ES = 1.0) and -0.9 ± 0.6 , ($p = 0.004$, ES = 0.8) by day 14 post training camp.

These changes were significantly different between groups ($p < 0.01$, ES = 1.8 and 1.7). Compared to baseline, the pNN50 increased in the responders at day 1 by 8.4 ± 6.4 , ($p = 0.01$, ES = 1.1) and by 9.1 ± 6.4 , ($p = 0.006$, ES = 1.2) at 14 days post training camp, whereas the pNN50 decreased in the non-responders. Compared to non-responders, the responders pNN50 was higher at 1 day (12.2 ± 11.5 , $p = 0.04$, ES = 1.6) and 14 days (10.1 ± 11.7 , $p = 0.09$, ES = 1.4) post training camp. We found large correlations between the change in 2800 m run performance from baseline to post training and changes in pNN50 ($r = -0.55$, $p = 0.01$), HF ($r = -0.43$, $p = 0.06$) and LF/HF ratio ($r = 0.61$, $p = 0.01$) (Figure 3).

Figure 3. Association between change in 2800 m run performance and change in LF/HF ratio, PNN50 and High Frequency heart rate variability.



Data are individual changes (filled circles) along with the regression line and the 95% confidence interval lines.

Blood lactate concentration either at rest or after exercise, decreased in both groups after the training camp with no significant difference between groups found (Table 1).

Discussion

The aim of this study was to determine whether any physiological variables could identify those players that responded well to the altitude training camp and those that did not. We chose a low altitude training camp to enable the ideal hypoxia for high-intensity training (825 m), while also stimulating the EPO pathway via intermittent exposure to ~3000 m. The principal finding was that players that responded well to altitude and had improved run performance showed a move to more cardiac parasympathetic dominance after the training camp which was indicated by the increase in pNN50 and decrease in LF/HF ratio.

Previous research has indicated that altitude training is not always beneficial for every athlete and there is substantial individual variability in performance (Robertson et al., 2010). The reasons suggested for this variability relate to the varied response found when living and training in hypoxia. Living at altitude introduces an added cardiometabolic stress on individuals which is reflected in a sharp increase in sympathetic activity

which then gradually declines as individuals acclimatize to the hypoxic environment (Jun et al., 2008). The current study found evidence for increased cardiac parasympathetic activity in the responders after the altitude camp which would suggest successful acclimation of this group. Indeed, when investigating the associations between change in 2800 m run time and physiological variables, only pNN50 and LF/HF ratio significantly correlated to changes in run performance (time). However, we also found that the HF domain associated with cardiac parasympathetic tone increased with improved run time performance. Buchheit et al. (2010) found similar changes in the cardiac parasympathetic nervous system in successfully adapted runners (Buchheit et al., 2010), while Lizamore et al. (2022) showed similar reductions in the LF/HF ratio in participants that underwent 10 weeks of intermittent hypoxia added to conventional strength and aerobic exercise training (Lizamore et al., 2022). Conversely, non-responders showed a reduction in cardiac parasympathetic activity post-altitude camp (reduced pNN50 and rMSSD) and increased resting LF/HF ratio that might also indicate an increased cardiac sympathetic response. These changes to the HRV lasted for 2 weeks after the altitude training camp had finished and may be useful correlates of run performance in these players. We speculate that the addition of the hypoxic environment along with the football training in the non-responders was such that it overwhelmed their physical capacity and produced excessive stress resulting in poor adaptation and a drop in 2800 m run performance. Allowing the fine adjustment of training loads according to stress levels and recovery for each athlete while at altitude would seem advisable.

Responders also had a lower resting heart rates in the post camp testing sessions which was probably related to the increased cardiac parasympathetic tone found by HRV analysis. Similar effects of hypoxic training have been previously reported by (Burtcher et al., 2024) and are thought to indicate improved cardiovascular efficiency.

The increase in haematocrit at day 14 post camp in the responders would normally indicate either an increase in red blood cells or a decrease in plasma volume. Lowlanders (i.e. people that normally reside at sea-level) that go to altitude normally experience haemoconcentration due to plasma volume reductions (Sawka et al., 2000), followed by re-expansion of plasma volume on returning to sea-level, therefore we suspect plasma change is not involved (although as we did not measure this it cannot be eliminated as a possibility). Rather, we believe that there was likely an increase in the large red blood cell portion of total red cells in the responder group because of the training camp. Although the red cell numbers did not change significantly in either group, there is research to show that exposure to erythropoietin release can result in an increase in the proportion of large red blood cells into the circulation (Casoni et al., 1993). While speculative, such a change might explain the increased haematocrit without any increase in total red cell numbers in the responder group. Why this occurred in the responder group and not the non-responders is again speculation, but has been suggested to be related to genetically inherited factors or differences in erythropoietin responses to hypoxia (Chapman et al., 1998). Similar to previous studies we found a significant decrease in the post-exercise blood lactate concentration following altitude training (Yu et al., 2022). Hypoxic exposure has been found to increase lactate transporter proteins (MCT1, MCT4) (Zoll et al., 2006), which may increase lactate removal and minimise pH increase during exercise. Along with an increase in lactate transporter proteins, hypoxia has also been associated with an increased ability of skeletal muscle to buffer hydrogen ions (Gore et al., 2001). These changes, along with other purported adaptations to exercise in hypoxia including increased capillarisation (Kon et al., 2021) and enhanced molecular mechanisms (Mallet et al., 2023) may have influenced the players in this study resulting in significantly less blood lactate accumulation after exercise in all athletes (responders and non-responders) at altitude. Previous research has indicated that athletes with low iron stores show a blunted erythropoietic response with altitude exposure and therefore may not benefit from altitude training (Garvican-Lewis et al., 2016). In the current study, iron status of the athletes at baseline was above recommended levels (60-170 ug/dL) and taking an iron supplement did not seem to affect the proportion of players classed as responders or non-responders. As a result of supplementation, the mean serum iron concentration increased equally in both groups at 14 days post training. A ceiling effect may prevent athletes from improving their cardiorespiratory fitness with altitude training. That is, because many athletes are close to maximising their athletic potential prior to altitude training, there is little room for additional improvement once at altitude. While there was a small association between players with the fastest baseline 2800 m run performance and subsequent change in this performance after the altitude camp ($r = 0.28$) in our players, we believe this was unlikely to play a significant role in the positive response to altitude training.

Limitations and Strengths

Firstly, the generalizability of our findings is limited to well-trained football players and may be different to non-athletes that may have different physiological profiles. Secondly, we did not have the equipment to measure haemoglobin mass and plasma volume changes but relied on standard blood test results which may not be sensitive enough to detect altitude training changes in high-performing athletes. Therefore, the haematological findings of this study are preliminary and require further validation. A strength of the study is that we were able to correlate changes in performance (run-time), with HRV data in a large sample of athletes undertaking an altitude training camp.

Conclusion

This study suggests that a simple, non-invasive heart rate variability (HRV) assessment capturing both parasympathetic and sympathetic nervous system activity may serve as a reliable tool for distinguishing athletes who respond positively to altitude training with improved aerobic capacity from those who experience limited or negative performance outcomes. As a marker of autonomic regulation, HRV not only reflects the physiological strain associated with hypoxic exposure but also provides actionable insights for customizing training loads. Incorporating HRV monitoring into altitude training strategies could help optimize performance adaptation and reduce the risk of overtraining or maladaptive responses.

The practical implications of these findings are significant, the results shown that changes in HRV measures are useful at identifying football players that respond well to altitude training compared to those that do not respond well. We would therefore recommend using HRV as a monitoring tool for athletes thinking about going to altitude.

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