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Effects of Simulated and Real Altitude Exposure in Elite Swimmers

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Abstract

Robertson, EY, Aughey, RJ, Anson, JM, Hopkins, WG, and Pyne, DB. Effects of simulated and real altitude exposure in elite swimmers. *J Strength Cond Res* 24(2): 487–493, 2010—The effect of repeated exposures to natural and simulated moderate altitude on physiology and competitive performance of elite athletes warrants further investigation. This study quantified changes in hemoglobin mass, performance tests, and competitive performance of elite swimmers undertaking a coach-prescribed program of natural and simulated altitude training. Nine swimmers (age 21.1 ± 1.4 years, mean ± *SD*) completed up to four 2-week blocks of combined living and training at moderate natural altitude (1,350 m) and simulated live high-train low (2,600–600 m) altitude exposure between 2 National Championships. Changes in hemoglobin mass (Hb_{mass}), 4-mM lactate threshold velocity, and 2,000 m time trial were measured. Competition performance of these swimmers was compared with that of 9 similarly trained swimmers (21.1 ± 4.1 years) who undertook no altitude training. Each 2-week altitude block on average produced the following improvements: Hb_{mass}, 0.9% (90% confidence limits, ±0.8%); 4-mM lactate threshold velocity, 0.9% (±0.8%); and 2,000 m time trial performance, 1.2% (±1.6%). The increases in Hb_{mass} had a moderate correlation with time trial performance ($r = 0.47$; ±0.41) but an unclear correlation with lactate threshold velocity ($r = -0.23$; ±0.48). The altitude group did not swim faster at National Championships compared with swimmers who did not receive any altitude exposure, the difference between the groups was not substantial (−0.5%; ±1.0%). A coach-prescribed program of repeated altitude training and exposure elicited modest changes in physiology but did not substantially improve competition performance of elite swimmers. Sports should investigate the efficacy of their altitude training program to justify the investment.

Key Words swimming, live high-train low, hemoglobin mass, performance

Introduction

Despite widespread popularity with elite athletes and coaches, the physiological mechanisms underpinning improved performance after altitude training remain elusive. Although some coaches advocate altitude training for enhanced athletic performance at sea level, the literature on central and peripheral adaptations is inconclusive. The current debate centers on whether performance enhancements are primarily mediated by hypoxia-induced hematological or nonhematological changes (15). In the erythropoietic pathway, increased erythropoietin (EPO) release at altitude increases oxygen carrying capacity of the blood and presumably enhances maximal oxygen uptake (14). However, whether a transient increase in EPO concentration with brief altitude exposure is sufficient to accelerate erythropoiesis and increase hemoglobin mass (Hb_{mass}) in elite athletes remains unclear (6,12). Alternate explanations for improved performance after altitude exposure include local muscle adaptations such as increased muscle buffer capacity (9) and improved exercise economy (24).

The live high-train low (LHTL) model of altitude training has gained popularity over traditional altitude training, where extended periods of hypoxia are reported to impair training quality as a consequence of reduced work rates (14). The rationale behind LHTL is to improve performance by living and sleeping at moderate altitude to facilitate acclimatization, while maintaining training velocities at lower altitudes (14). A further refinement of LHTL is using simulated altitude in the form of a nitrogen house or hypoxic tent. After 3–4 weeks of natural LHTL, increased erythropoietic activity and red cell mass have been observed (14,29). However, other studies using simulated LHTL altitude have reported no substantial change in reticulocytes or Hb_{mass} in athletes (2,3,24). The

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mechanisms of physiological adaptations with LHTL and their potential contribution to improved performance remain uncertain (15).

The relationship between change in Hb_{mass} and performance improvements after altitude training and exposure in elite athletes is unclear. Conflicting results from recent studies report increased Hb_{mass} with improved performance in elite endurance athletes (26) and junior swimmers (8), increased Hb_{mass} with no performance improvement in highly trained swimmers (21), and no change in Hb_{mass} or time trial performance after altitude training in well-trained triathletes (6) or world champion track cyclists (11).

Although maximal oxygen uptake ($\dot{V}O_2max$) is not the sole predictor of performance in elite athletes (25), many previous studies have used it to evaluate altitude training and reported $\dot{V}O_2max$ to be increased (14,26,29), decreased (9), or unchanged (6). Given these equivocal findings, actual competition performance or a sanctioned time trial may be a more appropriate means to evaluate performance changes with altitude training in elite athletes. To the best of our knowledge, other than a recent uncontrolled "double case" study of 2 elite runners (28), no other studies have used actual competition performance and parallel changes in Hb_{mass} to evaluate altitude training. Moreover, the focus has been on reporting group means, and although individual variation has been observed (23), the magnitude of individual responses has not been quantified directly.

Despite limited documented evidence on performance gains from altitude training in elite swimmers, several leading swimming nations use this preparation for competition. Although previous experimental studies have generally examined single bouts of natural or simulated altitude exposure, no studies have examined the benefits or otherwise of coach-prescribed altitude training programs. These programs typically consist of short duration (~10 days) and multiple bouts (3–4) of combined moderate natural and simulated altitude exposure within a training year. Evaluating the efficacy of this current training methodology on swimming performance is of considerable interest to coaches, sports scientists, and elite swimmers.

The aim of this study was evaluate a coach-prescribed altitude training program, quantifying changes in hemoglobin mass, training performance, and competitive performance of elite swimmers. An observational study design was employed to evaluate a typical altitude training methodology, consisting of 3 to 4 repeated 2-week altitude exposures, undertaken by elite swimmers in preparation for competition.

Methods

Experimental Approach to the Problem

This observational study evaluated the altitude training methodology employed by elite swimming coaches for the preparation of their swimmers for National Championships and Commonwealth Games (Figure 1). The altitude training and exposures were designed by the coaches, and there were no experimental manipulations of these elements by the study investigators. This study evaluated, using rigorous data analysis, the actual practices of elite athletes in contrast to the majority of the altitude studies in the literature that employ fully controlled experimental designs.

The altitude group undertook three to four 2-week altitude blocks comprising living and training at moderate natural altitude (LMTM) or simulated LHTL before National Championships (after block 3) and Commonwealth Games (after block 4). During each LHTL altitude exposure, swimmers spent 9–10 hours per night, in a normobaric hypoxic chamber with N_2 enrichment or an altitude tent with reduced O_2 concentration, and trained as normal in Canberra, Australia (LHTL, 2,600–600 m). Blocks 1 and 3 comprise 10 nights of simulated LHTL, whereas blocks 2 and 4 consisted of a combination of LHTL altitude for 5 nights, followed by 5 days of living and training in Thredbo, Australia (LMTM, 1,350 m). Hemoglobin mass and pool testing were performed under normoxic conditions in Canberra for the

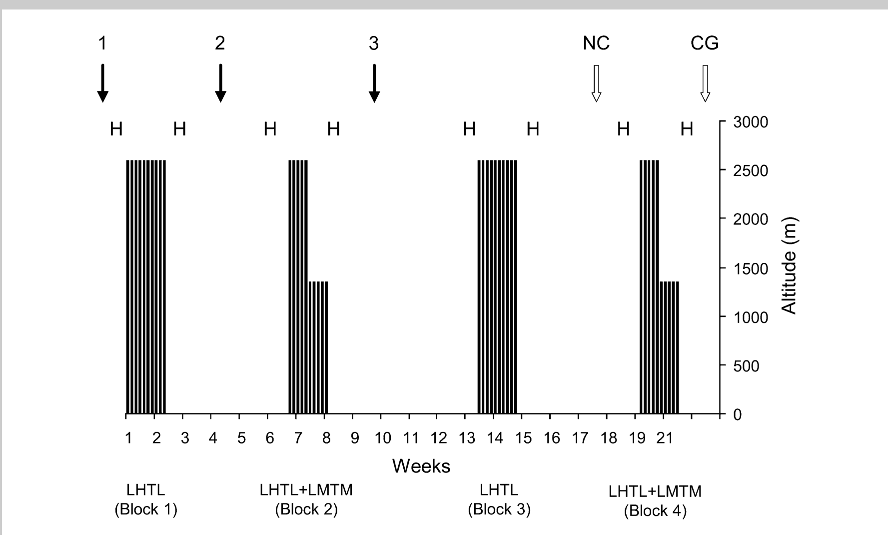

Figure 1. Time line of altitude training (living and training at moderate natural altitude [LMTM], 1,350 m) and exposure (live high-train low [LHTL], 2,600 m) in preparation for National Championships (NC) and Commonwealth Games (CG). Hemoglobin mass (H) was measured before and after blocks 1–4, and training performance tests (7 × 200-m step test and over distance time trial; tests 1, 2, and 3) were completed before blocks 1, 2, and 3.

altitude group, with only group 1 performing the training performance tests in the pool (modified 7 × 200-m step test and over distance time trial). All swimmers had their serum iron levels monitored routinely, and those with ferritin concentration less than 30 ng·mL^{-1} ($n = 2$) were given oral iron supplementation (Ferrogradumet; Abbott Australasia, Botany, Australia; 105 g elemental iron, daily for 3 months). The control group did not receive any altitude exposure and lived and trained as normal in Canberra (600 m) for the duration of the study. They did not participate in the hemoglobin mass or training performance tests and served as the control group for competition performance only.

Subjects

Eighteen elite male and female swimmers (21.1 ± 3.0 years, mean ± *SD*) were monitored over a typical 21-week preparation before national and international competitions. Swimmers were assigned by their team coach to the altitude group (group 1: 5 men and 1 woman; group 2: 3 women) who completed three to four 2-week altitude blocks or a group who trained as part of the same squad but received no altitude exposure ($n = 9$; 6 men, 3 women). Block 4 was completed by a subgroup of the altitude group ($n = 6$), who were selected to compete at the Commonwealth Games. All swimmers were scholarship holders at the Australian Institute of Sport and in regular training (~10 pool sessions/week). The group allocation was not experimentally randomized; however, the international points score (IPS) system used by the Fédération Internationale de Natation was employed to compare the performances of each group. The IPS ascribes a point score (range 0–1,100) to each swim time scaled up or down from 1,000 points based on the all time fastest performance in each event. Scores above 1,000 are considered world class. The mean baseline IPS from the National Championships were not substantially different between the altitude group (973 ± 58 points) and the control group (955 ± 30). These scores equate to 88.4 ± 5.3% and 86.8 ± 2.7% of the maximum IPS, respectively. Written consent was obtained from subjects after they were informed of the experimental procedures and possible risks involved with participation in the investigation. The study was approved by the Ethics Committee of the Australian Institute of Sport and the Committee for Ethics in Human Research at the University of Canberra.

Procedures

Competitive Performance. Performance was evaluated using official race times from 2 annual Australian National Championships and compared between the altitude group ($n = 9$) and the control group ($n = 9$). Competition race times from the Commonwealth Games (Melbourne, Australia) were also compared for a subgroup of the altitude group ($n = 6$) that underwent a fourth altitude training block and a subgroup of the control group ($n = 5$) that had no altitude exposure before competing. Typical race-to-race variation in international swimming competition presented as coefficient of variation (CV) is 0.8% (20,27).

Hemoglobin Mass (Hb_{mass}). Before and after each of the 4 altitude training blocks, Hb_{mass} was measured in the altitude group using a 2-minute carbon monoxide (CO) rebreathing technique (17). A bolus of CO (1 ml·kg^{-1} body weight) with 3 L of oxygen was rebreathed for 2 minutes. Percent carboxyhemoglobin (%HbCO) was measured in capillary blood at baseline and 6 and 8 minutes after administering the CO bolus. Duplicate capillary blood samples were analyzed on an ABL 700 Series blood gas analyzer (Radiometer Medical, Copenhagen, Denmark). The change in %HbCO (difference between baseline and the average of 6 minutes post inhalation of CO) was used to calculate total Hb_{mass}. Typical error for test-retest reliability using the ABL 700 Series was 1.2%. We estimated the smallest worthwhile change in total hemoglobin mass as 1%, using a standardized small effect size of 0.2 × the between-athlete CV (5).

Training Performance. Modified 7 × 200-m Test. The test consisted of 5 evenly paced 200-m swims of increasing velocity on a 5-minute cycle. Individualized target times for each swim were determined from each swimmer's 200 m personal best time. The first 200-m swim was 30 seconds slower than the personal best time of the swimmer for this distance, with the target time to complete the subsequent efforts decreasing by ~5 seconds for each effort. After the 200 m efforts, the swimmers completed 2 additional broken 200-m swims comprising 2 × 100-m and 4 × 50-m swims, with a 10-second rest period between each 100- or 50-m swim. All swims were conducted in a 50-m pool using the swimmers' main competitive stroke ($n = 3$, freestyle; $n = 2$, breaststroke; and $n = 1$, butterfly) and employed a push start. Elite Australian swimmers routinely perform this test to monitor training performance and calculate training velocities (19).

During each swim, the coach timed the 100-m split and total 200 m time manually. The stroke count on the last lap of each effort was self-reported by the swimmer, and stroke rate calculated by an investigator using the base 3 function on the stopwatch (Model S129-4020; Seiko, Tokyo, Japan). Heart rate was measured immediately at the end of each step with a Polar Heart Rate monitor (Polar Electro Oy, Kempele, Finland), and rating of perceived exertion was self-reported using the Borg 6-20 exertion scale. Blood lactate was measured on a portable lactate analyzer (Lactate Pro; Arkray, Kyoto, Japan) using 5 μL of capillary blood drawn from the earlobe. The 4-mM lactate threshold velocity (V_{LT}) was derived from the data using the average 100 m time and lactate after each step. Typical error for this test is 0.8%, and the reference value for the smallest worthwhile change in V_{LT} is 1% (1).

Training Performance. Time Trial. The over distance time trial involved the swimmers completing a 2,000 m freestyle (or 1,200 m breaststroke) swim in the shortest possible time, with individuals selecting their own pace. During the test, swimmers received feedback on elapsed distance but not time. These swimmers ($n = 4$ freestyle; $n = 2$ breaststroke) routinely perform this test in training. An improvement of 1% in time trial performance was considered the smallest worthwhile change, based on a smallest effect size of 0.2 × the between-athlete CV (5).

Statistical Analyses

To overcome the limitations of traditional statistical significance testing, which uses an arbitrary p value derived from a null hypothesis test, we used magnitude-based inferences and precision of the estimate to determine probabilities of practical significance (4). This method allows for detection of small effects of clinical or practical importance and is particularly useful in an elite athletic population where small changes can make a large difference to performance. All raw measures were log transformed for the analyses, to reduce any bias arising from nonuniformity of error, and back transformed to obtain mean ± *SD* in raw units. Mean effects (%) and precision of the estimate (90% confidence limits, CL) were calculated via the unequal variances t statistic computed for change scores between pre- and posttests.

The probability that the true value of the effect was practically beneficial, trivial, or harmful accounted for the smallest worthwhile difference, observed difference, and typical error of measurement (13). Effects were deemed unclear if the confidence interval overlapped the thresholds for both benefit and harm, and only effects greater than 75% likelihood were considered substantial. The smallest worthwhile change in performance was 0.5 × within-athlete CV for competitive performance, which is 0.4% in elite swimmers (20,27). For measures not directly related to performance, the smallest worthwhile change was calculated as a standardized small effect size of 0.2 × the between-athlete CV (5). Pearson's correlation (r) was calculated by linear regression and interpreted based on a scale of magnitudes (5) with thresholds of small (0.1), moderate (0.3), and large (0.5). Typical error of measurement was calculated from the square root of the *SD* of the effect and presented as a percentage. True individual responses were calculated from the square root of the square of the standard deviation of the effect minus the square of the standard deviation of the control group.

Results

Competition Performance

The altitude group did not swim substantially faster (−0.4%; 90% CL: ±0.9%) in the National Championships compared with the previous year and swam slower at the Commonwealth Games 6 weeks later (0.6%; ±0.6%). The group that received no altitude exposure swam substantially faster in the National Championships (−0.9%; ±0.5%) but substantially slower in the Commonwealth Games (1.2%; ±0.9%). There was no substantial difference in mean improvement between the groups at the National Championships (0.5%; ±1.0%); however, this level of imprecision means that some swimmers swam substantially faster (−0.5% of performance time), whereas other swimmers swam substantially slower (+1.5%). Similarly, in those swimmers who competed at the Commonwealth Games, there was no substantial difference between the groups (−0.6%; ±0.9%).

Typical race-to-race variation in performance, modeled as a CV for the control group, was 0.6% between successive National Championships and between the National Championships and Commonwealth Games.

Hemoglobin Mass

The different combinations of natural and simulated altitude yielded on average a trivial to small mean increase (0.9%; 90% CL: ±0.8%) in Hb_{mass}. Over each of the single altitude exposures, Hb_{mass} was substantially increased after block 2 (2.3%; ±1.7%) but was not substantially changed after block 1 (−0.3%; ±1.7%), block 3 (0.7%; ±1.9%), or block 4 (0.3%; ±1.8%).

Substantial individual variation in change in Hb_{mass} was evident after each of the altitude training blocks, with some swimmers showing substantially increased and others substantially decreased Hb_{mass} after each block (Figure 2). None of the swimmers exhibited a consistently increased or decreased Hb_{mass} after each block, with a variable pattern of changes in Hb_{mass} across each of the four 2-week blocks. The magnitude of the true individual response in the change in Hb_{mass} was 2.6% (90% confidence interval: −2.7 to 4.5%). Small mean effects and individual responses of similar magnitude to the typical error indicate that there is unlikely a substantial mean improvement in Hb_{mass} after a single bout of altitude training or exposure.

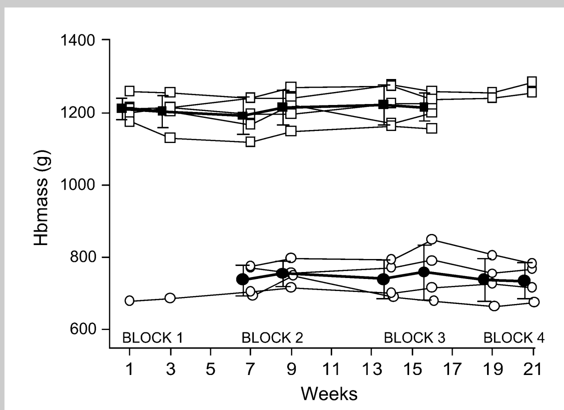

Figure 2. Individual data for hemoglobin mass were measured before and after each block for men (squares) and women (circles). Group mean ± *SD*s are represented by a darker line with solid symbols for men ($n = 5$) and women ($n = 4$) and have been offset for clarity. Hemoglobin mass shows trivial to small mean changes over each of the 4 blocks, with a substantial increase after block 2.

Table. Change in 4-mM lactate threshold velocity and time trial performance (mean ± *SD*) over tests 1, 2, and 3.

	Lactate threshold velocity ($s \cdot 100\ m^{-1}$)			Time trial (min:s)		
	1	2	3	1	2	3
Mean ± *SD*	70.9 ± 5.8	70.3 ± 5.5	69.6 ± 5.0	21:38 ± 3:16	21:33 ± 3:47	21:09 ± 3:25
Tests 2–1	−0.8% (0.4%)			−0.7% (3.3%)		
Tests 3–2		−1.0% (1.8%)			−1.7% (1.9%)	
Tests 3–1	−1.7% (1.9%)*			−2.4% (2.0%)*		

*Small mean improvement (±90% CL) from test 1 to 3 indicates training performance tests were faster after 2 altitude blocks, *n* = 6; 5 men, 1 woman.
CL = confidence limits.

Training Performance

The data for 4-mM lactate threshold velocity (V_{LT}) and the combined over distance time trial (2,000 m freestyle or 1,200 m breaststroke) are presented in the Table. There were small improvements in V_{LT} (1.7%; 90% CL: ±1.9%) and time trial performance (2.4%; ±2.0%) between tests 1 and 3 (after 2 altitude blocks), with trivial differences between successive tests. Time to complete the 2,000 m freestyle trial ($n = 4$) was 23:44 ± 0:28 minutes (mean ± *SD*) for test 1, 23:56 ± 1:07 minutes for test 2, and 23:18 ± 0:55 minutes for test 3, and the 1,200 m breaststroke time trial ($n = 2$) was swum in 17:27 ± 0:11 minutes for test 1, 16:49 ± 0:02 minutes for test 2, and 16:50 ± 0:00 minutes for test 3.

Improvement in time trial performance was moderately correlated to the change in Hb_{mass} after 2 altitude blocks ($r = 0.47$; 90% CL: ±0.41), but the correlation between improvement in 4-mM lactate threshold velocity and Hb_{mass} was not clear ($r = -0.23$; ±0.48).

Discussion

A 4 × 2-week coach-prescribed program of natural and simulated altitude training by national-level swimmers elicited measurable gains in physiology and hemoglobin mass but did not transfer directly to substantially improved competition performance. It seems that a typical altitude-based preparation for swimmers may elicit small mean changes, but with small subject numbers and large CL in this study, we could not reliably detect an improvement in competition performance. Individual responses indicate that some swimmers may benefit substantially from altitude training and some may not. It is therefore important to identify which individuals may respond positively to altitude in terms of improving race performance in competition.

While the importance of obtaining a well-matched control group in studies of athletes is recognized, this can be challenging when dealing with world-class athletes. The observational nature of this study, without fully controlled experimental manipulation, evaluated real-world training practices. This type of study has support in the literature (7). The lack of substantial improvement in competition performance in the altitude group, compared with those only undertaking regular training, indicates that further refinement of altitude training methodology is required.

The trivial to small changes in Hb_{mass} after single and repeated altitude training and exposure in this study is consistent with other studies. A 7% increase in red cell mass was reported in highly trained swimmers after 13 days of simulated LHTL at 2,500–3,000 m (21) and a 5% increase in national-level orienteers after 24 days at 2,500 m (29). However, no change in Hb_{mass} was found in elite cyclists after 12 nights at 2,650 m (3), in elite runners after 20 nights at 2,600 m (24), or in endurance athletes after 30 nights at 3,000 m (2). After LMTM, a 9% increase in hemoglobin mass was observed in elite biathletes after 3 weeks at ~2,000 m (12), whereas no change was found in highly trained athletes after 4 weeks at 1,740 m (10). In the only study to address the responses of 2 elite endurance athletes to LHTL (~2,500 m) before actual competition, individual improvements in red cell mass (3.9 and 7.6%) were reported after 26 days (28). Collectively, these findings indicate that a dose-response threshold exists for substantial increases in Hb_{mass}, and the combined hypoxic exposure in this investigation was below that threshold. Further studies are required to systematically examine the relationship between duration of hypoxic exposure, level of altitude, and the physiological responses in elite athletes to enhance the already top-level performances.

The failure to elicit moderate to large physiological and performance improvements likely relates to an insufficient total (cumulative) exposure to hypoxic conditions. The total exposure (9–10 hours/night for 10 days) of LHTL altitude in this study was below that recommended (>12 hours per day for at least 3 weeks) as the "threshold" to achieve the expected physiological adaptations (23). However, the primary purpose of this study was to evaluate the contemporary training used by elite swimmers. This observational investigation indicates that the current method of altitude training elicits only trivial to small increases in Hb_{mass}. A longer duration of single or repeated altitude exposures may be required to substantially improve competition performance. The question of whether the mechanisms of improved performance after altitude are erythropoietic or nonerythropoietic remains unclear (15). Large individual variation in Hb_{mass} suggests that enhanced performance after altitude training is not attributable to changes in Hb_{mass} alone.

The small overall improvement in 4-mM lactate threshold velocity (V_{LT}) is similar to 1.6% (~1.2 s·100 m^{-1}) reported for Australian National Team swimmers during preparations for the Commonwealth Games (19). The comparable improvement in V_{LT} in this study confirms the notion that measures of fitness can be improved substantially in elite swimmers preparing for major competition. However, the altitude-induced changes were small in nature, and presumably, moderate to large changes are required to elicit additional improvement in V_{LT} over and above regular training.

The over distance time trial (2,000 or 3,000 m) is commonly used to assess and monitor changes in endurance fitness. The small 26 second improvement observed in the 2,000 m freestyle time trial after 2 altitude blocks (LHTL and LHTL + LMTM) is in agreement with a previous study of 13 days at 1,200 m (LMTM) where endurance performance improved by 28 seconds (~1.9%), with no change in maximal oxygen uptake or hematological variables (22). However, this finding contrasts with a nonsignificant (~1.6%) improvement reported after 13 days (16 h/d) of LHTL at >2,500 m (21). Although there are measurable benefits underlying physiological attributes after this method of altitude training, it seems that these improvements can be overridden by other factors that might influence competition performance such as the taper, pacing strategies, illness, injury, fatigue, and psychological aspects.

The progression in competition performance of ~1% is consistent with previous reports for national- and international-level swimmers (20). Both progression and variability in performance time from competition to competition are important considerations for elite swimmers hoping for success in national and international competition (20,27). We assumed that the swimmers in this study were highly motivated in each competition to gain National Team Selection. The reliability of performance in this group compares favorably with 0.8% typical variation reported previously for elite swimmers (27). The high degree of reliability (reproducibility) between swimming competitions allows the detection of small worthwhile enhancements of performance elicited by altitude training. Variability and progression of performance, reliability of measurement, and the impact of training interventions, such as taper and altitude exposure, should all be considered when planning training programs.

Both the altitude group and the control group swam slower in the Commonwealth Games than the preceding National Championships after the final altitude training block. This lack of improvement in competition performance, compared with the 2.2% improvement reported in the final 3 weeks before competition in another study (16), might be a consequence of the very short preparation with the swimmers having to taper and peak for competition twice in 6 weeks. One consideration is whether swimmers would perform better if selection trials were earlier, allowing another full training cycle, or whether trials should be closer to the international competition to allow selection of those swimmers who are in the best form. Anecdotal reports of higher levels of anxiety experienced in the international competitions may also be a factor influencing performance. More research is required on the influence of the timing of selection trials on performance.

Anecdotally, coaches and swimmers consider that some swimmers respond more positively to altitude training and exposure than others. Although the mean changes in performance and physiological measures in this study were trivial, some individual swimmers showed substantial benefit. The large variability within a group may mask substantial changes in individuals in the group (11). In any intervention where the effects are small, it is important to consider the magnitude of both mean changes and individual variation (18). The magnitude of individual responses for Hb_{mass} indicates that not all the swimmers showed a substantial increase in Hb_{mass} from altitude training in this study, and some decreased Hb_{mass} over this period. Coaches can expect some swimmers to have moderate to large improvements in physiology and performance after altitude training. Identifying which swimmers are more likely to benefit substantially from altitude training, and whether it is any more effective than regular training, should be the focus of future investigations.

Practical Applications

We conclude that a coach-prescribed 4 × 2-week program combining real and simulated altitude training in preparation for national championships may elicit small gains in physiology but is unlikely to substantially benefit competitive performance. There was substantial individual response in competitive performance such that some swimmers swam slower, whereas others were substantially faster. The failure to observe substantial improvements raises the question of the benefits of this format (short duration, multiple bouts) of altitude training currently employed in international swimming. Given that altitude programs require a large investment of financial and human resources, sports should evaluate the cost-benefit of these training methods.

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References

1. Anderson, ME, Hopkins, WG, Roberts, AD, and Pyne, DB. Monitoring seasonal and long-term changes in test performance in elite swimmers. *Eur J Sports Sci* 6: 145–154, 2006.
2. Ashenden, MJ, Gore, CJ, Dobson, GP, and Hahn, AG. "Live high, train low" does not change the total haemoglobin mass of male

endurance athletes sleeping at a simulated altitude of 3000m for 23 nights. *Eur J Appl Physiol* 80: 479–484, 1999.

3. Ashenden, MJ, Gore, CJ, Martin, DT, Dobson, GP, and Hahn, AG. Effects of a 12-day "live high, train low" camp on reticulocyte production and haemoglobin mass in elite female road cyclists. *Eur J Appl Physiol* 80: 472–478, 1999.
4. Batterham, AM and Hopkins, WG. Making meaningful inferences about magnitudes. *Int J Sports Phys Perfrom* 1: 50–57, 2006.
5. Cohen, J. *Statistical Power Analysis for the Behavioural Sciences.* 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates, 1988.
6. Dehnert, C, Hutler, M, Liu, Y, Menold, E, Netzer, C, Schick, R, Kubanel, B, Lehman, M, Boning, D, and Steinaker, JM. Erythropoiesis and performance after two weeks of living high and training low in well trained triathletes. *Int J Sports Med* 23: 561–566, 2002.
7. Eston, RG and Rowlands, AV. Stages in the development of a research project: Putting the idea together. *Br J Sports Med* 34: 59–64, 2000.
8. Friedmann, B, Frese, F, Menold, E, Kauper, F, Jost, J, and Bartsch, P. Individual variation in the erythropoietic response to altitude training in elite junior swimmers. *Br J Sports Med* 39: 148–153, 2005.
9. Gore, CJ, Hahn, AG, Aughey, RJ, Martin, DT, Ashenden, MJ, Clark, SA, Garnham, AP, Roberts, AD, Slater, GJ, and Mckenna, MJ. Live high:train low increases muscle buffer capacity and submaximal cycling efficiency. *Acta Physiol Scand* 173: 275–286, 2001.
10. Gore, CJ, Hahn, AG, Burge, CM, and Telford, RD. $\dot{V}O_2$max and haemoglobin mass of highly trained athletes during high intensity training. *Int J Sports Med* 18: 477–482, 1997.
11. Gore, CJ, Hahn, A, Rice, A, Bourdon, P, Lawrence, S, Walsh, C, Stanef, T, Barnes, P, Parisotto, R, Martin, D, and Pyne, D. Altitude training at 2690m does not increase total haemoglobin mass or sea level $\dot{V}O_2$max in world champion track cyclists. *J Sci Med Sport* 1: 156–170, 1998.
12. Heinicke, K, Heinicke, I, Schmidt, W, and Wolfarth, B. A three-week traditional altitude training increases haemoglobin mass and red cell volume in elite biathlon athletes. *Int J Sports Med* 26: 350–355, 2005.
13. Hopkins, WG. Probabilities of clinical or practical significance. *Sportscience* 6: sportsci.org/jour/0201/wghprob.htm, 2002.
14. Levine, BD and Stray-Gundersen, J. "Living high-training low": Effect of moderate-altitude acclimatization with low-altitude training on performance. *J Appl Physiol* 83: 102–112, 1997.
15. Levine, BD, Stray-Gundersen, J, Gore, CJ, and Hopkins, WG. Point: Counterpoint. Positive effects of intermittent hypoxia (live high:train low) on exercise performance are mediated primarily by augmented red cell volume. *J Appl Physiol* 99: 2053–2057, 2005.
16. Mujika, I, Padilla, S, and Pyne, D. Swimming performance changes during the final 3 weeks of training leading to the Sydney 2000 Olympic Games. *Int J Sports Med* 23: 582–587, 2002.
17. Prommer, N and Schmidt, W. Loss of CO from the intravascular bed and its impact on the optimised CO-rebreathing method. *Eur J Appl Physiol* 100: 383–391, 2007.
18. Pyne, DB, Hopkins, WG, Batterham, AM, Gleeson, M, and Fricker, PA. Characterising the individual performance responses to mild illness in international swimmers. *Br J Sports Med* 39: 752–756, 2005.
19. Pyne, DB, Lee, H, and Swanwick, KM. Monitoring the lactate threshold in world-ranked swimmers. *Med Sci Sports Exerc* 33: 291–297, 2001.
20. Pyne, DB, Trewin, CB, and Hopkins, WG. Progression and variability of competitive performance of Olympic swimmers. *J Sports Sci* 22: 613–620, 2004.
21. Robach, P, Schmitt, L, Brugniaux, JV, Roels, B, Millet, G, Hellard, P, Nicolet, G, Duvallet, A, Fouillot, J-P, Moutereau, S, Lasne, F, Pialoux, V, Olsen, NV, and Richalet, J-P. Living high-training low: Effect on erythropoiesis and aerobic performance in highly-trained swimmers. *Eur J Appl Physiol* 96: 423–433, 2006.
22. Roels, B, Hellard, P, Schmitt, L, Robach, P, Richalet, J-P, and Millet, GP. Is it more effective for highly trained swimmers to live and train at 1200 m than at 1850 m in terms of performance and haematological benefits? *Br J Sports Med* 40: e4, 2006.
23. Rusko, HK, Tikkanen, HO, and Peltonen, JE. Altitude and endurance training. *J Sports Sci* 22: 928–945, 2004.
24. Saunders, PU, Telford, RD, Pyne, DB, Cunningham, RB, Gore, CJ, Hahn, AG, and Hawley, JA. Improved running economy in elite runners after 20 days of simulated moderate-altitude exposure. *J Appl Physiol* 96: 931–937, 2004.
25. Snell, PG and Mitchell, JH. The role of maximal oxygen uptake in exercise performance. *Clin Chest Med* 5: 51–62, 1984.
26. Stray-Gundersen, J, Chapman, RF, and Levine, BD. "Living high-training low" altitude training improves sea level performance in male and female elite runners. *J Appl Physiol* 91: 1113–1120, 2001.
27. Trewin, CB, Hopkins, WG, and Pyne, DB. Relationship between world-ranking and Olympic performance of swimmers. *J Sports Sci* 22: 339–345, 2004.
28. Wehrlin, JP and Marti, B. Live high-train low associated with increased haemoglobin mass as preparation for the 2003 World Championships in two native European world class runners. *Br J Sports Med* 40: e3, 2006.
29. Wehrlin, JP, Zuest, P, Hallen, J, and Marti, B. Live high-train low for 24 days increases hemoglobin mass and red cell volume in elite endurance athletes. *J Appl Physiol* 100: 1938–1945, 2006.