Altitude and Team-Sport Athlete Physical Performance:

Relevance and Time Course for Adaptation

Mathew William Hunter Inness

S3069596

This thesis is submitted to fulfil the requirements for the degree of

DOCTOR OF PHILOSOPHY

College of Sport and Exercise Science

Institute of Sport, Exercise and Active Living

Victoria University

Supervisor – Associate Professor Robert J Aughey

Co-Supervisor – Associate Professor Francois Billaut

Physical Performance Unit

Western Bulldogs Football Club

Date: June 2017

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PUBLICATIONS AND CONFERENCE

The following publications in International Peer Reviewed scientific journals and conference presentations are a direct result of the current thesis.

Team-Sport Athletes' Improvement in Performance on the Yo-Yo Intermittent Recovery Test Level 2, but not of Time-Trial Performance, following Intermittent Hypoxic Training. **Inness, MWH**. Billaut, F. Aughey, RJ. Int J Sport Phys and Perf. 2016. 11(1): 15-21

Live-High Train-Low Improves Repeated Time-Trial and Yo-Yo IR2 Performance in Sub-Elite Team-Sport Athletes. **Inness, MWH**. Billaut, F. Aughey, RJ. J Science Med in Sport. 2016. In press

Heavy Resistance Training in Hypoxia improves 1RM Squat. **Inness, MWH**. Billaut, F. Walker, EJ. Peterson, A. Sweeting, AJ. Aughey, RJ. Frontiers in Physiology. 2016. In press.

Conference Presentations

Intermittent Live-High Train-Low Improves Time-Trial and Yo-Yo IR2 Performance in Sub-Elite Team-Sport Athletes. **Inness, MWH.** Asian Pacific Conference for Futsal. 2014

FIGURES

Figure 5.1: Percentage difference in the change in performance from baseline for intermittent hypoxic resistance training (IHRT) compared with placebo (A) in study 3. Between-groups change in Absolute and Relative 1RM strength is expressed.

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ABSTRACT

Team-sport competition is intermittent in nature, with large amounts of low to moderate intensity activity interspersed with periods of repeated high intensity efforts. As well as the locomotor distance, there are game involvements that require excellent strength and power with a high metabolic cost. Therefore, team-sport athletes need a unique mixture of strength, power, speed, endurance, and intermittent running ability.

Altitude training can improve endurance and repeat sprint performance. There is also the potential to increase strength and hypertrophy when resistance training is performed in hypoxia. Taken together, these findings suggest that altitude training has the potential to increase team-sport athlete running performance, however, there is still a number of questions to investigate before establishing more precise guidelines of implementation for team-sport athletes.

The aim of this PhD thesis is to determine whether altitude training improves running performance in team-sport athletes, the time course for any adaptation and how long the benefits remain in this population. Three studies were undertaken to answer these questions.

The first study determined the efficacy of intermittent hypoxic training (IHT), the time-course for physical capacity adaptations, and the time-course for benefits remaining post-IHT. When Australian Footballers performed eleven 40-min bike sessions at 2500-m simulated altitude over 4 weeks, they outperformed the control group (CON) in the Yo-Yo intermittent recovery test level 2 (Yo-Yo IR2) after 6 sessions (27% greater change, Effect size 0.77, 90% confidence limits 0.20;1.33), and immediately after 4 weeks (23%, 0.68, 0.05;1.30). The IHT group change remained likely higher than CON 30 days post (24%, 0.72, 0.12;1.33), but was not meaningfully different 44 days post (12%, 0.36, -0.24;0.97). While the change in 2 kilometre time trial (2-km TT) performance between groups was not different at any stage

throughout, the IHT group maintained performance better after 3 weeks in the 1 kilometre time trial (1-km TT). Haemoglobin mass (Hb_{mass}) was higher post (2.7%, 0.40 -0.40;1.19).

The aim of study 2 was to determine the efficacy of live-high train-low (LHTL) on team-sport athlete physical capacity and the time-course for adaptation.

A group of Australian footballers spent 19 nights at 3000-m simulated altitude.

Compared to pre, Hb_{mass} was *possibly* higher after 15 (3.8%, effect size (ES) 0.19, 90% confidence limits .05 to 0.33) and *very likely* higher after 19 nights (6.7%, 0.35, 0.10;0.52).

For Yo-Yo IR2, LHTL group change was *possibly* greater after 15 nights (10.2%, 0.37, -0.29;1.04), and *likely* greater after 19 nights (13.5%, 0.49, -0.16;1.14).

Both groups improved 2-km TT, with LHTL improvement *possibly* higher than CON (1.9%, 0.22, -0.18;0.62). Only LHTL improved 1-km TT, with LHTL improvement *likely* greater than CON (4.6%, 0.56, -0.08;1.04).

The aim of study 3 was to determine if intermittent hypoxic resistance training (IHRT) is more effective at improving strength, power and increasing lean mass than the same training in normoxia.

Both groups improved both absolute (IHRT: 13.1 ± 3.9%, effect size (ES) 0.60, placebo 9.8 ± 4.7%, ES 0.31) and relative 1 rep max (1RM) (IHRT: 13.4 ± 5.1%, ES 0.76, placebo 9.7 ± 5.3%, ES 0.48) after four weeks. Similarly, at post both groups increased absolute (IHRT: 20.7 ± 7.6%, ES 0.74, placebo 14.1 ± 6.0%, ES 0.58) and relative 1RM (IHRT: 21.6 ± 8.5%, ES 1.08, placebo 13.2 ± 6.4%, ES 0.78).

The change in IHRT was greater than placebo at mid for both absolute (4.4% greater change, 90% Confidence Interval (CI) 1.0:8.0%, ES 0.21), and relative strength (5.6% greater change, 90% CI 1.0:9.4%, ES 0.31 (relative)). There was also a greater change for IHRT at post for both absolute (7.0% greater change, 90% CI 1.3:13%, ES 0.33), and relative 1RM (9.2% greater change, 90% CI 1.6:14.9%, ES 0.49).

The results from these studies confirmed that different altitude training interventions confer different adaptations for team-sport athletes. Short-duration IHT increased Yo-Yo IR2, compared to training-load matched control in only two weeks. An additional 2 weeks of IHT provided no further benefit. In comparison, LHTL didn't have the same magnitude of changes in Yo-Yo IR2, however the changes were greater the more time spent at altitude, with 15 days showing a possible change, while 19 nights had a likely change in Yo-Yo IR2. The changes in Yo-Yo IR2 seen through IHT remained until at least 30-d post-training. In contrast, IHT had no change in TT performance, while LHTL improved TT performance to a greater extent than the control group. If early changes to intermittent running performance are the aim, a short bout of IHT is recommended, however if changes in Hb_{mass} and TT performance are the goal, LHTL is the preferred altitude method. Combining altitude with resistance training proved more effective than placebo for improving absolute and relative strength. This occurred despite a lack of change in power, speed or lean mass. This increased strength despite no change in body composition has relevance to team-sport athletes looking to maintain running performance while increasing strength. Overall, this work suggests that when used appropriately, altitude training modalities have the potential to increase team-sport athlete physical capacity, and thus can be recommended as a training modality for team-sport athletes.

DECLARATION

I, Mathew Inness, declare that the PhD thesis entitled Altitude and team-sport physical performance: Relevance and time course of adaptation is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature: Date:

ACKNOWLEDGEMENTS

The move to quit full time work and go back to life as a full time student was a really difficult one, and one that I couldn’t have done without the support of so many people. The knowledge, skills and experiences I have gained over this time has been invaluable, and there are so many people that have helped me through this time, too many to name all of them, although there are a number I want to specifically mention.

Firstly to my Principal Supervisor, Associate Professor Rob Aughey. I first came across Rob a long time ago during my undergrad degree at VU, and came across him a number of times over the years. I didn’t imagine at the time that I would go on and do a PhD with Rob as my Principal Supervisor, but am so glad I have. Rob has taught me so much about altitude, physiology and research in general. He has given me the ability to think critically, and helped make me the scientist that I currently am. Not only are you my supervisor, but you are also now a good friend.

My Co-Supervisor Associate Professor Francois Billaut. Even though Francois moved to the other side of the world soon after I enrolled as a PhD student, the help you have provided, and the quick feedback you have always given has been really appreciated. Your knowledge in the area is amazing, and has added so much to this thesis.

To everyone I have been involved in at the Western Bulldogs, players, coaches and support staff, you have all been amazing in your support of me finishing my PhD. In particular to Bill Davoren, who was the High Performance Manager at the Bulldogs when I started, I didn’t know Bill at the time, but I will always be so grateful to you for emailing me about the PhD when you had never even met me. Without your email I would never have known about the PhD, and wouldn’t have had the opportunity to apply for it. All the other staff I have worked with during my time at the Bulldogs, thanks for all your help and support.

To our PhD working group, in particular Ali Esmaeili, Alice Sweeting, Amber Rowell, Brendan Lazarus, Emily Walker, George Elias, Jackson Fyfe, Kristal Hammond, Matt Varley, and Ramon Rodriguez. Thanks to you all for helping with study designs, supervising sessions, chatting about Sport Science and everything involved with going through a PhD. It has been great, and it is great that we have all either finished, or are close to finishing now. I couldn't ask for a better group to do a PhD with.

To my James McMahon, Raku Shimokowa and Jan Lemon. You three were an amazing help for me during my Resistance Training study in helping run sessions, and were great assistants throughout this study.

To all my participants, and everyone who has helped me with the studies in even the smallest ways, I appreciate your help, and hope you have also learnt something and got something out of your involvement.

And saving the best for last, my wife Jo, and my boys William and Jakob. Firstly to William and Jakob, thanks for being the most boisterous, fun, and energetic boys I could ever want. Coming home late made it all worthwhile to have you both full of energy and happy to see me. I couldn't ask for better boys, even though you drive your mum and I mad most of the time, we love you so much and wouldn't have it any other way. To Jo, to allow me to go back to full time study, I can't thank you enough for supporting me thought this. To support the family while I went back to a PhD scholarship was tough at times, and I will always remember it. I can't imagine how you managed to look after our two crazy Inness boys during all my long hours working at the club and staying in the altitude hotel, I love you more than words can describe and will remember your support during this time.

LIST OF ABBREVIATIONS

AF	Australian Football
AFL	Australian Football League
AU	Arbitrary Units
BFR	Blood Flow Restriction
BPM	Beats Per minute
BV	Blood Volume
CL	Confidence Limits
CO	Carbon Monoxide
CON	Control Group
CSA	Cross Sectional Area
d	Days
EPO	Erythropoietin
ES	Effect Size
FiO_2	Fraction of Inspired Oxygen
g	Grams
Hb_{mass}	Haemoglobin Mass
HIF	Hypoxia Inducible Factor
$hrs.d^{-1}$	Hours per day
IHT	Intermittent Hypoxic Training
IHRT	Intermittent Hypoxic Resistance Training
LHTH	Live-High Train-High
LHTL	Live-High Train-Low
LLTH	Live-Low Train-High
MAS	Maximal Aerobic Speed
Mins	Minutes
mL	Millilitres
O_2	Oxygen
PCr	Phosphocreatine
Q	Cardiac Output
RBC	Red Blood Cell
RM	Repetition Maximum

RPE	Rating of Perceived Exhaustion
SD	Standard Deviation
SpO_2	Oxygen Saturation of the Blood
SV	Stroke Volume
TS	Team-Sport
TT	Time-Trial
VFL	Victorian Football League
$\dot{V}O_{2max}$	Maximal Oxygen Uptake
$v\dot{V}O_{2max}$	velocity at Maximal Oxygen Consumption
Yo-Yo IR2	Yo-Yo Intermittent Recovery Test Level 2
W	Watts
$W.kg^{-1}$	Watts per kilogram of body weight
wk^{-1}	Per Week
°C	Degrees Celsius

1 INTRODUCTION

Field based team-sports including Hockey, Soccer and Australian Football (AF) are intermittent in nature, with low to moderate intensity activity interspersed with repeated high intensity efforts (Aughey, 2011). This activity profile calls for team-sport athletes to have a high aerobic capacity, excellent intermittent running performance combined with the ability to perform high-speed efforts. The ability to undertake repeated high intensity efforts is dependent on the available stores of phosphocreatine (PCr) (Gaitanos et al., 1993), with the regeneration of PCr achieved solely through aerobic pathways (Harris et al., 1976). Therefore, a high aerobic capacity is needed for the low to moderate intensity activity, but also to regenerate the PCr to perform the repeated high intensity efforts. To confirm the importance of physical capacity for team-sport performance, higher performing individuals achieve better results in both Time-Trials and the Yo-Yo Intermittent Recovery Test level 2 (Yo-Yo IR2) (Mooney et al., 2011, Gastin et al., 2013). As well as the running profile, there are also match involvements including tackling, jumping, and marking that affect the outcome of matches. These activities require strength, high force production and a large power output. Therefore, in addition to the aerobic and intermittent running capacity, team-sport athletes must have excellent strength and power. Any training modality that can increase these physical qualities has the potential to increase team-sport athlete physical performance.

Altitude and/or hypoxic training has been used extensively to increase physical performance in endurance trained athletes, with improvements in aerobic capacity and short, higher intensity exercise performance following altitude exposure (Stray-Gundersen et al., 2001, Faiss et al., 2013). There are also haematological and muscular adaptations that occur through altitude exposure (Zoll et al., 2006, Gore et al., 2007, Garvican et al., 2012). These changes all have relevance for team-sport athletes.

Furthermore, team-sport seasons can last for over six months (www.afl.com.au, 2016), whereas the length of time the benefits of altitude remain are yet to be determined, with no study tracking team-sport athletes for an extended period of time post study to determine how long benefits may last. This has obvious connotations for team-sport athletes, as unlike endurance athletes who must peak for a single competition, team-sport athletes must remain at or near peak physical performance for months on end.

There is very little research on team-sport athletes and the effects of resistance training and hypoxia, in particular using the type of resistance training protocol used by most team-sport (TS) athletes, which is using loads greater than 70% 1RM.

Resistance training using blood flow restriction (BFR) has increased strength and hypertrophy more than the same training without BFR (Takarada et al., 2000b). With BFR, a pressure cuff is attached to the proximal end of the upper arm or leg and inflated to restrict blood flow to the limb (Takarada et al., 2000b). Blood flow restriction training is usually performed at low intensities of 30 to 50% 1RM and higher volumes of around 15 to 20 reps (Takarada et al., 2000b).

Blood flow restriction causes many perturbations in the muscle, only one of which is hypoxia. By restricting blood flow to the muscle, the restricted tissue is placed in an ischemic state, which leads to hypoxia.

There are limitations to BFR when using traditional RT exercises such as squats, deadlifts and bench press. Firstly, it is only possible to restrict the limbs; therefore a large proportion of musculature used during these exercises is not in a hypoxic state. Further, as BFR usually employs low intensity RT, the changes in cross sectional area and strength gains may not be accompanied by a concomitant increase in connective tissue strength, due to decreased mechanical loading through low intensity RT (Scott et al., 2015a). Therefore the strength of muscles and connective tissue will adapt disproportionately, resulting in an increased risk of musculotendinous injuries when higher force is placed on the structures, which occurs with athletes in training and competition.

Although currently unknown, there is the possibility that increasing the strength of the muscle without allowing the tendons adequate time to adapt to this increased force production of the muscle may result in an increased risk of musculotendinous injuries. Due to these limitations in BFR, it is possible intermittent hypoxic resistance training (IHRT) may be more suited for athletes, as all musculature is exposed to the same level of hypoxia, allowing adaptation to occur at the same rate, and the high force production during training will also strengthen connective tissue to aid in injury prevention.

The only research on team-sport athletes and IHRT used low loads, with this research successful at increasing strength more than the same training close to sea level (Manimmanakorn et al., 2013). It is clear that many of the physical capacities important to team-sport athlete performance may benefit from altitude exposure. Most altitude studies use elite endurance athletes, however there are many unique characteristics for team-sport athletes when compared to elite endurance athletes that need to be examined before the relevance of altitude training for team-sport athletes is verified. Some of these include the length of the season, the weekly nature of matches, the intermittent, high intensity activity profile, and the strength and power requirements of the competition.

1.1 Statement of the problem

As well as skill and tactical ability, team-sport athletes require endurance, intermittent running ability, strength and power. When determining the efficacy of altitude for team-sport physical performance, all of these facets of physical capacity must be examined. As no research has looked at all of these areas on team-sport or strength trained athletes, it is important to examine these facets before recommending altitude training for team-sport athletes. The majority of research has been on endurance athletes, or untrained population.

2 REVIEW OF THE LITERATURE

2.1 Introduction

Elite athletes have been utilizing altitude to enhance endurance performance for decades, with one of the earliest studies on the effects of altitude training on athletic performance dating back to 1967 (Buskirk et al., 1967). More recently, TS athletes have begun utilising altitude training to enhance performance in sports of an intermittent nature, including Australian Football (AF) (McLean et al., 2013b). Despite the extensive research on altitude training, there is no consensus on the best methods to utilise altitude training for improved sea level performance.

Although endurance cycling is similar in some respects to team-sports with a repeated high intensity activity profile (Aughey et al., 2013a), most elite endurance activities have very different movement profiles compared to team-sport competition. Team-sports are intermittent in nature, whereas most endurance athletes require a much more constant effort, in particular endurance running (Angus, 2014). Altitude can be applied in a number of ways for team-sport athletes. Some of these methods include live high train high, (LHTH), where athletes live and train at altitude, live high train low (LHTL), whereby athletes live at moderate altitude and train at sea level, and intermittent hypoxic training (IHT), which is where athletes live at sea level, but train at altitude. Altitude can also be used in combination with resistance training, known as intermittent hypoxic resistance training (IHRT). With this method, athletes undertake resistance training whilst breathing hypoxic air. As the majority of research on altitude training uses endurance athletes, and due to the unique activity profiles of team-sport athletes compared to endurance athletes, determining the efficacy of altitude training for TS athlete physical performance is important.

2.2 Activity profiles and physical characteristics of team-sport athletes

2.2.1 Introduction

The measurement of movement undertaken in team-sports (TS) has become relatively easy and satisfactorily accurate due to the widespread use of tracking devices including global positioning system (GPS) (Aughey, 2011, Coutts et al., 2010), Local Positioning Systems (LPS) (Techie, 2016), multi-camera tracking systems such as Prozone (Buchheit et al., 2014b), and Radio Frequency Tracking (Sweeting et al., 2014). The majority of the research summarized below uses either 5 Hz or 10 Hz GPS, however there is some research that also uses some of the other methods mentioned above. For TS activities, GPS units with a signalling frequency of 5 Hz (5 samples per second) and 10 Hz (10 samples per second) are commonly used. Units with a higher sampling rate have a greater degree of reliability and validity when assessing maximal accelerations, high velocity running, and change of direction movements such as those seen in TS (Jennings et al., 2010).

2.2.2 Movement analysis and physical capacity of Australian Footballers

There are many studies from a range of different sports looking at movement undertaken by TS athletes. Although this thesis has applications to all TS athletes, this literature review will mainly focus on Australian Football (AF) due the large running volume compared to soccer and rugby league, but also the high collisions of AF (Varley et al., 2014). Other codes will be referenced throughout due to the larger body of research available in these codes.

A highly developed aerobic capacity is required for TS athletes for two reasons. Firstly, there is extensive low to moderate intensity movements undertaken by TS athletes during competition, which is predominantly aerobic in nature. Secondly, this lower intensity activity is interspersed with higher intensity efforts (Aughey, 2010, Aughey, 2011). Phosphocreatine plays a critical role in the work completed during repeated high-intensity efforts, with power output in the first few seconds of repeated 30-s sprints occurring in unison with the regeneration of PCr (Bogdanis et al., 1995). The time required for PCr resynthesis is typically greater than rest periods available in competition (Dawson et al., 1997). Therefore the contribution of the aerobic energy system increases to meet the energy demands with each subsequent effort (Bogdanis et al., 1996). It is common for these high-intensity efforts to have rest periods of less than 20 s (Aughey, 2011). Thus, by promoting muscle oxygenation and accelerating PCr resynthesis during recovery, repeat high-intensity performance in TS athletes can be increased (Sperlich et al., 2011, Bogdanis et al., 1996).

2.2.3 Australian Football total distance

The average distance covered in an Australian Football League (AFL) match ranges from 11,700 m to 13,455 m, with between 3,334 m and 3,885 m covered at a high velocity (HiVR, generally classed as >15 km·hr^{-1} or 4.17 m·s $^{-1}$) (Brewer et al., 2010, Aughey, 2010, Coutts et al., 2010, Wisbey et al., 2010). This equates to between 109 and 139 m·min^{-1} of game time (Coutts et al., 2010, Aughey, 2010, Johnston et al., 2012, Mooney et al., 2011, Brewer et al., 2010). Anecdotally however, this total distance can be above 19 kms, with more than 5,000 m considered HiVR, with values as high as 200 m·min^{-1} of game time recorded (unpublished data). Players in the AFL cover more total distance than players in 2nd tier competitions, with 128 ± 12 vs 117 ± 15 m•min^{-1} for AFL players and 2nd tier players respectively (Brewer et al., 2010, Aughey, 2013). A summary of distance covered is reported in Table 2.1. km·hr^{-1}

2.2.4 Other sport total distance

To put the AFL data in context, total distance and m·min^{-1} in soccer is lower than that reported in the AFL. In the English Premier League (EPL), total distance ranged from 10,690 m ± to 10,746 m (Bradley et al., 2013b, Bradley et al., 2013a, Di Salvo et al., 2013). Different top Leagues in different countries appear to have similar total distance, with distances in Australian Professional Soccer of between 10,063 m and 10,100 m, or approximately 111 m·min^{-1} being reported (Wehbe et al., 2014, Burgess et al., 2006). While players cover more distance in lower leagues in the same country, with English League 1 (3rd tier competition) and Championship division (2nd tier competition) covering more total distance than the top tiered EPL (11,607 ± 737, 11,429 ± 816, and 10,722 ± 978 for League 1, Championship and EPL respectively) (Bradley et al., 2013a). These results are in agreement with other research, with 11,102 ± 916 for Championship League, and 10,746 ± 964 for EPL (Di Salvo et al., 2013). This increasing distance with a lower level of competition is possibly due to a greater technical efficiency at higher levels, or different game styles between levels of competition (Bradley et al., 2013a). Metres per minute of game time were not presented in many of these studies; however, dividing the distance by a standard game of soccer of 90 minutes (mins) gives approximately 118 to 128 $m \cdot min^{-1}$ of game time. That said, it should be noted that this is an estimate, as stoppage time is also added on at the end of each game. A summary of total distances in soccer is shown in Table 2.1.

Of the other field based sports, field hockey has similar $m \cdot min^{-1}$ as AF, with approximately 130 $m \cdot min^{-1}$ per player (Lythe and Kilding, 2011). However the total distance is much lower due to the lower game time per player, with only 6,798 ± 2,009 m covered per player over 51.9 ± 17.8 min of game time. Rugby League has one of the lowest $m \cdot min^{-1}$ of the field based sports, with only 97 $m \cdot min^{-1}$ reported (Varley et al., 2014). A number of reasons for the lower distance in Rugby League may be related to the rules and style of play, where the ball must be passed backwards, and the constant front on contacts not allowing free flowing play.

The lower distance covered in Soccer compared to AF could partly be explained by differences in the interchange rule, with only 3 substitutes allowed in soccer, whereas up to 90 rotations are permitted per team per game in the AFL, and unlimited subs in sub elite AF competitions. Increased interchanges allow for increased rest periods, possibly increasing the output from the participants (Orchard et al., 2011). Also in Rugby League, the rules of the game state that the ball must be passed backwards, and as there is constant front on contact with tackling and scrimmages (Kempton et al., 2013), the game is intermittent with much less free flowing play compared to AF and Soccer.

2.2.5 High intensity activity in field based sports

Looking purely at total distance covered greatly underestimates the metabolic cost of intermittent TS competition. Much of the distance covered in TS competition is done at high velocities, with repeated efforts (Aughey, 2011).

Studies have used slightly different thresholds for high velocity running (HiVR). Total distance above 14.4 $km \cdot hr^{-1}$ (4 $m \cdot s^{-1}$) in Australian Football (AF) was 3,885 m in one study (Coutts et al., 2010), and approximately 3,500 m above 4.17 $m \cdot s^{-1}$ (Aughey, 2011), or 34 ± 9 $m \cdot min^{-1}$ in different studies using a slightly different threshold (Aughey, 2010). However, more than 6,000 m above 4.17 $m \cdot s^{-1}$ has been recorded in unpublished research in AF for certain individuals.

Once again, total distances at this speed in professional soccer are less than those reported in AF, with 2,640 ± 762 m, 3,098 ± 761 m and 3,297 ± 663 m covered above 4 $m \cdot s^{-1}$ in English Premier League, Championship, and Division 1, respectively (Bradley et al., 2013a), however when expressed in $m \cdot min^{-1}$, the distance is similar to AF (29 and 36 $m \cdot min^{-1}$ of game time). Although $m \cdot min^{-1}$ is similar in Field Hockey, there is a greater percentage of total distance covered at lower speeds, with only 21.5% of distance above 3.92 $m \cdot s^{-1}$ (Lythe and Kilding, 2011). A summary of high intensity running in TS athletes is shown in table 2.1.

Table 2.1 Distance covered in team-sports. Data expressed as total distance, and metres per minute ($m \cdot min^{-1}$) for low intensity activity (LIA), High intensity running (HIR), and Total distance travelled. [1]m/min are an estimate from game time and total metres, as m/min were not given in original text. [2]Distance was an estimate from stride length and frequency. [3]Total metres are an estimate from $m \cdot min^{-1}$ multiplied by game time. [4]Distances at low and high speed were not reported. [5]Distance is reported per position rather than per player. [6]HIA reported as distance covered above 5.5 $m \cdot s^{-1}$.

Authors	Total LIA (m)	LIA $m \cdot min^{-1}$	Total HIR (m)	HIR m/min^{-1}	Total metres	Average $m \cdot min^{-1}$
AFL						
Aughey 2010	9,011 ± 1,137	89 ± 11	3,334 ± 756	34 ± 9	12,734 ± 1,596	127 ± 17
Coutts et al. 2010	9,060 ± 1,350	76[1]	3,885 ± 885	32[1]	12,939 ± 1,757	109[1]
Dawson et al. 2004	14,084[2]	118[1]	2,891[2]	24[1]	16,975[2]	142[1]
Johnston et al. 2010	8,924[3]	88 ± 7.0	4,562[3]	45 ± 11	13,455 ± 1,764	134 ± 18
Brewer et al. 2010[4]					12,311 ± 1,729	128 ± 12
Australian Soccer						
Burgess et al. 2006	7.2 km	0.08 $km \cdot min^{-1}$	2.9 kms	0.03 kms	10.1 $km \cdot min^{-1}$	0.1 $km \cdot min^{-1}$
Wehbe et al. 2014	7,162	79.6[1]	2,901 ± 903	32.2[1]	10,063 m	111.8[1]
English Soccer						
Bradley et al. 2013	8,083 – 8,310	89.8 – 92.3[1]	2,640 – 3,297	29.3 - 36.6[1]	10,722 – 11,607	119 - 129[1]
Di Salvio et al. 2013	8,044 – 8,172	89.4 – 90.8[1]	2,672 – 2,900	29.7 – 32.2[1]	10,746 – 11,102	119.4 – 123
Field Hockey						
Lythe and Kilding 2011[5]	6,419 ± 477		1,711 ± 442		8,130 ± 360 m	
Rugby League						
Varley et al. 2013[6]	5950 ± 1845	92 ± 15	357 ± 218	5.66 ± 2.88	6276 ± 1950	97 ± 16

High intensity efforts are important for AF, as these are vital in setting up scoring and the ability to impact the outcome of the game due to match involvements. In AF, the number of efforts over 4.17 $m \cdot s^{-1}$ per match can be as high as 271, with 74 of these efforts reaching a maximum speed of greater than 5 $m \cdot s^{-1}$ (Brewer et al., 2010), however total distance at high intensities or number of accelerations were not stated (Brewer et al., 2010). It should be noted when looking at the higher intensity efforts stated above that 1 Hz GPS units were used in this study, and 1 Hz units greatly underestimate the number of maximal accelerations and high speed running distance (Jennings et al., 2010). Therefore it is likely that the number of efforts reported would be higher than what was actually performed.

Accelerations are a rate of change in velocity over a given time epoch. Accelerations are common in many team-sports, however as with high intensity efforts, there are issues with the reliability of measuring accelerations based of different sampling rates and differences between GPS units (Buchheit et al., 2014a, Jennings et al., 2010). The differences in sampling rate used in studies may partly explain the wide variety of accelerations measured in different studies. The accuracy of measurement using GPS decreases as the speed of locomotion increases in both a straight line and with a change of direction, however a higher sampling rate (number of samples per second) increases the reliability (Jennings et al., 2010). The possible reason for the low reliability for maximal accelerations is the small number of samples taken during a maximal acceleration (Jennings et al., 2010).

Despite the limitations in measuring accelerations, it is important to understand that accelerations are an important component of team-sport athlete activity profiles due to metabolic demands of maximal accelerations.

Using a 1 Hz GPS unit, there were approximately 240 moderate accelerations (change of speed of between 1.11 and 2.78 $m \cdot s^{-2}$) per game reported, with only 10 of these classed as rapid accelerations (increase in speed of more than 2.78 $m \cdot s^{-2}$) (Wisbey et al., 2010).

However it is possible that the reason only 10 maximal accelerations were detected is that 1 Hz units were used, and these units have poor reliability for detecting accelerations compared to units with a higher sampling rate (Jennings et al., 2010). To support this, using a GPS with a sample rate of 5 Hz, 96 ± 41 maximal accelerations were reported in a game of Australian Football (Aughey, 2010). Another reason for the greater number of accelerations detected in the Aughey study is that accelerations only had to be maintained for 0.4 s to register, compared to 1 s for Wisbey (Aughey, 2010, Wisbey et al., 2010). Similarly to the Aughey study, using 10 Hz units, Australian Footballers completed between 82 and 101 maximal accelerations depending on player position during a match (Coutts et al., 2015).

In elite AF, both high velocity running (HiVR) and maximal accelerations are reduced later in quarters and games (Aughey, 2010). This is despite no decrease in total distance or low intensity activity. The decrease in HiVR and maximal accelerations throughout a match may be related to fatigue, but it may also be related to tactics, state of the game or even opposition. Interestingly, low intensity running is not affected later in quarters and games (Aughey, 2010). This is in disagreement with others, who suggest subconscious pacing plays a part in TS athlete match running output (Coutts et al., 2010). It was suggested that reducing efforts at lower speeds permits the maintenance of high speeds as the game progresses (Coutts et al., 2010). Regardless of whether pacing plays a part in TS competition, if physical capacity is increased (through training for example), the drop off in physical output may be minimized later in games and quarters.

The high intensity efforts outlined above often occur in a repeated nature. In AF finals, the majority of maximal accelerations occur with less than 40 s between efforts. With 3.7 ± 3.3 efforts occurring with less than 19 s, 2.7 ± 2.5 with between 20 and 39 s break, and 4.8 ± 3.4 occurring with greater than 40 s between efforts (Aughey, 2011). This indicates that the ability to repeat high intensity efforts is an important factor for TS running performance.

2.2.6 *Physiology of repeated high intensity efforts typical of team-sport competition*

With repeated high intensity efforts, the resynthesis of PCr is needed to maintain exercise intensity, however when recovery periods are short, which is typical in TS competition, PCr is not resynthesised quickly enough to maintain exercise intensity (Gaitanos et al., 1993, Dawson et al., 1997). During a repeat sprint protocol of 10 x 6 s sprints with 30 second break, there is a 57% decrease in PCr concentration after the first six second sprint, showing a high reliance on anaerobic pathways for energy contribution for a single short sprint (Gaitanos et al., 1993). Phosphocreatine contributes approximately 50% of the anaerobic energy contribution to this single 6s sprint (Glaister, 2005). Prior to the 10th sprint, PCr concentration is 51% lower than prior the first sprint, and falls to only 16% of baseline after the 10th sprint (Gaitanos et al., 1993). Mean power output decreased by 26.6% by the 10th sprint, while there was a decrease in ATP of 32% before the last sprint, which remained unchanged post sprint (Gaitanos et al., 1993). There was also a 10-fold decrease in the rate at which glycogen was degraded to lactate in the final sprint compared to the first sprint (Gaitanos et al., 1993). It was estimated that by the 10th 6-s sprint, the ATP production from anaerobic sources was reduced to 35.6% of that estimated during the first sprint. The rapid drop in PCr after a sprint is offset by an increase in the rate of glycolysis, which combined with PCr regeneration, maintains ATP turnover to a sufficient level to perform repeated high intensity activity (Glaister, 2005, Gaitanos et al., 1993).

It is clear that a greater aerobic energy contribution through glycolysis is required to meet the ATP production to maintain exercise intensity in repeated high intensity efforts.

Full resynthesis of PCr takes longer than 30 s (Gaitanos et al., 1993), which is longer than many of the rest periods available between efforts in TS competition (Dawson et al., 1997). As the resynthesis of PCr is oxygen dependent (Harris et al., 1976), the contribution of the aerobic energy system increases to meet the energy demands with each subsequent sprint

(Balsom et al., 1994). Thus, by promoting muscle oxygenation and accelerating PCr resynthesis during recovery, repeat high-intensity running performance can be better maintained (Bogdanis et al., 1996, Billaut and Buchheit, 2013).

2.2.7 Physical capacity and team-sport performance

There are many factors that relate to match running performance in TS athletes, and not all of these factors relate to physical capacity. Other factors, such as tactics, player ability, score line, playing position and opposition all influence match running (Johnston et al., 2012, Rampinini et al., 2007).

In AF, the ability to perform more work appears to discriminate between the better performing teams and individuals. Better performing teams and individuals have a greater activity profile during games (Aughey, 2010, Aughey, 2011), however this does not necessarily mean that fitter players cover more distance in games, as players only move as far as required to perform the skills of that particular game. Better performing teams do however have superior performance in time trials (TT) (Gastin et al., 2013), and the Yo-Yo intermittent recovery test level 2 (Yo-Yo IR2) (Young et al., 2005, Mooney et al., 2011).

Total distance decreased towards the end of games in a team ranked in the bottom 25% of the competition (Coutts et al., 2010). While for a team in the top 25%, total distance covered did not change throughout the game (Aughey, 2010). The higher ranked team covered 127 $m \cdot min^{-1}$ (Aughey, 2010), compared to the lower ranked team which travelled approximately 109 $m \cdot min^{-1}$ (Coutts et al., 2010). Likewise, when comparing players in the elite AFL with state league AF, players in the AFL had higher $m \cdot min^{-1}$ and a greater number of high intensity efforts per minute than stage league players (Aughey, 2013). The drop off in distance covered and high intensity efforts in the state league game cannot be solely contributed to inferior fitness, as different opponents, match style and game situations all play a part in total distance covered (Aughey, 2013). Further, as AFL players had greater rest time during games through time spent on the interchange bench, this allows them to sustain a higher effort whilst on the ground (Brewer et al., 2010).

Aerobic fitness, as measured through the 6-minute run displayed a positive relationship with individual player performance in elite Australian Footballers (Gastin et al., 2013). Player performance in the Gastin et al. study related to coach determined criteria, and not physical criteria. It should be noted that no GPS during matches was reported.

Furthermore, AFL finals have a higher m·min^{-1}, more HIR, and almost double the maximal accelerations compared to regular season games (Aughey, 2011). The greatest increase in maximal accelerations occurred from higher starting speeds, meaning that not only did players spend more time at higher velocities, but they were required to accelerate maximally at these higher running velocities more regularly during finals matches (Aughey, 2011). Further, there were more maximal accelerations with less than 19 s break between efforts in finals. Thus, players accelerate more often, from a higher starting velocity, and with less break between efforts in AFL finals when compared to regular season games (Aughey, 2011). It is possible that players in this study increased their aerobic capacity leading into the finals. Training load increased by approximately 8% in the 4-8 weeks leading into finals games (Aughey, 2011). This was followed by a 12% decrease in training load in the 4 weeks immediately before finals games. Players Ratings of Perceived Exertion were unchanged in finals football when compared to regular season games, indicating players were able to increase their work capacity while maintaining the same perceived effort, supporting the notion of increased aerobic capacity for these players (Aughey, 2011). To support this, improvements in maximal aerobic speed (8.1%) and 40-m sprint times (3.1%) were reported in a group of soccer players who undertook a high intensity interval training block in season. Unfortunately there was no control group, so it is not possible to determine whether these changes were due to a training effect from games, from the intervention, or from the starting fitness levels of the players (Dupont et al., 2004).

On the contrary, high calibre Australian Footballers, as rated by coaches, performed less high intensity running, and covered less $m \cdot min^{-1}$ than lower calibre players in the same team (Johnston et al., 2012). It should be noted that the high calibre players were three years older and presumably more experienced, meaning that efficient running patterns, rather than physical capacity is a possible contributing factor for the lower $m \cdot min^{-1}$ reported.

There is debate as to whether a higher aerobic capacity and match running performance increases team-sport athlete performance. Athletes with a higher aerobic capacity, as measured through the Yo-Yo IR tests compete at a higher level in team-sport competition (Young et al., 2005, Veale et al., 2010, Bangsbo et al., 2008). Regarding match performance, in a group of 9 AFL players, those undertaking more HiVR $m \cdot min^{-1}$ had more ball disposals than players with less HiVR $m \cdot min^{-1}$ (Mooney et al., 2011). Importantly, these players also showed a greater performance in the Yo-Yo IR2 (Mooney et al., 2011). However, only non-key position players, such as wingmen, on ballers and smaller type running players showed this correlation between HiVR and ball disposals. This was thought to be due to the tactical constraints placed upon key position players limiting the space they can move in, whereby running capacity may not be as important as the nomadic type players (Mooney et al., 2011). Thus, limiting the space a player can work within may reduce the importance of HiVR for successful performance. Therefore, it was suggested key position players may not receive the same performance benefit from increased intermittent running capacity (Mooney et al., 2011). They may be better served focusing on developing other physical capacities more likely to improve performance in their position, such as muscular strength and power, repeated sprint ability, speed and tactical awareness (Mooney et al., 2011). In soccer, a training intervention to improve aerobic capacity in season increased the number of ball involvements, doubled the number of sprints, and increased the total distance covered (Abe et al., 2006). A control group had no improvements in any of these areas. The training group also spent more time at a heart rate above 90% max post intervention when compared to the control group; with no differences evident before the training intervention (Abe et al., 2006). Likewise, players with a higher aerobic capacity as measured through the Yo-Yo intermittent recovery test level 1 (Yo-Yo IR1), covered more distance at high intensities in matches (Castagna et al., 2009). Collectively, this indicates that in team-sports aerobic capacity may discriminate between better and lesser performing teams and individuals.

Contrary to the above research, physical capacity is not always directly related to running during games (Mendez-Villanueva et al., 2013). In youth soccer players (who may not have maximised their technical skills yet), physical capacity as measured through an incremental field based running test related to total distance covered during games for strikers only, with all other positions displaying no relationship (Mendez-Villanueva et al., 2013). Interestingly, there was a moderate to large positive correlation for distance covered at low intensities (below maximal aerobic speed (MAS)), but a large to very large negative correlation between MAS and distance covered at high intensities, or above MAS (Mendez-Villanueva et al., 2013). This indicates that in TS competition, other factors such as playing position and tactics have a greater bearing on total distance and intensity than aerobic fitness per se. However, the authors state that although increased capacity will not directly increase the running output during games, it will reduce the individuals running physiological demands, which could protect against fatigue-related decreases in technical skill execution (Mendez-Villanueva et al., 2013). Another possible conclusion is that participants with a lower capacity decrease their low intensity running to allow them to perform the higher intensity running that can be important on the match outcome, thus pacing themselves throughout the game (Coutts et al., 2010). In AF, there is a greater distance above 4 $m \cdot s^{-1}$, more sprints per minute and a higher maximal velocity when losing as opposed to winning a quarter (Sullivan et al., 2014). This same study reported a greater skill involvement when winning quarters, with the conclusion that skill is more important than physical capacity on match outcome (Sullivan et al., 2014). In summary, there are conflicting findings as to whether improved physical capacity translates into greater match activity profiles. However, training modalities that increase aerobic and/or anaerobic capacity may potentially improve TS athlete match running performance, or allow the same work to be performed at a lower relative intensity, thus decreasing and/or delaying fatigue.

2.2.8 Physical capacity, technical performance and fatigue

In Rugby League, technical skill performance is decreased later in games (Kempton et al., 2013), with the number of ball involvements, quality of skill execution as rated by a skilled observer, and the total distance covered decreasing later in games (Kempton et al., 2013). This suggests that fatigue decreases a player's ability to maintain skill, and also the ability to be involved in the play. To support this, passing performance of a soccer skill test decreased in the final 15 mins of a 90 min intermittent running simulation test (Ali and Williams, 2009).

Technical efficiency does not always change in soccer match play in the second half despite a decrease in physical output measured through GPS decreases, indicating fatigue did not impact on technical performance (Carling and Dupont, 2010). The discrepancy between skill efficiency in a skills based test and soccer match play could be related to the athlete's motivation to perform the skill during the skill test, whereas in a match, motivation of winning and performing could be greater than during the test. Although there was no change in technical efficiency, there was a drop of skill-related involvements during the final five mins of games. This was thought to be due to a decline in high-speed running, which did not allow participants to reach as many contests (Carling and Dupont, 2010). In summary, although it remains inconclusive whether fatigue decreases technical efficiency in TS athletes, fatigue appears to decrease the number of ball involvements, therefore decreasing player effectiveness towards the end of games. As highlighted earlier, increasing capacity can delay fatigue, therefore increasing ball involvements, which may increase effectiveness of players towards the end of games.

2.2.9 The importance of strength and power for team-sport competition

As highlighted above, there is an abundance of research regarding activity profiles, aerobic capacity and performance in TS athletes. However, there is very little on how strength and power relate to TS athlete performance. There are many instances where intuitively, strength and power would be important for TS athletes. Some of these instances include physical contests, game involvements and the maximal accelerations described earlier. Some examples include tacking, kicking, marking, bumping, and wrestling (Appleby and Dawson, 2002, Roberts et al., 2008, Deutsch et al., 2007). In elite English Rugby Union, there were 89 ± 21 static exertion efforts by forwards, with a mean duration of 5.2 ± 0.8 s, where a large force is required to push against an opponent (Roberts et al., 2008). In AF, an average of 259 marking opportunities per game have been recorded, with 117 of these contested between opposite teams (Appleby and Dawson, 2002). There was an average of 99 Ruck contests per game, with 51 of these from boundary throw ins, and 48 from bounce downs (Appleby and Dawson, 2002). In contested marking situations, ruck contests and static exertion efforts, players are jostling for the best position on the field. In such situations, the ability to apply a high degree of force to the opposition team, along with optimal execution of the technical skill becomes a determining factor of success. In elite Rugby Union, players perform an average of 23 tackles and 36 to 39 scrimmages per game (Deutsch et al., 2007). Again, this requires a high degree of force to execute effectively. As described above, maximal accelerations occur regularly in AF (Aughey, 2011), while jumping for a mark, sprinting or centre bounce ruck contests all require high power outputs with no external load.

Although minimal research relates to strength and power for many team-sports, it is clear from the activity profiles that highly developed strength and power capacities are of benefit to TS athletes. Consequently training modalities that improve strength and power will help performance in many of these situations during TS matches.

2.3 Hypoxia

Hypoxia can be achieved either through exposure to real altitude, or simulated altitude, through an altitude room. Hypobaric hypoxia (HH) is achieved through a decrease in barometric pressure that is seen through ascent to altitudes above sea level. At sea level, the barometric pressure is approximately 760 mmHg. The percentage of oxygen remains constant at 20.9%, however due to a decrease in barometric pressure, there is a lower partial pressure of O_2, therefore there is less absolute oxygen in the atmosphere, even though the same percentage of oxygen is present. Barometric pressure is dependent upon air temperature, weather, latitude, gravitational pull, and altitude (West, 1996). Barometric pressure falls to approximately 550 mmHg at 2,700 m above sea level (Guger et al., 2005, Storz and Hideaki, 2008, Sandberg and Nayor, 2011). This decreased barometric pressure causes a decrease in the partial pressure of oxygen in the blood as altitude increases. At altitudes commonly seen through altitude training in team-sport athletes, the partial pressure of oxygen in the blood decreases, which causes a cascade of events, which will be discussed in greater details later.

Normobaric hypoxia (NH) is where hypoxia is simulated through a decrease in the percentage of oxygen in the air without a change in barometric pressure through increased nitrogen content. This is the premise for many simulated altitude rooms (Ashenden et al., 1999b).

The object of both HH and NH is to reduce oxygen saturation in the blood. Both methods of hypoxia are successful in decreasing the arterial oxygen saturation to the same extent (Guger et al., 2008, Nishi, 2011). It is thought that the two methods of inducing hypoxemia are interchangeable (Mounier and Brugniaux, 2012). However, it has been suggested that HH induces different physiological responses compared to NH (Millet et al., 2012). These different responses include lower ventilation for HH compared to NH, and a negative fluid balance for NH compared to HH. This has led to a school of thought that hypobaric hypoxia is a more severe condition (Millet et al., 2012). Despite HH being a more severe condition, there is still no consensus that one method of hypoxia is superior to the other when it comes to performance and haematological changes (Millet et al., 2012, Mounier and Brugniaux, 2012).

2.4 Altitude exposure at rest: Physiological response to altitudes commonly used during training and competition by team-sport athletes.

Team-sport athletes from sports such as soccer and rugby are often required to perform at moderate altitude. Some of these venues include Johannesburg in South Africa (approx. 1600 m above sea level), and La Paz in Bolivia (3600 m above sea level) (Aughey et al., 2013b). As well as competing at altitude, many teams now hold training camps at moderate altitudes (McLean et al., 2013b). Hence determining the effects of moderate altitude on TS athletes is of great practical importance. Improved knowledge on the effects of altitude can assist TS athletes in a number of ways, including providing appropriate training stimuli during altitude training camps, optimal altitude dosage for improving both physiological adaptations and performance improvements, acclimation for improved performance at altitude, and best ways to use altitude for sea level performance improvements.

Upon initial exposure to moderate altitude as used by TS athletes, there is a cascade of events within the body that occur due to the changes in either atmospheric pressure (terrestrial altitude), or the decreased availability of oxygen in the air (simulated altitude). Having an understanding of what these changes are, and determining the effects of moderate altitude on team-sport athletes both at rest and during exercise can help with the optimal use of altitude training in team-sport athletes. The following section will describe the molecular, respiratory and cardiovascular responses to hypoxic exposure at rest.

2.4.1 Hypoxia Inducible Factor response

Hypoxia inducible factors (HIF) are proteins that have been described as key players in the hypoxia response (Jewell et al., 2001). The HIF proteins induce specific expression of several genes regulated by hypoxia. These include vascular endothelial growth factor, and transferrin, which can restore blood supply and energy availability to the hypoxic tissue (Jewell et al., 2001). One of these HIF proteins, HIF-1, is made up of two subunits, HIF-1alpha (HIF-1α) and HIF-1beta (HIF-1β). The availability of oxygen in the kidneys and liver is the main regulator of the production of EPO (Rodríguez et al., 2000). Under normoxic conditions, HIF-1α is rapidly degraded which prevents accumulation (Jewell et al., 2001). However when cells are in a hypoxic state, degradation of HIF-1α decreases, and is translocated into the nucleus (Jewell et al., 2001). Here it binds with HIF-1β to form HIF-1, where it begins to accumulate inside the nucleus of the cell (Jewell et al., 2001, Rusko et al., 2004). In cell culture studies, this accumulation begins almost immediately upon exposure to extreme hypoxia, with HIF-1α detectable inside the cell nucleus after only 2 mins (Jewell et al., 2001). Again in cell culture, the half-life of HIF-1 in normoxia is 5 min, while in extreme hypoxia it increases to 30 mins, with the increased degradation time allowing accumulation of HIF-1 within the cells (Huang et al., 1998).

2.4.2 Erythropoietin response to hypoxia

After accumulation, HIF-1α binds to target genes, simulating erythropoiesis, resulting in erythropoietin (EPO) production (Rodríguez et al., 2000, Hahn et al., 2001, Ashenden et al., 2000, Gore et al., 2006). Increased concentration of EPO are vital to stimulate the production of reticulocytes (immature red blood cells) (Ashenden et al., 2000), which increases the oxygen carrying capacity of the blood (Ashenden et al., 2000). The majority of EPO is produced in the kidneys, with a small contribution from the liver (10-15%) (Rodríguez et al., 2000).

The time course for increased EPO production is governed by the level of hypoxia, and the length of hypoxic exposure. An altitude threshold for hypoxic-induced increases in EPO has been suggested at between 2100 and 2500 m (Mackenzie et al., 2008, Rusko et al., 2004). Increased plasma [EPO] can occur after only 114 mins of exposure to 3,000 m simulated altitude, with concentrations continuing to increase in a linear fashion until four hours of exposure, when increases in serum EPO begin to flatten (Eckardt et al., 1989). At greater altitude, this time course is much shorter, with increased plasma EPO occurring after only 84 mins at 4,000 m simulated altitude (Eckardt et al., 1989), with increases continuing in a linear fashion for the duration of a 5.5 hour exposure (Eckardt et al., 1989). Therefore, the greater the hypoxic stimulus, and in turn, the greater the decrease in SaO_2, the greater the [EPO] (Rusko et al., 2004). Further, the amount of time at altitude also governs the release of EPO, with EPO production continuing to increase for up to 5.5 hours into hypoxic exposure (Eckardt et al., 1989). And continuing to rise for a further 90 mins after descent to sea level from 4,000 m altitude (Eckardt et al., 1989).

Chronic elevation of [EPO] stimulates production of Haemoglobin mass (Hb_{mass}) (the oxygen carrying component of red blood cells (RBC)) in the bone marrow (primarily in the iliac crest and sternum for adults) (Ciesla, 2007), potentially increasing maximal oxygen consumption (Levine and Stray-Gundersen, 1997) (Figure 2.1). With increased RBC production, a reduction in plasma volume occurs, ensuring total blood volume remains unchanged (Saunders et al., 2010).

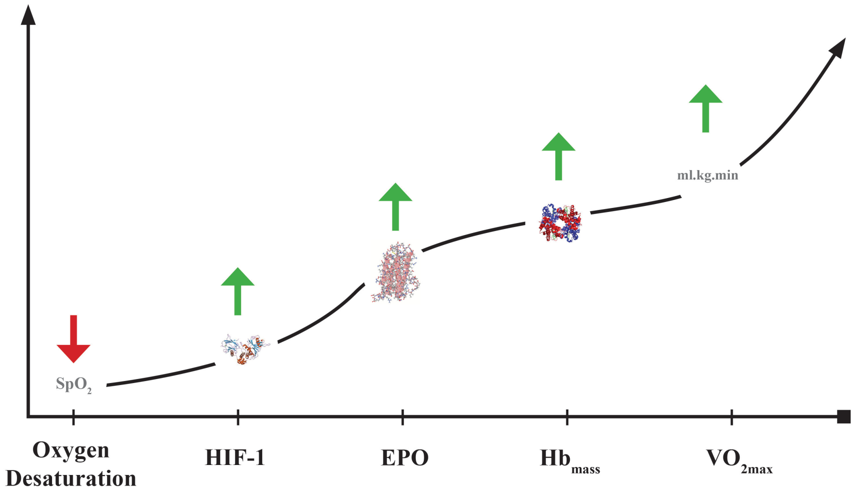


Figure 2.1. Decreased arterial oxygen saturation causes a cascade of events, beginning with an accumulation of HIF-1, leading to increased Hb_{mass}, and potentially increasing $\dot{V}O_{2max}$.

2.4.3 Arterial Oxygen Saturation

Ascent to altitude decreases the percentage of available haemoglobin that is saturated with oxygen, or a decrease in arterial oxygen saturation (S_pO_2) (Clark et al., 2007, Wehrlin and Hallén, 2006, Guger et al., 2008).

In healthy subjects, an S_pO_2 of 82.7 ± 6.8% has been recorded after 5 hours at a simulated altitude of 4,000 m, down from 97.5 ± 0.5% at sea level (Guger et al., 2008). This is substantially less than the SpO_2 at 3000 m, with reports of an S_pO_2 of 89.1% ± 0.3% at midnight, increasing to 92.1 ± 0.3% at 6.00 am (Hahn et al., 2001). The increase in S_pO_2 from midnight through to 6.00 am is a consistent theme. Athletes sleeping at 2,650 m had an S_pO_2 of 92.7 ± 0.2% at midnight, increasing to 94.4 ± 0.1% at 6.00am. In comparison, S_pO_2 levels were 97.7% between midnight and 6am for athletes sleeping at 600 m (Hahn et al., 2001). From the above studies reporting S_pO_2, the greater the altitude, the greater the oxygen desaturation. Over 11 nights of altitude exposure, S_pO_2 values gradually increased for the first four nights, then stabilized (Hahn et al., 2001).

2.4.4 Respiratory and cardiovascular response to acute altitude exposure

There is an increase in heart rate (HR) with acute altitude exposure, with this remaining elevated during a 12 hour exposure to 4,000 m (HR of 68.9 ± 9.3 bpm, 80.3 ± 11.5 bpm, and 81.6 ± 8.8 bpm at sea level, 1 hour into exposure and 11 hours into exposure respectively) (Guger et al., 2008).

The increased HR is caused by an increase in sympathetic activity (Hughson et al., 1994). This elevated HR occurs both at rest (Guger et al., 2005, Guger et al., 2008), and during submaximal exercise to compensate for the lack of O_2 in the blood, as indicated by lower S_aO_2 (Sutton et al., 1988, Mazzeo, 2008). This increased HR ensures global O_2 delivery remains similar to sea level while at rest (Holdsworth and Wolff, 2013). As cardiac output (Q) is equal to HR x stroke volume (SV), resting Q also increases upon initial exposure (Mazzeo, 2008).

Before acclimatization, during prolonged submaximal exercise at high altitude, SV is marginally supressed in comparison to sea level (Wolfel et al., 1991), while there is an initial increase in ventilation due to increasing sensitivity of the peripheral chemoreceptors to hypoxia (Bärtsch and Saltin, 2008). While the mechanisms responsible for decreased SV are unknown, loss of plasma volume may play a role (Wolfel et al., 1991). Lower plasma volume reduces venous return, left ventricular filling, and consequently SV (Mazzeo, 2008).

2.5 Physiological response to chronic altitude exposure

With chronic exposure to altitude, SpO_2 increases over time (Hahn et al., 2001), indicating a clear acclimatisation to chronic altitude exposure. This increased SpO_2 following acclimatisation allows greater oxygen delivery when performing at altitude (Calbet et al., 2003). The following section will discuss the physiological responses that are responsible for acclimatisation to chronic altitude exposure.

2.5.1 Haematological response:

With repeated, short doses of high altitude (4,000 to 5,500 m), reticulocyte percentage, Hb concentration, red blood count and packed cell volume are all increased after 2 to 3 weeks (Rodríguez et al., 2000). Many of these changes remain for up to 2 weeks post altitude exposure (Rodríguez et al., 2000). Within days of being exposed to altitude, resting ventilation and heart rate have increased by more than 25% from sea level (Bärtsch and Saltin, 2008). The increased ventilation rate is due to increased sensitivity of the peripheral chemoreceptors to hypoxia, resulting in a substantial increase in arterial oxygen saturation for the first two week at altitude (Bärtsch and Saltin, 2008).

2.5.2 Chronic respiratory and cardiovascular response:

After 1 to 2 weeks, SV during submaximal exercise declines by around 25%, and remains at these levels for at least another two weeks (Wolfel et al., 1991). While the mechanisms responsible for decreased SV are still unknown, loss of plasma volume may play a role through reduction in venous return (Wolfel et al., 1991, Mazzeo, 2008).

There is a continuing increase in sympathetic activity over time at altitude (Hansen and Sander, 2003). Despite this increased sympathetic activity, maximal HR decreases at altitude, with this occurring at altitudes as low as 2,100 m (Saltin, 1996). This decreased maximal HR is due to an increase in parasympathetic neural activity (Boushel et al., 2001). Which combined with an increased resting HR at altitude, means the HR range at altitude is greatly reduced compared to sea level (Bärtsch and Saltin, 2008). Therefore sea level HR ranges should not be used while exercising at altitude.

After an initial increase, there is a continued rise in ventilation over the first 10-14 days of altitude exposure due to increasing sensitivity of the peripheral chemoreceptors to hypoxia (Bärtsch and Saltin, 2008). This increased ventilation results in substantial increases in S_aO_2 over the first 2 weeks at altitude (Bärtsch and Saltin, 2008). Thus, an increase in ventilation at altitude, combined with an increased Q through higher HR allows similar levels of O_2 as seen at sea level to be transported during rest. This may also be a possible reason why submaximal exercise intensity appears to be unaffected to exposure to altitude (Hahn et al., 2001).

2.5.3 Physiological responses to exercise at altitude

As previously mentioned, S_pO_2 decreases upon initial exposure to altitude (Clark et al., 2007, Guger et al., 2008, Wehrlin and Hallén, 2006). This lower S_pO_2 decreases $\dot{V}O_{2max}$ at altitudes as low as 600 m (Gore et al., 1996).

The changes in S_pO_2 through altitude are greater in endurance trained athletes due to their higher maximal cardiac output (Bärtsch and Saltin, 2008). With chronic endurance training, SV, and in turn cardiac output (Q) increases, while pulmonary capillary blood volume (BV) remains unchanged (Dempsey et al., 1977). This results in erythrocytes being required to cross to the pulmonary capillary at a faster rate during maximal exercise at altitude, which in turn decreases the time for O_2 to diffuse from the alveoli to the erythrocyte (Chapman, 2013). This decreased erythrocyte transit time is shorter than the time needed for haemoglobin to become fully saturated with O_2 in many endurance athletes (Chapman, 2013). Therefore, P_aO_2, and subsequently S_pO_2 decreases to a greater extent in endurance trained athletes during exercise at altitude (Bärtsch and Saltin, 2008), with a decline in S_pO_2 from 89.0 ± 2.9% at 300 m to 76.5 ± 4.0% at 2,800 m reported (Wehrlin and Hallén, 2006). Due to the high aerobic capacity compared to recreationally trained athletes (Casajus, 2001), the drop in S_pO_2 for many team-sport athletes would be greater than that of untrained, or recreationally trained people exposed to moderate altitude. A decrease in S_pO_2 is strongly correlated to a decrease in $\dot{V}O_{2max}$, with 70 to 86% of the decrease in $\dot{V}O_{2max}$ explained by lower S_pO_2 levels (Wehrlin and Hallén, 2006, Ferretti et al., 1997). Conversely, there was no correlation between the individual rate of decrease in S_pO_2 at $\dot{V}O_{2max}$ and individual rate of the decrease in $\dot{V}O_{2max}$, indicating other factors also contribute to a lower $\dot{V}O_{2max}$ at altitude (Wehrlin and Hallén, 2006). The individual difference in P_aO_2 at altitude may be partly due to less hyperventilation in some individuals upon initial altitude exposure (Gore et al., 1996).

The decrease in $\dot{V}O_{2max}$ occurs in a linear fashion, with the change in $\dot{V}O_{2max}$ between 300 m and 1300 m of the same magnitude as between 1800 m and 2800 m (approximately 6.3% per 1,000 m) (Wehrlin and Hallén, 2006). Although there is an increase in submaximal Q while at altitude (Mazzeo, 2008), maximal Q is reduced with acute hypoxia compared to normoxia. Maximal Oxygen Uptake is also attenuated while exercising at altitude. Maximal HR also decreases with increasing altitude because of an increased vagal tone (Hansen and Sander, 2003).

2.6 The application of Altitude training

There are four commonly applied, yet very different methods of altitude training; Live High/Train high (LHTH), Live High/Train Low (LHTL), Live Low/Train High (LLTH, or Intermittent hypoxic training (IHT)), and Intermittent hypoxic exposure (IHE) (short altitude doses while at rest). Performance changes obtained through the first three methods will be discussed in this section, with LHTL and IHT being the main focus.

2.7 Live-High Train-High (LHTH):

Living and training at altitude (LHTH) first became popular after the 1968 Mexico City Olympics, which were held at an altitude of approximately 2,240 m. Live-High Train-High was the first altitude training method used, and is when athletes lived and trained at a moderate altitude (1,500 to 3,000 m) for between two and four weeks (Gore et al., 2007, Friedmann-Bette, 2008). Individual endurance athletes have been the predominant users of LHTH, however team-sport athletes have begun using this method to increase physical performance (Girard et al., 2013).

2.7.1 Sea level performance changes following LHTH

Performance changes at sea level following LHTH are equivocal. A number of studies point to an increase in performance (McLean et al., 2013b, Daniels and Oldridge, 1970, Chapman et al., 2013a), however others fail to show any improvement in sea level performance following LHTH (Levine and Stray-Gundersen, 1997, Robertson et al., 2010c).

A summary of LHTH studies is shown in table 2.2. As mentioned, most LHTH studies are on elite endurance athletes. One of the earliest altitude studies showed improved race performance in elite runners following a LHTH training camp at 2,300 m (Daniels and Oldridge, 1970). In total, the LHTH exposure lasted for six weeks, and was broken up into 2x14, and 2x7 day blocks, with between 5 and 11 days break between blocks. Unfortunately, very little information was given on the methods in this study, with no training data or information on the type of training undertaken. Even though no control group was used for this study, these athletes had recently completed a competitive season, and considering their already high levels of performance, it was thought that they were close to maximal fitness; therefore improvements in performance at this stage of the season are difficult to achieve.

Considering there was an increase in $\dot{V}O_{2max}$, which was accompanied by 14 Personal Best times, including two World Records in the 1 Mile shows a positive effect of the training camp despite the lack of a control group (Daniels and Oldridge, 1970). However, whether the improved performance post-camp was due to the altitude stimulus or simply the training camp is impossible to determine.

More recently, in elite runners following a training camp at four different altitudes (1,780 m, 2,085 m, 2,454 m and 2,800 m), 3-km TT performance increased in the 2,085 and 2,454 m groups only (Chapman et al., 2013a). This was not a classic LHTH study, with all groups performing the higher intensity interval training sessions at the same moderate altitude (1,250 m), with the low and moderate intensity sessions held at 1780 to 3000 m (Chapman et al., 2013a). The hypoxic dose between groups was different due to the living altitude being different for all groups, despite the training component being performed at the same altitude for all groups. The authors described this study as LHTL, however, as all living and training was at an altitude of at least 1,250 m, it cannot be described as LHTL. Furthermore, there was no sea level control group, therefore it cannot be established whether the change in 3-km TT performance in the two middle groups was due to the altitude exposure, or the training in general. Increased altitude causes an increased erythropoietic response (Ri-Li et al., 2002), however, all four groups displayed altitude-induced erythropoiesis, meaning the altitude was sufficient to create a response. Further, although all groups trained at the same altitude, the hypoxic stimulus may have been too great for the group living at the highest altitude to recover adequately to allow the same training as the other three groups. Therefore the highest group may have found the training tougher, creating more fatigue and thus not allowing optimal adaptation. It is clear from this study that inducing an erythropoietic response is important, but not the only reason for changes seen through altitude.

Researchers have used an observational case study on two Olympic level endurance athletes (a race walker and marathon runner) prior to an Olympic games (Pugliese et al., 2014). The athletes lived at 2,030 m above sea level for three weeks, with performance testing undertaken before, during and after exposure. Post LHTH there was an increase in race performance, with both participants subsequently winning Olympic Gold medals shortly following the LHTH camp. A large proportion of the training prior, during and post LHTH was documented in this study. Interestingly, and in contrast to other research (Gore et al., 1997), these two participants were able to maintain training intensity even while training at altitude. A possible reason as to why some studies fail to find a change in performance post LHTH is the decreased intensity possible whilst performing at altitude (Aughey et al., 2013b). It was concluded that the reason for their ability to maintain a high level of training was due to their familiarity with training at altitude (Pugliese et al., 2014). It should be noted that external training load was higher during the altitude training camp than before or after the camp, and being a case study there was no control group, so once again, it is not possible to determine whether these changes were due to the LHTH intervention, or the training camp in general.

Not all LHTH studies have improved performance more than sea level training. In contrast to the studies mentioned above (Pugliese et al., 2014, Gore et al., 1997), despite changes occurring in $\dot{V}O_{2max}$ and red cell mass following 4 weeks of LHTH, there was no change in performance compared to a control group, while a group exposed to LHTL increased 5,000 m TT performance (Levine and Stray-Gundersen, 1997). The Levine and Stray-Gundersen study compared a LHTH, LHTL and sea level only group for 5,000 m performance. Training was well controlled, with participants undertaking a 2 week lead in, as well as four weeks of sea level training prior to altitude exposure, this ensured that participants were in a similar training state prior to the study beginning (Levine and Stray-Gundersen, 1997). With a sea level control, this study was better placed than the above-mentioned studies to determine the effects of altitude exposure on performance as opposed to the training camp effect. As mentioned, training was described in this study, and although not stated as significant by the authors, the differences in training between groups during the altitude intervention may be meaningful, as the sea level group training volume was less than the two altitude groups (Levine and Stray-Gundersen, 1997). Unfortunately the authors didn't quantify the differences in training between groups, but based off the published figure, it appears the sea level group undertook 300 to 350 mins of training per week, while the altitude groups both performed 400 to 450 mins per week. The non-significant, but possibly meaningful difference in training may have contributed to changes in performance.

Of the limited research in team-sport athletes following LHTH, Australian Footballers improved 2-km TT performance following 19 nights of LHTH (McLean et al., 2013b). This improvement was *likely* greater than the control group change (2.1 ± 2.1% greater change); however the training load was *almost certainly* higher for LHTH compared to control (24 ± 10%). Because of the difference in training load between groups, the authors used training load as a covariate, with the change between groups only possibly different after allowing for differences in training load (1.5 ± 4.8%) (McLean et al., 2013b). As mentioned above, this highlights the importance of taking into account training load in training studies.

In summary, the studies finding changes in sea level performance generally have methodological issues such as no control group, or differences in training load between groups that make it difficult to isolate the effects of the LHTH intervention on performance changes. Further, there are issues with prescribing a LHTH intervention for TS athletes. These issues include cost of sending a large squad and support staff away for the required three to four weeks, the effect that training at altitude has on the training intensity required, and also the lack of facilities at sufficient altitude to run a normal training block for these athletes.

Aerobic performance at altitude is supressed, with a decrease in both $\dot{V}O_{2max}$ and exercise intensity of approximately six to seven percent per 1,000 m of increasing altitude (Clark et al., 2007, Wehrlin and Hallén, 2006). This has been discussed in greater detail in section *2.5.3*. This decreasing exercise intensity has implications for adaptation to training, in particular for TS athletes who are required to train at a high intensity to handle the high intensity movement required during games (Aughey, 2011). In summary, for maximal performance enhancement for team-sport athletes, LHTH as a strategy appears to be suboptimal.

2.7.2 Physiological adaptation to LHTH

2.7.2.1 Haematological changes

Although not the sole mechanism for improved performance, haematological changes are important for enhanced endurance performance due to changes in the oxygen carrying capacity of the blood (Levine and Stray-Gundersen, 2005). Although originally showing an r of only 0.137 between Blood volume (BV) and an increase in $\dot{V}O_{2max}$ (Levine and Stray-Gundersen, 1997), a review established an r of between 0.52 and 0.92 from six articles, indicating a strong correlation between BV and maximal oxygen uptake (Sawka et al., 2000). There is also a strong correlation with improved $\dot{V}O_{2max}$ and an increase in Hb_{mass}. In fact, the correlation between $\dot{V}O_{2max}$ and Hb_{mass} is stronger than BV and $\dot{V}O_{2max}$ (Kanstrup and Ekblom, 1984). Further, in a study of 145 endurance athletes, there was a large correlation for change in Hb_{mass} and change in $\dot{V}O_{2max}$ following a LHTH intervention (Saunders et al., 2013). In fact the increase in $\dot{V}O_{2max}$ was more than half the magnitude of the increase in Hb_{mass} (Saunders et al., 2013). As $\dot{V}O_{2max}$ is vital for endurance performance (Coyle, 1995), any training modality that increases $\dot{V}O_{2max}$ has the potential to improve endurance performance, and therefore team-sport physical performance.

For altitude exposure, whether it be LHTL or LHTH, a minimum dose is required to elicit an erythropoietic response, which if elevated long enough may lead to increases in red cell mass, erythrocyte volume and Hb_{mass} (Wilber, 2007, Gore et al., 2007). Therefore, due to the large accumulated time at altitude, haematological changes generally occur following LHTH (McLean et al., 2013b, Garvican et al., 2012, Garvican-Lewis et al., 2015, Levine and Stray-Gundersen, 1997). Increases in plasma EPO concentration occur after only 90 mins of exposure, peaking 3 h after hypoxic exposure (Rodríguez et al., 2000).

It is possible that changes to Hb_{mass}, and in turn oxygen carrying capacity occur quite early through LHTH. In fact, following 19 nights at 2,760 m, Hb_{mass} increased by 2.9% (90% CL: 1.5-4.2%) after only 11 days, which increased to 3.5% (90% CL: 1.6-5.3) (Garvican et al., 2012). This change in Hb_{mass} after 11 nights is earlier to that in most LHTH research. For example, 19 days exposure to 2,130 m altitude resulted in a *likely* greater change in Hb_{mass} (2.8 ± 3.5%) than a control group in elite Australian Footballers (McLean et al., 2013b). However, as stated earlier, training load was *almost certainly* higher for LHTH than the control group, therefore the extra training load may have contributed to the greater increases in Hb_{mass} for the LHTH group. With training load as a covariate, Hb_{mass} was only possibly higher for LHTH than control (2.2% ± 7.7%) (McLean et al., 2013b). The same researchers repeated the study 12 months later with a group of the same TS athletes, with Hb_{mass} again increased (McLean et al., 2013a). Although the group mean change was similar from year to year, there was no correlation between individual changes from year to year, indicating that in elite footballers, there is wide variety in the individual response, with changes not consistent for individuals from year to year (McLean et al., 2013a). Therefore, the theory of "responders" and "non-responders" to altitude appears too simplistic regarding Hb_{mass} changes in TS athletes (McLean et al., 2013a), this is due to things including training and health status affecting the performance outcomes of altitude intervention.

Not all LHTH studies have reported changes in Hb_{mass}. In a group of 8 elite male track cyclists there was no change in Hb_{mass} or $\dot{V}O_{2max}$ following 31 days of LHTH (Gore, 1998). The authors concluded that due to the already high level of Hb_{mass} and $\dot{V}O_{2max}$, participants had less scope for improvement as they were already near their physiological limit (Gore, 1998). Contrary to this, others have found elite level endurance athletes increased Hb_{mass} (Garvican et al., 2012).

In summary, due to the large amount of time accumulated at altitude through LHTH, if the hypoxic dose is sufficient, haematological changes generally exist in LHTH studies (Garvican-Lewis et al., 2016).

Table 2.2 Performance and Physiological changes seen through LHTH.

Authors	Participants	Altitude	Study length	Altitude hours[1]	Findings
McLean et al. (2012)[2]	Elite Australian footballers	2,130 m	19 nights	971 (approx.)	↑ Hb_{mass} (3.6 ± 1.6%) ↑ 2km TT performance (1.5 ± 4.8%)
Daniels and Oldridge (1970)[3]	Elite endurance runners	2,300 m	42 (2x14 & 2x7 day blocks)	2,318	↑ race performance ↑ $\dot{V}O_{2max}$
Pugliese et al. (2014)	Elite endurance athletes	2,030 m	21 days	1,023	↑ race performance
Chapman (2013)	Elite endurance athletes	1,780 to 2,800 m	28 days	1,196 to 1,881 (approx..)	↑ race performance (2,085 & 2,454 m only) ↑ $\dot{V}O_{2max}$ (2,085, 2,454 & 2,800 m only) ↑ Erythrocyte content
McLean et al. (2013)[3]	Elite Australian footballers	2,100 m	18 and 19 days	864 to 957	↑ Hb_{mass} (approx. 4%)
Levine & Stray-Gunderson (1997)	Highly trained runners	2,500 m	28 days	1,680	↑ Red Cell Mass (approx. 9%) ↔ 5,000 m running performance
Saunders et al. (2009)	Elite endurance runners	2,860 m	46 ± 8 days	3,157 (approx.)	↑ Running Economy (3.2%) ↔ $\dot{V}O_{2max}$
Garvican et al. (2012)	Elite endurance cyclists	2,760 m	19 days	1,258 (approx.)	↑ Hb_{mass} (3.5 ± 2.5%)
Gore et al. (1998)[3]	Elite track endurance cyclists	2,690 m	31 days	2,001 (approx.)	↔ Hb_{mass} ↔ 4,000 m TT performance ↔ $\dot{V}O_{2max}$

[1]Altitude hours are based off the method prescribed by Garvican et al. (Garvican-Lewis et al., 2016). [2]Training load almost certainly higher for LHTH compared to control, therefore training load used as a covariate to determine between group change. [3]No control group. [*]Possibly greater improvement than control. [#]Likely greater improvement than control.

2.8 Live-High Train-Low (LHTL):

Even though there are improvements in performance and haematological markers through LHTH due to the "dose" of exposure (both length and altitude), training intensity decreases at altitude compared to training at sea level (Clark et al., 2007), with a drop in $\dot{V}O_{2max}$ of up to 7% per 1,000 m (Clark et al., 2007). As accumulated time at exercise intensities at or above $v\dot{V}O_{2max}$ is critical to increase aerobic capacity and performance (Buchheit and Laursen, 2013), this may decrease the efficacy of LHTH to improve sea level performance due to a decreased time spent at $v\dot{V}O_{2max}$. Further, for team-sport athletes where training at high intensities is crucial for specificity due to the high intensity efforts of competition (Aughey, 2011), LHTH has its drawbacks. Therefore, living at altitude and training at, or close to, sea level has become the preferred method for many elite athletes (Alvarez-Herms et al., 2015). This method is known as live-high train-low (LHTL) (Levine and Stray-Gundersen, 1992). With LHTL, athletes can maintain exercise intensity by training at, or close to, sea level, but still get the effects of altitude by spending up to 16 hours per day at a moderate altitude (2,500 to 3,500 m) (Robertson et al., 2010a, Siebenmann et al., 2012, Robertson et al., 2010b). One study has compared the effects of performance and haematological changes for LHTH vs LHTL (Levine and Stray-Gundersen, 1997). Both groups improved $\dot{V}O_{2max}$ by approximately 5%, however only the LHTL group improved the estimated velocity at maximal steady state and 5,000 m TT performance (Levine and Stray-Gundersen, 1997). It was concluded that LHTL may be the preferred method of altitude training over LHTH. Firstly due to the maintenance of training velocities and oxygen flux through training at low altitude, and secondly still benefiting from the physiological adaptations to hypoxia, including increased Hb_{mass}, and RCV, resulting in increases in blood oxygen-carrying capacity and $\dot{V}O_{2max}$ through accumulated time at altitude (Siebenmann et al., 2012, Levine and Stray-Gundersen, 1997). The ability to train at a high intensity is important for team-sport athletes, due to the large amount of high-velocity running seen in many team-sports (Aughey, 2011).

As mentioned in section 2.3, hypoxia can be achieved through either real or simulated altitude. Simulated altitude through nitrogen houses has a number of clear advantages for many team-sport athletes due to the reduction in the time spent travelling to high altitude from low altitude regions (Richalet and Gore, 2008), minimising the cost of sending a large squad of up to 50 athletes plus dozens of support staff, and also minimizing the disruption to regular training of these athletes. Further, LHTL allows team-sport athletes to maintain a higher training intensity than LHTH, which is more specific to the game demands (Aughey, 2011). Therefore, LHTL offers many advantages over LHTH, in particular to team-sport athletes.

2.8.1 Performance and Physiological changes through LHTL

The majority of LHTL studies use endurance athletes as participants, with only two on team-sport athletes. Although far from unanimous, a large portion of literature points to a positive improvement in either sea level performance or haematological changes following LHTL. A summary of LHTL studies is reported in Table 2.3.

Table 2.3. Summary of Live High Train Low studies.

Authors	Study Length (nights)	Daily exposure (hours)	Altitude (m)	Altitude hours	Participants	Findings	Change from control group
Buchheit et al. (2013)[1]	12	14	2,500 – 3,000	420 (approx.)	Elite Australian Footballers	↑ Plasma volume ↑ Hbmass ↑ Yo-Yo IR2	No control
Brocherie et al. (2015)[2]	14	14	2,500 – 3,000	490 (approx.)	Elite Field Hockey Athletes	↑ Yo-Yo IR2 ↑ Repeat sprint ↑ Hbmass	↑ Yo-Yo IR2 ↑ Repeat sprint
Brugniaux et al. (2006)	18	14	2,500 – 3,000	630 (approx.)	Elite middle distance runners	↑ Economy ↑ $\dot{V}O_{2max}$ ↑ Aerobic power ↑ Hb_{mass}	↑ Economy ↑ $\dot{V}O_{2max}$ ↑ Aerobic power
Garvican et al. (2011)[3]	26	14	3,000	1,092	Highly trained cyclists	↑ Hb_{mass} ↑ repeat TT performance	↑ repeat TT performance
Garvican-Lewis et.al (2013)	9 to 11	14	2,500 – 3,000	315 – 462	Elite Water Polo Players	↑ Hb_{mass}	No control
Humberstone et al. (2013)	17	14.1	3000	719	Elite triathletes	↑ Hb_{mass} ↑ RE ↔ Performance	↑ Hb_{mass} ↑ RE ↔ Performance
Stray-Gunderson et al. (2001)[4]	27	Not reported	2,500	Not available	Elite Distance Runners	↑ 3 km TT ↑ $\dot{V}O_{2max}$ ↑ Hb_{mass}	No control
Robertson et	21	14	3,000	882	Highly Trained Runners	Variable 4.5 km TT performance	4.5km TT unclear

al. (2010a)[5]						↑ $\dot{V}O_{2max}$ ↑ Hb_{mass}	↑ $\dot{V}O_{2max}$ ↑ Hb_{mass}
Saunders et al. (2010)	21	14	3,000	882	Elite Race Walkers	↑ treadmill test ↑ $\dot{V}O_{2max}$ ↑ Hb_{mass}	No change in performance ↑ $\dot{V}O_{2max}$ ↑ Hb_{mass}
Robertson et al. (2010b)[6]	21	14	3,000	882	Highly Trained Runners	↑ 3 km TT ↑ $\dot{V}O_{2max}$ ↑ Hb_{mass}	3km TT unclear ↑ $\dot{V}O_{2max}$ ↑ Hb_{mass}
Robertson et al. (2010c)	10	9-10	2,600	247 (approx.)	Elite Swimmers	No change in Hb_{mass}, or race performance	Decreased Swim performance
Pottgessier et al. (2012)	26	16.6	3,000	1,295	Well Trained Cyclists	↑ Hb_{mass} 2 days post 3% decrease Hb_{mass} 9 days post	No control
Hahn et al. (2001)	11-23	8-11	2,650 - 3,000	233 – 759 (approx.)	Elite Endurance Athletes	↔ Hb_{mass} ↓ Performance	↑ Hb_{mass}

[1]Participants were also exposed to heat and IHT. [2]Participants were also expose to repeat sprints in hypoxia, control group did not perform repeat sprints. [3]The control group was also exposed to LHTL, but had Hb_{mass} gains removed. [4]Low intensity training performed at 2,000 m to 2,800 m while high intensity training performed at 1,250 m. [5]Groups exposed to 2 blocks with a 5-week washout between. [6]Group also exposed to three sessions per week of IHT

2.8.1.1 Evidence for the efficacy of LHTL: Endurance athletes

With an increase in Hb_{mass} and RCV, there is an increase in the oxygen carrying capacity of the blood. There is also a strong correlation between increased BV and an increase in $\dot{V}O_{2max}$ (Sawka et al., 2000). With an increased $\dot{V}O_{2max}$ there is a theoretical link to an improved endurance performance. This is the case in most, but not all LHTL studies. It appears that LHTL increases performance in endurance athletes, with both runners and cyclists showing improved performance following a LHTL intervention.

Many studies using elite endurance athletes occurred shortly after major competition, where these athletes were presumably already at a high level of fitness. Despite having trained for major competition, after 27 days of LHTL, 3 km time trial (TT) performance improved by 1.1% (90% confidence limits 0.3 to 1.9%) in elite runners, while $\dot{V}O_{2max}$ and Hb_{mass} both increased compared to pre (Stray-Gundersen et al., 2001). Although there was no control group, it was assumed the participants were at an elite level of fitness due to the study being conducted shortly following the National Championships. Therefore, as 1/3 of athletes ran personal best times post-study, it was concluded that the LHTL camp improved performance in these already high performing athletes (Stray-Gundersen et al., 2001). However without a control group it cannot be determined with certainty whether the change in performance was due to the intervention, or the training, particularly as training was not detailed in the study. Further, although described as LHTL, training was undertaken at varying altitudes between 1,250 and 3,000 m, and therefore could just as easily be classified as LHTH. In another study on elite endurance athletes, a mixture of LHTH and LHTL for 44 days gave a performance improvement of 1.9% compared to the beginning of the study; again, no control group could be used due to the extended nature of the study, and the high level of participants used (Saunders et al., 2009b).

The improvements in endurance running performance seen in elite endurance athletes has relevance to team-sport athletes, with better performing team-sport athletes showing better performance in TT's (Gastin et al., 2013).

It has been suggested that LHTL may be less effective in highly trained athletes who are already close to their genetic potential (Robach and Lundby, 2012), with the authors speculating that the modest increase in Hb_{mass} through LHTL was insufficient to further increase the athlete's already high $\dot{V}O_2$, and therefore increase performance. In contrast, the research by Stray-Gundersen et al. using elite athletes in peak physical condition as shown by the timing of the study shortly following major competition refutes this claim, as personal best times were still achieved in a number of these athletes (Stray-Gundersen et al., 2001).

Not all studies have shown improvements in performance after LHTL, with a number of studies showing no additional performance benefit. Although 2 x 3 week blocks of simulated LHTL (14 $hrs.d^{-1}$ and 3,000-m simulated altitude) with a five week washout period showed reproducible improvements in $\dot{V}O_{2max}$ (2.1% for both blocks), and Hb_{mass} (2.8% for block one and 2.7% for block two), performance changes compared to a control group were inconsistent (Robertson et al., 2010a). The LHTL group was substantially faster than control in 4.5-km TT performance following the first block (1.9% faster), but possibly slower after the 2nd block (1.4% slower). It should be noted training load was higher for LHTL and when adjusted for training load, differences between groups were unclear after block 1, and LHTL was substantially slower after block two (2% Slower). Percentage changes for the group for physiological markers were more consistent, with group averages for $\dot{V}O_{2max}$ showing repeatable changes following LHTL. However, individual responses indicated there was no association between percentage changes between blocks one and two for either performance or physiological change, with some athletes improving in the first block but not the second block, and vice versa (Robertson et al., 2010a). The authors concluded that factors such as fatigue and motivation may have played a part in the inconsistent performance measures between blocks (Robertson et al., 2010a). It should be noted this was an observational study, with all training and altitude exposure controlled by the coach (Robertson et al., 2010a). As post testing was performed immediately following LHTL, it is also possible that there may have been residual fatigue present which did not allow the best performance in the LHTL group, especially considering the higher training load in this group. The best performance may occur several weeks following LHTL (Brugniaux et al., 2006).

An observational study on elite swimmers preparing for major competition has been conducted, and again found no differences in performance, and only a trivial change in Hb_{mass} and $\dot{V}O_{2max}$. However this study was of a much shorter exposure to that which is recommended for LHTL, with only 10 nights and a minimum of 9-10 hours per night vs other studies with 12 nights, and up to 16 hours exposure per night, indicating exposure may have been insufficient to elicit a response (Robertson et al., 2010c). Further, this was not a classic LHTL study, with a mixture of methods between living and training at moderate altitude (1,350 m), and LHTL.

Other LHTL studies have achieved performance changes after a relatively small altitude dose, with well trained cyclists improving 4 minute mean power after only 12 nights of LHTL at 2,650 m, however 30 min mean power did not change (Martin et al., 2002). Very little information was given on this study and the training undertaken, however there was a matched control group that reportedly undertook the same training as the LHTL group (Martin et al., 2002).

In the Robertson et al. study above, there was also no pre altitude race performance, with the changes in performance assessed in comparison to the same competition the previous season. There are obviously a number of factors that can affect performance over a 12-month period; therefore it is impossible to tell whether the altitude exposure was effective at improving performance. Although some athletes showed substantial improvement, as a number showed a decreased performance, with the small sample size the group change was unclear (Robertson et al., 2010c). With pooled data from six studies of elite endurance athletes including cross-country skiers, cyclists, kayakers, triathletes and runners, there was a non-significant change in performance post LHTL, whereas the control group showed no change (Hahn et al., 2001). There was however a slight trend towards a reduction in $\dot{V}O_{2max}$ post LHTL, whereas the matched control group showed now change (Hahn et al., 2001). Interestingly, and in contrast to most other altitude research, the largest reductions in $\dot{V}O_{2max}$ occurred when altitude was the highest (3,000 m vs 2,650 m) and exposure the longest (23 vs 11 days) (Hahn et al., 2001).

In elite endurance runners, repeated doses of LHTL produced inconsistent changes in TT performance, with the LHTL group faster than control following the first 3 week LHTL dose, but were actually slower than baseline after a subsequent 3 week dose 5 weeks later. There were, however reproducible changes in Hb_{mass} and $\dot{V}O_{2max}$ (Robertson et al., 2010a). The different responses for performance and haematological changes suggest that non-haematological factors also influence performance changes, since improvements in Hb_{mass} were not associated with increases in performance following the second 3 week dose. These non-haematological factors will be discussed in greater detail in the next section. Further, as the individual responses were different between the two training camps, this indicates that adaptations to altitude are not consistent for individuals, and other factors come into play when determining whether an athlete will show changes in performance through an altitude camp.

Although conflicting, the majority of research shows that LHTL is a useful performance enhancement tool for endurance athletes. For this reason, LHTL has become a staple of many endurance athletes preparation for competition (Alvarez-Herms et al., 2015).

2.8.1.2 LHTL for Team-Sport athletes

The only two studies on LHTL in team-sport athletes have used a combination of LHTL and other environmental stimuli (IHT and/or heat exposure); therefore it is difficult to isolate the effects of LHTL separate to other environmental factors. In the first study, two LHTL groups of hockey players were exposed to 14 $h.night^{-1}$ for 14 nights of 2,500 m to 3,000 m of simulated altitude (Brocherie et al., 2015). These two LHTL groups also performed repeat sprint (RS) sessions either in normoxia (LHTL) or hypoxia (LHTL+TH) (Brocherie et al., 2015). A control group performed the same training as the two altitude groups at sea level without the repeat sprints. The two LHTL groups had a greater improvement in Yo-Yo IR2 and repeat sprint (RS) performance than the control group (Brocherie et al., 2015). However as the control group did not perform RS training, it is not possible to determine whether all of the changes were through LHTL or the RS training performed by the altitude groups. The LHTL+TH group displayed twice the improvement in RS performance compared to LHTL only, indicating that to improve RS performance, performing RS in hypoxia combined with LHTL is more effective than LHTL alone. The only other study using team-sport athletes used elite Australian Football players, and combined heat with LHTL (Buchheit et al., 2013). There were two LHTL groups as part of this study. As well as the LHTL intervention, one group performed cycling sessions at simulated altitude and the second group performed these cycling sessions at sea level, however there was no control group exposed to no altitude (Buchheit et al., 2013). Both LHTL groups improved Yo-Yo IR2, with a percentage change of 25% at mid, and 44% at post compared to pre testing with no difference in change between groups. Interestingly, the group that performed additional bike sessions in hypoxia had a possible better maintenance in Yo-Yo IR2 performance four weeks post exposure than the LHTL only group (Buchheit et al., 2013), again indicating that IHT combined with LHTL may be more important for high intensity intermittent running performance than LHTL alone. Due to a lack of a control group, it is not possible to determine whether the changes in Yo-Yo IR2 performance in both LHTL groups were through the hypoxia, or the training camp. Haematological changes occurred in both LHTL groups, with plasma volume (PV) increasing in both groups. Similarly to performance changes, both PV and Hb_{mass} were higher in LHTL + TH compared to LHTL only at four weeks post study (Buchheit et al., 2013), again showing the importance of training in hypoxia for team-sport athlete performance.

It is clear from the two studies on team-sport athletes that LHTL has the potential to improve team-sport athlete intermittent running performance, with LHTL increasing Yo-Yo IR2 performance. Importantly for team-sport athletes, to maximally develop the ability to perform repeated high intensity efforts such as Yo-Yo IR2 and RS performance, it appears an IHT stimulus on top of LHTL is required. However the question remains as to whether LHTL alone improves team-sport athlete running performance, therefore further research on team-sport athletes is required to isolate the effects of LHTL on team-sport athlete running performance.

In summary, most well designed studies on endurance athletes show an increase in performance for LHTL interventions if the altitude exposure is sufficient.

2.8.1.3 Haematological changes after LHTL

One of the major goals of a LHTL intervention is to elicit changes in haematological markers, such as increased Hb_{mass}. Evidence for the importance of Hb_{mass} for increased performance was shown in a study of elite women cyclists following LHTL. Both groups were exposed to the same LHTL intervention, with Hb_{mass} clamped in one group and free to adapt in a second (Garvican et al., 2011). Both groups improved 4-min mean power, although the group that had Hb_{mass} clamped could not match the group with improved Hb_{mass} for performance during a subsequent aerobic effort (Garvican et al., 2011). Importantly, participants were blinded as to whether they were in the group that had blood removed, therefore there was no placebo or nocebo effect, and the only difference between groups was the changes in Hb_{mass}, as all participants were exposed to the same training and altitude exposure. The authors concluded Hb_{mass} is important not only to improve oxygen carrying capacity during sustained efforts, but also to improve the rate of recovery, allowing greater performance in subsequent efforts. This finding has critical relevance to team-sport athletes due to the intermittent nature of most team-sport competition, and thus a repeated TT performance test should be used to ascertain team-sport specific performance changes through LHTL.

When hypoxic exposure is sufficient, Hb_{mass} generally increases through LHTL (Garvican et al., 2012). Further, it appears that whether hypoxia is achieved through hypobaric or normobaric hypoxia, a similar change in Hb_{mass} occurs (Hauser et al., 2016). In 28 well-trained triathletes who were exposed to 2,250 m of either hypobaric (HH) or normobaric (NH) hypoxia, both groups improved Hb_{mass} by a similar amount after a similar hypoxic exposure (+4.4% from 230 hours for HH, and +4.1% after 238 hours for NH), while a control group only improved by 1.9%. This exposure was achieved after 13 days for HH and 18 days for NH. Interestingly, although this change was seen after 13 nights of exposure for HH, after 18 nights there was no further benefit (+4.5%) (Hauser et al., 2016). Three km running performance changed for all three groups, with the LHTL groups changing by a greater amount than the control group, whereas only the two hypoxic groups improved cycling performance (Hauser et al., 2016). When using HH compared to NH, there is usually a greater accumulated time at altitude seen through HH.

Although Hb_{mass} generally increases following LHTL, this is not always immediately accompanied by changes in performance. In a study by the same research team, the HH group accumulated 300 hours of altitude compared to only 220 for NH (Saugy et al., 2014). However once again, there were similar changes in both $\dot{V}O_{2max}$ (6.1 ± 6.8 vs 5.2 ± 4.8% for NH and HH), and Hb_{mass} (2.6 ± 1.9 vs 3.4 ± 2.1 for NH and HH) (Saugy et al., 2014). Contrary to the above study, 3 km TT did not change between groups immediately post study, however 21 days post LHTL, 3 km TT time was faster in HH (3.3 ± 3.6%) compared to NH (1.2 ± 2.9%) (Saugy et al., 2014). The authors concluded that the greater change in 3km TT 21 days post LHTL was due to the greater hypoxic dose for the HH group. Again using elite triathletes, Hb_{mass} changed after 14 hours per night at 3,000 m simulated altitude for 17 nights in comparison to a control group, with the change in Hb_{mass} 3.2% greater than a placebo group, and 4.7% greater compared to a group exposed to intermittent hypoxic exposure (IHE, breathing extreme hypoxia for 1 hour per day for 17 days) (Humberstone-Gough et al., 2013). However, this change was again not accompanied by changes in performance, this time measured by velocity at $\dot{V}O_{2max}$, or $v\dot{V}O_{2max}$.

It is currently thought that altitude exposure for 12 to 14 hours per night for at least 14 nights is needed to increase Hb_{mass} and performance (Rusko et al., 2004, Nummela and Rusko, 2000, Pottgiesser et al., 2012, Clark et al., 2009). This has been further refined to suggest that with sufficient altitude, a change in Hb_{mass} of 1% for every 100 hours of exposure (Garvican-Lewis et al., 2016). Bouts of less than this have shown inconsistent changes in Hb_{mass} (Robertson et al., 2010c, Ashenden et al., 1999b, Ashenden et al., 2000). Thus, bouts of LHTL of less than 12 hours may be insufficient to increase Hb_{mass} (Rusko et al., 2004). A possible reason for the lack of change in Hb_{mass} with less than 12 hours exposure per day is twofold. Firstly, the exposure is insufficient to allow EPO to be raised for sufficient durations, and secondly, the break between altitude bouts is too long to allow a sustained release of erythropoietin to stimulate Hb_{mass} changes. There is an increase in EPO over the first 48 hours of exposure to living at 2,760 m above sea level and training at moderate altitude (1,000 to 3,000 m), then after 12 nights EPO decreased to the same levels as baseline (Garvican et al., 2012). This has been consistently shown over varying durations, with serum EPO not different to baseline after 11 to 23 days (Hahn et al., 2001). It is possible that the breaks in exposure seen through LHTL may also allow a more sustained release in EPO through a "resetting" of the response for each additional exposure.

2.8.1.4 Haematological Changes in Team-Sport Athletes

The only two LHTL studies using field based team-sport athletes to date have both found changes in Hb_{mass}. With exposure to 2,500 to 3,000 m altitude for 14 hours per night for 12 to 14 nights showing an increased Hb_{mass} of between 2.6 and 4% (Buchheit et al., 2013, Brocherie et al., 2015). This change in Hb_{mass} is of similar magnitude to that expected to be seen with elite endurance athletes. Many running based team-sport athletes, including Australian footballers and soccer players play competition matches each week, so an unbroken LHTL block of >14 nights is difficult to administer in season. Therefore research is needed to determine if smaller blocks of intermittent LHTL still get the same haematological and performance benefit as a single unbroken block of >14 days. Although a very different TS to both soccer and Australian football, Water polo athletes have shown improvements in Hb_{mass} after only 9 to 10 nights of LHTL for 14 $h.night^{-1}$ at 2,500 to 3,000 m (Garvican-Lewis et al., 2013). These changes were repeatable over three blocks of LHTL ranging from 9 to 11 days. The improvements in Hb_{mass} ranged from 3.7 (90% CL 1.3-6.2%) to 4.5 (90% CL 3.8-5.1%) for the three blocks (Garvican-Lewis et al., 2013). As the participants were elite Water polo athletes competing in the Olympics, there was not enough participants for a control group, therefore it cannot be determined if these changes were purely through the LHTL intervention or the training camps undertaken by the group.

Even when these minimum exposure recommendations are exceeded, haematological changes do not always occur (Ashenden et al., 1999a, Hahn et al., 2001). Other factors including health status of the athlete (McLean et al., 2013b), starting Hb_{mass} (McLean et al., 2013a), a reduction in body mass (McLean et al., 2013a, McLean et al., 2013b), and low iron levels (Stray-Gundersen et al., 1992), can have a large bearing on the haematological changes seen through both LHTL and LHTH.

In summary, in healthy athletes, if a sufficient altitude exposure has been achieved, haematological changes generally occur through LHTL. However these changes in Hb_{mass} are not always accompanied by changes in performance.

2.8.2 Non-Haematological changes after LHTL

Although changes in Hb_{mass} are a goal of both LHTH and LHTL training camps, there are instances when haematological changes are not accompanied by changes in performance (Levine and Stray-Gundersen, 1997, Humberstone-Gough et al., 2013). Likewise, there may be changes in performance despite no change in Hb_{mass} or other haematological adaptations (Hahn et al., 2001). This indicates that there are other, non-haematological factors during altitude exposure that affect performance. Some of these non-haematological changes include improved running economy (Saunders et al., 2009a).

2.8.2.1 Running Economy following LHTL

Using elite athletes, running economy has improved compared to a control group following LHTL (Saunders et al., 2004b, Brugniaux et al., 2006, Humberstone-Gough et al., 2013). This was demonstrated through a decreased $\dot{V}O_2$ of 3.3% (Saunders et al., 2004b), and a decrease in heart rate (Brugniaux et al., 2006) at the same submaximal running speeds after LHTL. However, there was no change in running economy between a group who lived at approx. 600 m, and a group who lived and trained at moderate real altitude (LMTM, living at 1,570 m, and training between 1,500 and 2,000 m) (Saunders et al., 2004b). Once again, training was not described in this study, therefore it is not possible to determine if groups undertook the same training. There were no changes in Hb_{mass} in any group (Saunders et al., 2004b), therefore the change in RE in the LHTL group were through non-haematological mechanisms. It is possible that the relatively small altitude dose of the LHTL group (8 to 12 hours per night), and the LMTM group (1,570 m) was insufficient to elicit a haematological response.

The changes in economy mentioned above were accompanied by improvements in $\dot{V}O_{2max}$ (9.6%) and aerobic power (8.6%) (Brugniaux et al., 2006). Of note, submaximal intensity for these runners was 19.5 $km.h^{-1}$, indicating the highly trained nature of the participants. These performance changes were still apparent at least 15 days post LHTL, with both $\dot{V}O_{2max}$ (5.2% higher) and running power at $\dot{V}O_{2max}$ (3.5% higher) both elevated compared to baseline 15 days post (Brugniaux et al., 2006). A different group also showed increases in running economy compared to a group exposed to no LHTL. In this study, the LHTL group had a 2.8% greater improvement in running economy compared to the group exposed to IHE (Humberstone-Gough et al., 2013). Importantly, in this study training load was used as a covariate to remove any bias from differences in training load on changes between groups (Humberstone-Gough et al., 2013). Mechanisms behind increased running economy post altitude exposure include decreased cardiorespiratory cost, and a greater reliance on carbohydrate as a fuel source (Burtscher et al., 2010)

Improved running economy after LHTL has relevance to many team-sport athletes, due to the large amount of low to moderate intensity movement in many team-sport competitions (Aughey, 2010). Therefore the ability to perform this low to moderate intensity running with a lower $\dot{V}O_2$ can potentially lead to less accumulated fatigue, allowing for greater performance in the higher intensity efforts required during competition (Aughey, 2011).

2.8.2.1.1 Muscular Adaptations after LHTL

There are a number of adaptations occurring to skeletal muscle as a result of exposure to altitude. One of these through chronic altitude exposure is an increased capillary density of up to 12% (Hoppeler and Vogt, 2001). There is no increase in the number of capillaries after chronic altitude exposure, however there may be an increase in capillary density caused by a decrease in muscle mass seen through chronic exposure to altitude, resulting in a net decrease in the distance from capillaries to muscle fibres (Hoppeler and Vogt, 2001). Therefore, these changes are more likely due to the adverse affect of a decrease in muscle cross sectional area rather than the positive adaptation of increased capillaries. Other muscular changes include an increase in myoglobin content, increased levels of hypoxia inducible factor 1, increased mitochondrial capacity, reduced production of lactate, and changes in the use of substrates (Gore et al., 2007).

2.8.2.1.2 Placebo effect and LHTL

It has been suggested that the placebo effect may be at least partly responsible for increased performance following LHTL (Siebenmann et al., 2012). A double blind placebo controlled study design has been employed to test this theory. In elite cyclists, 16 hours per day for 28 days at a simulated altitude of 3,000 m provided no additional benefit to 26-km TT performance, Hb_{mass}, $\dot{V}O_{2max}$ or exercise economy (Siebenmann et al., 2012). This was despite a large hypoxic dose, higher reticulocyte count and elevated urine EPO levels in the

LHTL group (Siebenmann et al., 2012). As this study successfully blinded LHTL and control groups, the authors concluded that performance gains in other altitude studies may be at least partly due to a placebo effect (Siebenmann et al., 2012). It was noted however, that due to the individual response to altitude exposure, the selection of athletes in the altitude group may have negated any positive effect of LHTL on performance and haematological markers (Siebenmann et al., 2012). Even though half the LHTL group showed increases in Hb_{mass} greater than the 2.6% typical error of the CO rebreathing technique, as three showed a decrease in Hb_{mass}, the mean group change was not different. In comparison, only 1 of the 5 athletes in the placebo group showed a greater than 2.6% increase in Hb_{mass} (Siebenmann et al., 2012). Further, the natural altitude was 1,135 m, indicating that the placebo group were still exposed to moderate altitude, perhaps masking the positive effects of altitude for the LHTL group. It is clear that further placebo controlled LHTL studies are required to determine the effects of placebo.

One other study unsuccessfully attempted to blind participants to altitude to assess the placebo effect. Using elite race walkers exposed to a simulated altitude of 3,000 m for 14 hours per day for 21 days, there was an increase in Hb_{mass} (8.6 and 5.5%) and $\dot{V}O_{2peak}$ (2.7 and 5.8%) in comparison to the placebo and nocebo groups respectively (Saunders et al., 2010), however changes in performance were not significantly different between LHTL and the placebo and nocebo groups (Saunders et al., 2010). Therefore, although there were physiological changes, these did not translate into performance benefits. There is currently little evidence that the placebo effect is responsible for the performance or physiological changes seen through LHTL, and further research is required to determine the effects of placebo.

In summary, the majority of studies show a physiological and/or performance benefit from LHTL. Physiological changes appear more consistent, however these are not always accompanied by changes in performance. Time course for adaptation will be discussed in detail later, however a minimum of 12 hours per night may be required to elicit altitude induced gains in performance or physiology, while the optimal number of day's exposure is yet to be determined. More research needs to be undertaken on LHTL and team-sport athletes.

2.9 Intermittent Hypoxic Training (IHT):

Intermittent hypoxic training involves athletes living at sea level while training at real or simulated altitude of 2,000 to 3,000 m for between 45 and 90 mins per exposure, usually 2 to 4 times per week (Czuba et al., 2011, Hamlin et al., 2010b, Volkov, 2012). Intermittent hypoxic training is a popular altitude training method due to minimal travel, lower expense than LHTL and negligible disruption to daily life (Hamlin et al., 2010b). A summary of IHT studies is shown in table 2.4.

2.9.1.1 Aerobic Changes Following IHT

The evidence of IHT for enhancing sea level endurance performance is mixed (Hamlin et al., 2010b, Morton and Cable, 2005, Volkov, 2012, Czuba et al., 2011, Vogt et al., 2001, Zoll et al., 2006, Dufour et al., 2006). A number of studies show improvements in performance (Czuba et al., 2011, Hendriksen and Meeuwsen, 2003, Dufour et al., 2006), no change (Truijens et al., 2003, Morton and Cable, 2005) and even decreased performance following IHT (McLean et al., 2015, Roels et al., 2007).

As mentioned, although not universal, increased aerobic performance has occurred in a number of studies following IHT, with $\dot{V}O_{2max}$ increased in comparison to a control group after 9 to 12 sessions (Dufour et al., 2006, Czuba et al., 2011, Czuba et al., 2013).

Exercise intensity close to, but not over the anaerobic threshold appears to be the most effective in eliciting gains in aerobic capacity through IHT (Czuba et al., 2011, Dufour et al., 2006, Czuba et al., 2013). Three IHT sessions per week for three weeks at a simulated altitude of 2,500 to 2,600 m improved work rate at lactate threshold (8.3%), $\dot{V}O_{2max}$ (4%), maximal workload achieved in a number of aerobic performance indicators, including incremental cycling test performance (6.6%), time to complete a 30-km TT (2.6%), 30-km TT average power (5.6%) and oxygen uptake at lactate threshold (9.1%). Whereas the control group only improved TT power (Czuba et al., 2011). This study described in great detail training undertaken by the participants, with both groups undertaking the same training. Both groups performed a warm up and cool down, then the IHT group sessions consisted of 30 to 40 mins at a power output corresponding to 95% sea level lactate threshold, while the control group performed the same sessions at a workload of 100% sea level lactate threshold (Czuba et al., 2011). A different group of researchers found exercising at ventilatory threshold improved $\dot{V}O_{2max}$ and time to exhaustion at $v\dot{V}O_{2max}$, while the control group once again did not show the same improvements (Dufour et al., 2006). Likewise, in a group of highly training runners, $\dot{V}O_{2max}$ and time to exhaustion in a treadmill running test improved after 2 sessions per week at 3,000 m over 6 weeks, while no change was evident in a control group (Dufour et al., 2006). Again, training was well described in this study, with no difference between groups for training load. Exercise intensity was similar to the previously mentioned study, with similar time spent in hypoxia (24 to 40 mins) at the second ventilatory threshold (Dufour et al., 2006).

Team-sport athletes have also benefited from IHT, with 4 minute intervals at 2,500 m simulated altitude, exercising at 90% $\dot{V}O_{2max}$ improving $\dot{V}O_{2max}$ more than a control group after only 3 weeks, despite no change in haematological markers (Czuba et al., 2013).

Using lower intensities for IHT has also increased aerobic capacity, with 105 mins per day for 10 days at 60 to 70% heart rate reserve showing a change in both anaerobic and aerobic power (Hendriksen and Meeuwsen, 2003). Although there was a difference in aerobic power between the IHT and control groups, the difference was unclear, and there was no difference in $\dot{V}O_{2max}$ between groups (Hendriksen and Meeuwsen, 2003). Considering that elite athletes were used, and IHT was prescribed for only 10 days, this non-significant, but substantial improvement in aerobic power appears worthwhile for elite athletes where small changes in performance can be the difference between success and failure. Further, this study found meaningful changes in Wingate test performance, both in terms of relative and absolute power.

There is a reduced cardiovascular response when performing interval sessions in hypoxia compared with the same session in normoxia (Buchheit et al., 2012). With a shorter time spent near both $\dot{V}O_{2max}$ and maximal heart rate during three minute running intervals interspersed with 90 seconds passive recovery (Buchheit et al., 2012). The authors noted a reduced running speed during hypoxia might have contributed to the lower HR and $\dot{V}O_2$. It appears that a decreased work rate at altitude may only be apparent at higher exercise intensities. At exercise intensities up to 55% sea level $\dot{V}O_{2max}$, a simulated altitude of 1800 m had no effect on blood lactate concentration, pulmonary ventilation, HR or RPE in a group of highly trained cross country skiers (Hahn et al., 2001). However, as workload increased to 80% sea level $\dot{V}O_{2max}$, mean lactate increased from 3.9 ± 0.2 mmol in normoxic conditions to 5.7 mmol at simulated altitude (Hahn et al., 2001). As lower intensities are not compromised due to hypoxia, this is a possible reason why exercise intensities below anaerobic threshold are more likely to increase aerobic performance than higher intensity exercise. Any change in performance seen using this intensity is magnified due to the hypoxic stimulus.

Although studies show improved performance through IHT, there are a number of studies showing no greater change in aerobic performance following IHT compared to a placebo or control group. In a group of elite swimmers, although there was an improvement in 100 m and 400 m swimming time trial performance, the change was no greater than a placebo group (Truijens et al., 2003). These swimmers were matched for training load and performance. These results, whereby IHT showed no greater change than control were replicated in endurance trained athletes, where both IHT and placebo improved 20 km mean power, however there was no greater change in 20 km mean power compared to placebo following 10 days of training in hypoxia (Hamlin et al., 2010b). The exercise intensity in the Hamlin et al. study was quite low for the majority of the training program, with participants training for 90 mins at 60 to 70% heart rate reserve. There was, however 2 x 30-s maximal sprints as part of this intervention. Interestingly, 30-s mean power increased in comparison to the placebo group (to be discussed in section *2.8.3.1*) (Hamlin et al., 2010b). This increased 30-s mean power is possibly due to the 2 x 30-s all out sprints. Similarly, following two studies in well trained endurance athletes, incremental maximal power, or $\dot{V}O_{2max}$ increased in both the hypoxic and placebo group following three weeks of IHT (Roels et al., 2007, Morton and Cable, 2005), however once again, there was no added benefit to the hypoxic group. In one of these studies the hypoxic group actually performed worse than the placebo group in 10 km TT average power following IHT (Roels et al., 2007). In these two studies, a higher intensity protocol was used, and as all intervals were either performed at sea level (placebo group) or hypoxia (IHT) group, it is possible that the higher intensity performed for the placebo group allowed for a higher power output to be maintained for the 10 km TT in this group. Meaning it may be necessary to continue performing some high intensity training at sea level to improve high intensity exercise performance. Further, as IHT decreases the time spent at $\dot{V}O_{2max}$ during an interval session (Buchheit et al., 2012), and training at an intensity around $\dot{V}O_{2max}$ is considered important to improve $\dot{V}O_{2max}$ (Robinson et al., 1991), it is not surprising that aerobic changes following IHT are inconsistent, especially for higher intensity training when time spend at $\dot{V}O_{2max}$ is the goal of the training session.

2.9.1.2 High intensity exercise performance following IHT

As briefly mentioned in section *2.8.3.1*, IHT may improve high intensity exercise performance rather than aerobic capacity (Hamlin et al., 2010b, Hendriksen and Meeuwsen, 2003). Following 10 consecutive days of IHT there was greater improvement in 30 second cycling mean power for an IHT compared to a control group (Hamlin et al., 2010b, Hendriksen and Meeuwsen, 2003). There are also changes in both 30 second peak power (Hendriksen and Meeuwsen, 2003), and absolute peak power (7.3% improvement in peak power compared to a 1.1% decrement in the control group), however due to a large error of measurement in this study, it was not possible to determine if this was a true change in performance (Hamlin et al., 2010b). Both of these studies found greater 30 second peak power results 9 days post intervention compared to 2 days post (Hendriksen and Meeuwsen, 2003, Hamlin et al., 2010b), indicating that the greatest benefits with IHT are apparent after any residual fatigue from the training program has dissipated, such as during a taper for an individual athlete. This is more difficult to plan in TS athletes, as training and matches continue for months after the end of pre season. A higher Respiratory Exchange Ratio (RER) and blood lactate levels were also present in the IHT group in comparison to the placebo group (Hamlin et al., 2010b). The higher RER and blood lactate levels points to a greater reliance on carbohydrate utilization for both 30 second and 20 km cycling performance after IHT. Further, due to a decreased oxygen flux, a greater anaerobic contribution may occur during training (Truijens et al., 2003), which increases the likelihood of these changes post study.

There is limited research into IHT and highly trained team-sport athletes. In Australian Footballers, an IHT group performed better than a placebo group in a protocol designed to mimic match running performance (McLean et al., 2015). However the majority of this increased distance was at a lower intensity, which may not be as important for improved match running performance and match involvements than if there was an increase in distance at faster running speeds (Mooney et al., 2011). In this same study, although both groups improved Yo-Yo IR2 performance, the IHT group change from pre to post was less than that in the placebo group (McLean et al., 2015), indicating IHT in isolation may be sub-optimal for increasing high intensity running performance in team-sport athletes. The authors suggested that the lower training intensity in the IHT group might have contributed to a smaller increase in performance in this group (McLean et al., 2015). It was concluded when using IHT on athletes, and team-sport athletes in particular, it is important to maintain a proportion of training at sea level (McLean et al., 2015). This sea level training allows exercise intensity to be maintained during training to allow adaptation for higher intensity activity during competition that would not be possible if performing IHT alone.

Much of the early research in IHT used intensities below threshold, or steady state training. However repeat sprint (RS) training combined with hypoxia is gaining more attention. It appears RS performance is increased when using RS in hypoxia compared to normoxia (Faiss et al., 2013). Although peak power was not different between groups, the ability to maintain RS performance was greater in the RS hypoxia group compared to the RS normoxia group (Faiss et al., 2013), with RS hypoxia improving the number of sprints until exhaustion post training, whereas RS normoxia showed no difference after training. However performance in a three minute all out time trial was not different between groups following training, nor was 30 second Wingate performance (Faiss et al., 2013). As the rate of PCr resynthesis has improved following IHT (Holliss et al., 2013), and PCr availability is important for RS performance (Gaitanos et al., 1993) this greater availability of PCr is a possible reason for the increased number of sprints following IHT.

Table 2.4 Summary of Intermittent Hypoxic Training studies

Authors	Study Length	Ave exposure per bout	Altitude	Participants	Exercise protocol	Findings	Change from control group
Morton and Cable (2005).	3 x pw for 4 wks	30 min	2,750 m	Moderately trained male team-sport athletes	10 x 1 min at 80% Wmax 2 min recovery	↑ $\dot{V}O_{2max}$, ↑ Wmax, ↑ mean power, ↑OBLA	No change
Roels et. al (2005).	2 x pw for 7 wks	114.9 min 79.4 min[1]	3,000 m	Well trained male cyclists and triathletes	6 x 2 min at 100% Wmax 2 min recover (wk 1) to 8 x 4 min at 90% Wmax 4 min rest (week 7)	↑ 10 min TT power, ↑ $\dot{V}O_{2max}$ [1]	No change TT power, ↑ $\dot{V}O_{2max}$
Hendriksen and Meeuwsen (2003).	10 consecutive days	105 min	2,500 m	Elite male triathletes	60 to 70% heart rate reserve	↑ aerobic power, ↑ Wingate performance, ↑ peak power	↑ Wingate performance, No change aerobic power
Hamlin et al. (2010)	10 consecutive days	90 mins	3,200 to 4,400 m	Sixteen well trained athletes	60 to 70% heart rate reserve	↑ 20km TT performance, ↑ 30-sec Wingate power	↑ 30-sec Wingate power. ↔ 20-km TT performance
Czuba et al. (2013)	3 x pw for 3 wks	57 to 65 min	2,500 m	Moderately trained male basketballers	4 to 5 x 4 min intervals at 90% v$\dot{V}O_{2max}$	↑ Wmax, ↑ $\dot{V}O_{2max}$	↑ Wmax, ↑ $\dot{V}O_{2max}$
Czuba et al. (2011)	3 x pw for 3 wks	60 to 70 min	2,500 to 2,600 m	Elite male cyclists	30 to 40 mins at 95% LT	↑ $\dot{V}O_{2max}$, ↑ Wmax, ↑ 30-km TT power	↑ $\dot{V}O_{2max}$, ↑ Wmax, ↑ 30-km TT power
Dufour et al. (2006)	2 x pw for 6 wks	24 to 40 min	3,000 m	Highly trained male runners	24 to 40 mins at 2nd ventilator threshold	↑ v$\dot{V}O_{2max}$, and vVT_2 , ↑ time to	↑ hypoxic v$\dot{V}O_{2max}$ and vVT_2, ↑ time to

						exhaustion	exhaustion
McLean et al. (2015)	2 x pw for 4 wks	30 min	3,000 m	Sub elite Australian Footballers	90 to 110% v $\dot{V}O_{2max}$ for 30s to 3 min, 30s to 1 min rest	↑ Yo-Yo IR2, ↑ time to exhaustion, ↑ TS running performance	↓ Yo-Yo IR2, ↔time to exhaustion, ↑ TS running performance
Roels et al. (2007)	5 x pw for 3 wks	60 min	3,000 m	Endurance Trained Athletes	60% $\dot{V}O_{2max}$ (3 x wk) 2 sets of 3 x 2 min intervals (2 x wk)	↑ Wmax	↔ Wmax, ↓ 10km TT power
Truijens et al. (2003)	3 x pw for 5 wks	20 min	FiO_2 0.153	Elite Swimmers	30 s to 1 min intervals. Work:Rest 2:1	↑ 100m and 400 m TT performance	No change

2.9.1.3 Haematological Changes Following IHT

Although performance changes occur with IHT, haematological variables, including red cell volume, haemoglobin concentration and haematocrit are generally not affected by IHT (Czuba et al., 2011, Czuba et al., 2013, Truijens et al., 2003). It is quite clear that accumulated time at altitude is important for haematological changes, therefore it is not surprising that there are minimal changes to haematological markers post IHT. Therefore the mechanisms behind changes in performance are likely to originate from changes in the muscle.

2.9.1.4 Muscular Changes Following IHT

As haematological changes generally do not occur with IHT, non-haematological adaptations are the primary mechanism behind any performance change, with muscular adaptations in particular behind improved performance (Faiss et al., 2013, Zoll et al., 2006). There are many changes to gene expression, and muscle metabolism post IHT that can positively influence both aerobic and anaerobic capacity.

There have been improvements in the glycolytic pathway, glucose transport, and pH regulation after IHT (Dufour et al., 2006, Melissa et al., 1997, Vogt et al., 2001). Further, the rate of PCr resynthesis increased to a greater extent following repeat sprints in hypoxia compared normoxia (Holliss et al., 2013). All of these changes allow for a greater exercise capacity through increased substrate availability or less build up of metabolic waste products. Changes in PCr regeneration have been studied post IHT. In recreationally trained men, following 15 sessions of IHT over 5 weeks, PCr recovery kinetics are enhanced in comparison to a control (Holliss et al., 2013). In the Holliss study, the participants had one leg train under hypoxic conditions, and the other leg was a sea level control. As mentioned earlier, this is an important adaptation for team-sport athletes due the importance of PCr availability for repeated high intensity activity (Gaitanos et al., 1993). However, even though the rate of PCr regeneration was greater following IHT, the PCr levels post exercise were not different between groups, raising questions over the practical importance of this finding (Holliss et al., 2013).

There are also key molecular adaptations following IHT. Elite endurance runners undertook two IHT sessions per week of 24 to 40 mins. After 6 weeks, HIF-1α concentrations increased by 104% in the IHT group but not the control group (Zoll et al., 2006), with another study by the same group showing a 78 to 82% increase in HIF-1α, with no change in control (Vogt et al., 2001). Hypoxia Inducible factor-1 alpha protein is a key player in the hypoxic response, with HIF-1α regulating transferrin and glycolytic enzymes (Jewell et al., 2001). There have also been changes in pH regulation, the glycolytic enzyme PFKm and mitochondrial metabolism (Zoll et al., 2006). As well as these changes, other genes implicated in oxidative metabolism including myoglobin displayed positive adaptations after IHT (Zoll et al., 2006, Vogt et al., 2001). These all indicate there are positive muscular adaptations for both endurance and high intensity athletic performance following IHT. The up-regulation of both aerobic and glycolytic potential could have a positive influence on team-sport performance due to the short, high intensity intermittent efforts required in many team-sports.

2.9.1.5 Exercise intensity at altitude

A decrease in $\dot{V}O_{2max}$ and exercise intensity with increased altitude has been repeatedly demonstrated in highly trained endurance athletes. For example, $\dot{V}O_{2max}$ in endurance trained runners decreased from 66.1 ± 4.3 ml kg^{-1} min^{-1} at 300 m altitude, to 55.4 ± 3.6 ml kg^{-1} min^{-1} at 2,800 m, corresponding to a 6.3% decrease per 1,000 m (Wehrlin and Hallén, 2006). The supressed $\dot{V}O_{2max}$ noted in runners is similar to the decreased $\dot{V}O_{2max}$ seen in highly trained cyclists, with $\dot{V}O_{2max}$ decreasing by 7.2% and power by 7.0% per 1,000 m of increasing altitude during a 5 minute time trial (Clark et al., 2007). Time to exhaustion is also decreased at increased altitude, with a decrease already occurring at 800 m altitude when compared to 300 m simulated altitude (Wehrlin and Hallén, 2006).

It is not only single efforts that are compromised in hypoxia compared to sea level, repeated efforts of varying durations show a decrease in power due to hypoxia, with competitive women cyclists average power during 3 x 10 min efforts decreased from 244 ± 6 W when performed in normoxia to 226 ± 6 W at a simulated altitude of 2100 m (Brosnan et al., 2000). Even short, maximal efforts are supressed, with average power in the first set of six sprints decreasing from 477 ± 18 W in normoxia to 459 ± 11 W in hypoxia. In the second and third sets average power continued to be compromised, with 452 ± 20 W vs 429 ± 17 for the second set, and 403 ± 19 W vs 373 ±15 for the third set for normoxia vs hypoxia respectively (Brosnan et al., 2000). A possible reason for the decreased intensity of repeat sprints in hypoxia is due to the decreased PCr resynthesis following exercise in hypoxia (Holliss et al., 2013). Resynthesis of PCr is oxygen dependent (Haseler et al., 1999), and sprint performance is reliant on PCr levels (Gaitanos et al., 1993). Secondly, there is a decrease in muscle reoxygenation following repeat sprints in hypoxia, causing a decrease in work completed in subsequent sprints (Billaut and Buchheit, 2013). The decreased muscle reoxygenation is combined with greater deoxygenation, which is thought to occur through greater muscle oxygen extraction in order to counteract reduced oxygen availability (Legrand et al., 2005). Therefore, due to a decrease of available oxygen in hypoxia compromising PCr regeneration, it is not surprising that repeat sprint performance is compromised as a result of hypoxia.

The decreased work rate at altitude may only be apparent at exercise intensities above 80% sea level $\dot{V}O_{2max}$ (Hahn et al., 2001). This is in contrast to a group of highly trained cyclists, where lactate concentration was not meaningfully different during a 5 min TT at altitudes ranging from 200 m to 3200 m (Clark et al., 2007). Blood lactate concentration did increase in this group at 200 W and 250 W, but only at the most extreme altitude (3,200 m) (Clark et al., 2007). Likewise, at the same absolute submaximal intensities, $\dot{V}O_2$ was the same, despite increasing altitudes of 200 m, 1200 m, 2200 m, and 3200 m (Clark et al., 2007). A possible reason for the decreased power output at intensities approaching $\dot{V}O_{2max}$ may be the decreased maximal HR at altitude, with HR decreasing in a linear fashion with increasing altitudes (Rusko et al., 2004). This linear decrease HR is approximately 1.9 bpm per 1,000 m (Wehrlin and Hallén, 2006). In contrast to the linear decrease of HR max, the lower limit for suppressed HR has been suggested at close to 3,100 m, which is possibly why no change in HR was found at altitudes of 1,200 m, 2,200 m and 3,200 m in comparison to 200 m (Clark et al., 2007).

Changes in HR and $\dot{V}O_2$ response combined with the increased use of type 2 muscle fibres when performing exercise at altitude may cause premature fatigue. While the preferential use of carbohydrate as an energy source may also be responsible for fatigue when exercise intensity is maintained for a prolonged duration (Hamlin et al., 2010b). The fatigue seen in short, high intensity efforts at altitude are possibly due to the body's inability to regenerate PCr at the same rate as seen in normoxia (Holliss et al., 2013), combined with the preferential use of type 2 muscle fibres, which will fatigue more quickly.

In contrast, the lower work rate at altitude may come from central, and not peripheral mechanisms, with no EMG signs of fatigue present with exhaustive exercise at 5,000 m when compared to sea level (Kayser et al., 1994). This suggests that exercising at altitude may not provide a sufficient neuromuscular stimulus to produce peripheral adaptations. This could partly explain the conflicting research with IHT and performance gains using high intensity training (Czuba et al., 2011, Volkov, 2012, Beidleman et al., 2009, Hamlin et al., 2010a, Hamlin et al., 2010b, Ponsot et al., 2006, Morton and Cable, 2005). Because of this, when implementing IHT in athletes, and team-sport athletes in particular, it is important to also combine IHT with sea level training to allow training intensity to be maintained (McLean et al., 2015). This is due to the requirement of team-sport athletes to perform high intensity activity during training and games for optimal neuromuscular function.

Central mechanisms limiting performance may be supported by research showing that when participants close to exhaustion at altitude are exposed to an oxygen content similar to sea level, work rate is then increased to a similar level to that seen at sea level, while also developing signs of peripheral fatigue which are not seen at altitude (Kayser et al., 1994). Endurance trained males tend to experience exercise induced hypoxemia (EIH) during maximal exercise at sea level, EIH is characterized by a SaO_2 of below 92% and arterial Oxygen tension of 2.4kPa below resting levels (Dempsey and Wagner, 1999). This decreased SaO_2 is thought to be another reason behind the drop off in maximal work rate at increasing altitudes, with each 1% decrement in S_aO_2 corresponding to a 1-2% reduction in $\dot{V}O_{2max.}$ (Dempsey and Wagner, 1999).

In summary, the evidence is mixed as to whether IHT improves sea level endurance performance, however it is more conclusive for an improvement in anaerobic performance. Intensities around, but not above ventilator threshold appear the most appropriate intensity, while RS protocols are becoming better understood, and may improve maximal sprint performance. For team-sports of an intermittent nature, it is important to maintain a large portion of training at sea level to ensure training intensity is maintained, if all training is done in hypoxia, the decrease in training intensity may have a detrimental effect.

The optimal time course for an IHT intervention will be discussed in detail in the next section.

Table 2.4 Summary of Intermittent Hypoxic Training studies

Authors	Study Length	Ave exposure per bout	Altitude	Participants	Exercise protocol	Findings	Change from control group
Morton and Cable (2005).	3 x pw for 4 wks	30 min	2,750 m	Moderately trained male team-sport athletes	10 x 1 min at 80% Wmax 2 min recovery	↑ $\dot{V}O_{2max}$, ↑ Wmax, ↑ mean power, ↑OBLA	No change
Roels et. al (2005).	2 x pw for 7 wks	114.9 min 79.4 min[1]	3,000 m	Well trained male cyclists and triathletes	6 x 2 min at 100% Wmax 2 min recover (wk 1) to 8 x 4 min at 90% Wmax 4 min rest (week 7)	↑ 10 min TT power, ↑ $\dot{V}O_{2max}$ [1]	No change TT power, ↑ $\dot{V}O_{2max}$
Hendriksen and Meeuwsen (2003).	10 consecutive days	105 min	2,500 m	Elite male triathletes	60 to 70% heart rate reserve	↑ aerobic power, ↑ Wingate performance, ↑ peak power	↑ Wingate performance, No change aerobic power
Hamlin et al. (2010)	10 consecutive days	90 mins	3,200 to 4,400 m	Sixteen well trained athletes	60 to 70% heart rate reserve	↑ 20km TT performance, ↑ 30-sec Wingate power	↑ 30-sec Wingate power. ↔ 20-km TT performance
Czuba et al. (2013)	3 x pw for 3 wks	57 to 65 min	2,500 m	Moderately trained male basketballers	4 to 5 x 4 min intervals at 90% v$\dot{V}O_{2max}$	↑ Wmax, ↑ $\dot{V}O_{2max}$	↑ Wmax, ↑ $\dot{V}O_{2max}$
Czuba et al. (2011)	3 x pw for 3 wks	60 to 70 min	2,500 to 2,600 m	Elite male cyclists	30 to 40 mins at 95% LT	↑ $\dot{V}O_{2max}$, ↑ Wmax, ↑ 30-km TT power	↑ $\dot{V}O_{2max}$, ↑ Wmax, ↑ 30-km TT power
Dufour et al. (2006)	2 x pw for 6 wks	24 to 40 min	3,000 m	Highly trained male runners	24 to 40 mins at 2nd ventilator threshold	↑ v$\dot{V}O_{2max}$, and vVT_2 , ↑ time to	↑ hypoxic v$\dot{V}O_{2max}$ and vVT_2, ↑ time to

						exhaustion	exhaustion
McLean et al. (2015)	2 x pw for 4 wks	30 min	3,000 m	Sub elite Australian Footballers	90 to 110% v $\dot{V}O_{2max}$ for 30s to 3 min, 30s to 1 min rest	↑ Yo-Yo IR2, ↑ time to exhaustion, ↑ TS running performance	↓ Yo-Yo IR2, ↔time to exhaustion, ↑ TS running performance
Roels et al. (2007)	5 x pw for 3 wks	60 min	3,000 m	Endurance Trained Athletes	60% $\dot{V}O_{2max}$ (3 x wk) 2 sets of 3 x 2 min intervals (2 x wk)	↑ Wmax	↔ Wmax, ↓ 10km TT power
Truijens et al. (2003)	3 x pw for 5 wks	20 min	FiO_2 0.153	Elite Swimmers	30 s to 1 min intervals. Work:Rest 2:1	↑ 100m and 400 m TT performance	No change

2.10 Individual response to altitude exposure

There is a variable response to altitude training among athletes, with the majority of athletes showing increases while a minority show no change, or even a decrement to performance (McLean et al., 2013a). Those showing improved performance have an increase in [EPO] to acute altitude exposure (Levine and Stray-Gundersen, 2005).

Although there is an individual response to performance changes post altitude exposure, with some athletes displaying change, and others showing no benefit, the same athlete may respond very differently to future training camps. In a group of elite Australian footballers exposed to two moderate LHTH camps separated by 12 months, there was only a small correlation between the individual responsiveness to the first and second training camp, with the group as a whole had a repeatable increase in Hb_{mass} (McLean et al., 2013a). Therefore, the thought of altitude responders and non-responders may not be a fixed trait regarding changes in Hb_{mass} (McLean et al., 2013a).

More pertinent may be the physical health of the athlete before, and during the altitude exposure. In elite TS athletes, those that missed a training session due to illness throughout the intervention had a trivial 0.2 ± 2.4% change in Hb_{mass}, which was 3.9 ± 1.1% lower than healthy participants. This change was almost certainly less than healthy participants (McLean et al., 2013a).

Another suggestion for the lack of improvement in Hb_{mass} is that athletes with a higher starting Hb_{mass} may be closer to their physiological limit, with less room for further adaptation than those with lower starting levels (Gore et al., 1998). This has again been disproven, as athletes with high starting levels of Hb_{mass} can increase their levels after only 11 (2.9 ± 2.0%), and 19 days (3.5 ± 2.5%) (Garvican et al., 2012). This indicates that a combination of factors is at play to determine the individual Hb_{mass} response following an altitude training camp. These factors may include EPO response (Levine and Stray-

Gundersen, 2005), starting Hb_{mass} (Gore et al., 1998), and illness prior to and during altitude exposure (McLean et al., 2013a). Further investigation is required to determine the reason for differing responses to the same altitude exposure.

2.11 Time Course for Physiological and Performance Change

2.11.1 Importance of determining the time-course for altitude adaptation

Determining both the earliest time-course for performance changes, and the time-course these benefits remain has relevance for team-sport athletes. It is generally thought 12-21 days of exposure is required to elicit altitude-induced performance changes (Robertson et al., 2010c, Robertson et al., 2010a, Saunders et al., 2004b, Gore et al., 2001, Roberts et al., 2003, Martin et al., 2002). As many team-sport competitions have weekly matches, extended blocks of two to three weeks of altitude exposure are difficult to administer, particularly in season. However, if shorter blocks were proven to have a performance or haematological benefit, altitude becomes a much more viable option in season.

As well as the earliest time course for adaptation, discovering the length of time any altitude induced adaptation remains is important for team-sport athletes. A team-sport season may last for six months or more (www.afl.com.au, 2016, www.premierleague.com, 2016), therefore determining the length of time any adaptation remains allows for optimal timing of exposure to maximise benefits around important periods of the season. By combining the minimum time course, and the length benefits remain, repeated bouts throughout a season may allow for optimal use of altitude for team-sport athletes.

Hypoxic dose is determined by a number of factors. These include the length of exposure, level of hypoxia (optimal altitude), passive or active exposure, and the exercise design for active hypoxic exposure.

2.11.2 Number of nights for LHTL

2.11.2.1 Performance

It is generally thought that approximately two to three weeks is required to see clear changes in performance following LHTL (Saunders et al., 2004b) (Robertson et al., 2010a, Robertson et al., 2011, Saunders et al., 2004a). However, very few studies undertake performance testing mid exposure. Therefore most studies are not designed to determine the earliest time course, but merely whether the altitude exposure increased performance over the length of study.

It is plausible that a reason behind not finding performance changes earlier than two to three weeks is simply due to the failure to undertake performance testing during the intervention. Indeed, studies in which Hb_{mass} and reticulocyte were measured throughout showed blood markers increased in the first week of altitude exposure (Robertson et al., 2011, Robertson et al., 2010a). This suggests adaptation is occurring very early on, and improved performance may occur before the three-week time frame indicated above.

To support the theory of earlier performance improvements, maximal mean power output over 4 mins showed clear improvements compared to a control group following a short exposure to LHTL (Roberts et al., 2003). The same improvement in performance occurred regardless of whether five, 10 or 15 nights of exposure were undertaken (Roberts et al., 2003). These changes occurred without an improvement in $\dot{V}O_{2max.}$ However there was an increase in maximal accumulated oxygen deficit, indicating a greater anaerobic contribution. Each group participated in the study twice, once acting as a control for one group, and as one of the LHTL groups with a four-week washout period between conditions. Although it may seem surprising that the five night LHTL had the same improvement as the 10 and 15 night, it should be noted that the control group for the 5-night condition were the 10 night LHTL group, and completed their LHTL intervention prior to this. Therefore it is possible that the effects of the LHTL exposure were still apparent when acting as a control group for the 5-night group. As the benefits of altitude wear off after time, there may have been a slight detraining affect when acting as a control group for the 5-night LHTL group, potentially magnifying the effect of 5 nights for the LHTL group. Further, both the 10 and 15 night control groups did not have a preceding LHTL block prior to acting as a control (Roberts et al., 2003). Therefore, the LHTL interventions may have affected the outcomes.

There have been other studies showing improvements in performance in less than two weeks. After only 9.5 hours per night of exposure to 3,000 m of simulated altitude for 11 nights, cycling efficiency improved, although changes in muscle buffer capacity were not apparent until after 23 days of LHTL (Gore et al., 2001).

Likewise, in elite runners, 10 nights of LHTL was enough to enhance 400 m race time, while the control group did not improve (Nummela and Rusko, 2000). These athletes spent 16.5 ± 1.5 hours per night for the 10 nights of the study exposed to a simulated altitude of 2,200 m.

In summary, although it is currently thought that two to three weeks of altitude intervention are required for changes in performance, most studies only test pre and post, making it impossible for these studies to find the earliest time course. If testing is undertaken throughout the intervention, earlier performance changes have been observed. Therefore if detecting time course for adaptation is an aim, regular testing throughout the study is needed. Determining the time-course for adaptation for team-sport athletes is vital, due to the limited time available to undertake altitude training, a traditional 3 to 4 week block in season is difficult to administer, however if shorter blocks were proven to have a performance benefit, altitude training suddenly becomes a viable in season training modality.

2.11.3 Heamatological changes through LHTL:

For haematological changes, it has been suggested that 1% change occurs per 1,000 hours of hypoxic exposure (Garvican et al., 2012). With this dose refined to include the level of altitude as a variable to consider when determining the earliest time course for haematological changes (Garvican-Lewis et al., 2016), which has been dubbed kilometre hours. Kilometre hours is determined by height in kms, multiplied by total hours of exposure (Garvican-Lewis et al., 2016).

The half-life of serum EPO (sEPO) is only 5.5 hours; therefore during LHTL exposure, if daily doses are insufficient, EPO levels may not be raised for much of the day. For this reason, LHTL studies with insufficient daily altitude exposure are unlikely to show increases in haematological variables including $Hb_{mass.}$ After an initial rise over the first couple of days, sEPO gradually decreases, with levels 26 ± 21% below baseline levels after 21 nights of simulated LHTL (Clark et al., 2009).

While no performance test was undertaken, increases in Hb_{mass} have occurred after 11 nights in a group of endurance cyclists exposed to LHTH (Garvican et al., 2012). This study was not purely a LHTL study, with much of the training occurring at moderate altitude, making it not possible to classify as LHTL, and more likely LHTH (Garvican et al., 2012).

In male field hockey players, 14 days of exposure to 3,000 m altitude for 14 hours per day was enough to improve Hb_{mass} by 3 to 4% (Brocherie et al., 2015). This change to Hb_{mass} was the same for groups who performed either LHTL only, or LHTL combined with IHT, with both groups increasing more than a LLTL control group (Brocherie et al., 2015).

Of the few studies to test for Hb_{mass} changes throughout, and not merely pre and post study, in a 3 week LHTL protocol comprising 14 hours per day at 3,000 m increased Hb_{mass} by 1% per week for a total of 3.3% total change (Clark et al., 2009). As increased Hb_{mass} is considered a possible mechanism for improved performance following altitude exposure, it is plausible that short exposures can have a beneficial effect on performance in athletes.

In summary, although most research states 14-21 days is required to elicit changes in performance, studies using shorter time frames have shown performance benefits in 5 to 12 days. While changes in Hb_{mass} appear to occur at a rate of 1% per week, this depends on the altitude height, and length of exposure per day, with total accumulated hours an important marker for determining expected Hb_{mass} response. It is clear that more work is required to determine the minimum time course for altitude induced performance and haematological changes. For altitude exposure to become a viable in season training modality for team-sports, it is critical to determine the shortest time course for altitude induced performance changes.

2.11.4 Time Course for Altitude Induced Haematological and Performance Changes Remaining on Return to Sea Level

Although performance may still be raised at least 15 days post LHTL (Brugniaux et al., 2006), changes to Hb_{mass} seen through LHTL start to disappear more quickly (Pottgiesser et al., 2012). Altitude induced haematological changes begin to return to pre exercise values shortly after return to sea level. After 26 nights of simulated altitude, Hb_{mass} increased by 5.5%, but had decreased by 3.0% only 9 days on return to sea level (Pottgiesser et al., 2012). Compared to the Hb_{mass} increase of 1.5% per week through altitude exposure, the rate of Hb_{mass} loss on return to sea level was two to three fold higher (Pottgiesser et al., 2012). This rapid degradation in Hb_{mass} has also been shown in elite cyclists. Following 21 days of LHTH, Hb_{mass} remained likely higher than baseline 10 days after returning to sea level (Garvican et al., 2012), but compared to a control group, this mean increase in Hb_{mass} was unclear (Garvican et al., 2012).

It appears that the rapid return to pre-altitude Hb_{mass} is not only seen through LHTL, but is also apparent in IHT. Two days following IHT, Haemoglobin and Haematocrit were likely, and very likely greater than a placebo group respectively, however 9 days following, these levels were not different to placebo, while reticulocytes were very likely lower than placebo (Hamlin et al., 2010b). Again, 2 days after 10 sessions of moderate intensity IHT over 10 days, both haemoglobin (Hb) concentration and haematocrit levels were significantly increased, but 1 week later both parameters had returned to baseline (Hendriksen and Meeuwsen, 2003). Surprisingly, a sea level group had the same increases in blood values 2 days post training, and these increases remained until day 9 (Hendriksen and Meeuwsen, 2003).

It is clear that Hb_{mass} has returned close to baseline after approximately 10 days of sea level exposure. This rapid return to baseline Hb_{mass} is thought to be due to a phenomenon termed "neocytolysis", where Hb turnover is up regulated due to what is deemed "excessive" Hb production (Pottgiesser et al., 2012). As such, when Hb production decreases on return to sea level, degradation remains increased for a number of days, effectively providing a negative Hb turnover environment (Pottgiesser et al., 2012). This reduction in red cell mass upon return to sea level is thought to be through a selective destruction of young, but relatively mature red cells (Chapman et al., 2013b). This conclusion was made after reductions in red cell mass were found despite no change in reticulocyte count days after return to sea level (Chapman et al., 2013b). Two studies had similar findings, firstly, a 9.6% reduction in red cell mass three to seven days post altitude descent in long-term altitude residents (4390 m) (Rice et al., 2001). This occurs despite no change in reticulocyte count during the first 6 days at sea level (Rice et al., 2001). Similarly, a mean reduction of 9% in erythrocyte volume in the first week on return to sea level has been reported, with no decline in reticulocyte count until 8 to 10 days (Huff et al., 1951). Conversely, elite Kenyan runners permanently residing between 1,900 m and 2,200 m showed no change in total haemoglobin mass (tHb_{mass}) during the first 14 days after descent to 340 m (Prommer et al., 2010). However there was a 6% drop after 33 days at 340 m. Interestingly, the permanent altitude residents had almost identical starting tHb_{mass} as the control group of sea level resident elite endurance runners (Prommer et al., 2010). Therefore the permanent altitude residents had a significantly lower tHb_{mass} after

33 days low altitude living compared to the control group. This reduction in tHb_{mass} was attributed to suppressed EPO levels of the Kenyan runners in comparison to CON after initial arrival at near sea level conditions (Prommer et al., 2010). After Hb_{mass} adapted to near sea level conditions, EPO increased to levels similar to CON. While reticulocyte count gradually decreased in the Kenyan runners after day 7 (Prommer et al., 2010).

2.11.5 Optimal time for peak performance following altitude exposure

There is very little research detailing the timeline for performance benefits remaining post altitude exposure. As previously stated, the acclimatisation effects of altitude begin to dissipate shortly after altitude exposure is removed. Therefore the timing of an altitude training camp before competition is crucial. The optimal time for peak performance post altitude has been proposed to rely on a number of factors: firstly the decay in red cell mass, the consequences of ventilatory acclimatisation, and alterations in biomechanical and neuromuscular factors associated with force production (Chapman et al., 2013b). For those athletes that are required to travel large distances for an altitude camp, removing the fatigue associated with travel also must be considered. Athletes unaccustomed to altitude also display a poorer quality of sleep for at least two weeks after exposure to moderate altitude (Roach et al., 2013).

Elite swimmers were tracked for 28 days following 21 days of either LHTL (14 h day^{1}) or LHTH, both groups were slower in the first week post exposure, with LHTH slower 1 day post exposure, and LHTL slower 7 days post exposure compared pre (Gough et al., 2012). Both groups were also slower than a control group for up to 7 days post (Gough et al., 2012). There was also no clear improvement in either group for up to 28 days following altitude exposure (Gough et al., 2012). Both LHTH and LHTL groups had greater tHb one day post exposure ($3.8 \pm 1.3\%$ and $4.0 \pm 1.1\%$ respectively) (Gough et al., 2012). While 14 days post altitude exposure tHb was reduced slightly in both groups, but remained “likely” higher than pre exposure (Gough et al., 2012). Training volume and intensity was different between altitude methods, making it difficult to make inferences as to the effectiveness on performance of one method over the other. The LHTH groups training volume was 27% higher than LHTL (52 ± 10 km for LHTH vs 41 ± 8 km for LHTL, while the LHTL group intensity was 20% higher than LHTH. However the difference in accumulated training load was small (4%) (Gough et al., 2012). This indicates that despite the positive haematological adaptation experienced by the altitude group, there was no performance advantage for the swimmers in the altitude groups (Gough et al., 2012). However as training load was not reported for the control group, it is impossible to say whether training load was matched between all three groups.

Performance improvements in the wingate test remain for at least nine days following 10 days of IHT. This is despite the IHT intervention consisting of 90 to 105 mins of moderate intensity activity for 10 days (Hamlin et al., 2010b, Hendriksen and Meeuwsen, 2003).

Maximal benefit from altitude training may not occur immediately post exposure. This may be due to the extra stress of altitude, combined with accumulated fatigue through training, with a few days to several weeks required to dissipate fatigue and allow increased fitness to become apparent (Morton et al., 1990). To support this, 28 days post exposure; race walkers averaged a 6% improvement on their pre altitude best over 20km (Saunders et al., 2010).

Determining the time course for performance benefits remaining post altitude training is vital for TS athletes. Considering the length of seasons for many team-sports, refining this time course, combined with the shortest time course for altitude-induced performance change, could allow sport scientists to plan altitude exposures intermittently throughout the season to maintain benefits.

2.12 Hypoxia and Resistance Training

2.12.1 Introduction

The development of aerobic capacity, and intermittent running performance are important for team-sport athlete physical performance. The benefits of hypoxia on TS athlete running performance have also been discussed in detail in section 2.2.

When determining the efficacy of altitude and team-sport athlete physical performance, as team-sport athletes regularly undertake concurrent strength and endurance training in their preparation for matches (Helgerud et al., 2011), therefore the effects of hypoxia in combination with strength training must be determined.

Hypoxia has long been used in combination with endurance training (Terrados et al., 1988), while the positive effects of resistance training in hypoxia are becoming more evident (Takarada et al., 2000b).

The two methods that are commonly used to achieve hypoxia in combination with RT are blood flow restriction (BFR), and systemic hypoxia, or intermittent hypoxic resistance training (IHRT).

2.12.2 The Importance of Strength and Power for Team-Sport Athletes

The development of strength and power is important for many team-sport athletes due to the physical involvements in collision sports including Australian football and the Rugby codes (Dawson et al., 2004, Roberts et al., 2008). Some of these physical involvements include tackles, jumps for marking contests, and scrimmages in Rugby (Dawson et al., 2004, Kempton et al., 2013). All of these require high force and power to be executed effectively. Strength is also important for TS athletes due to the correlation between 1RM squat strength and sprint times over 10 m in team-sport athletes (Duthie et al., 2006). While increased strength through heavy resistance training have led to improved running economy by 4.7% in soccer players (Hoff, 2001). This indicates that high levels of strength are important for physical involvements, to help improve speed and acceleration, and can potentially improve markers of aerobic performance, all of which are vital for team-sport athlete performance. For this reason, resistance training plays an integral part in the training programs of team-sport athletes (Helgerud et al., 2011).

2.12.3 Systemic Hypoxia

With IHRT, participants perform RT while breathing hypoxic air, either by simulated altitude through decreased oxygen content of the air (Friedmann et al., 2003, Nishimura et al., 2010), or decrease partial pressure of air seen at moderate to high altitude (Feriche et al., 2014). There is limited research on IHRT, and even less using athletes. Most of the research using IHRT has used untrained individuals (Nishimura et al., 2010, Kon et al., 2014), with only one study on team-sport athletes (Manimmanakorn et al., 2013). While the evidence that is currently available shows conflicting findings on the effectiveness of IHRT, on closer inspections there are reasons for these contradictory results, which will be examined in detail.

2.12.3.1 Strength and Hypertrophy changes through Intermittent Hypoxic Resistance Training

One of the first studies using IHRT showed increased strength and hypertrophy compared to the same training in normoxia (Nishimura et al., 2010). In untrained university students, participants undertook two IHRT sessions per week for six weeks; with a moderate intensity training intervention undertaken, with four sets of 10 repetitions at 70% 1RM used for the French press and arm curl exercises. Following the six weeks training, the IHRT group showed greater increases in muscular hypertrophy and strength than the control group (Nishimura et al., 2010). After three weeks, muscular strength had already increased more in the IHRT group than the control group. Unfortunately it was not possible to isolate increases in strength due to neural mechanisms and muscle hypertrophy at this mid point, as measures of cross sectional only occurred pre and post study (Nishimura et al., 2010). It should be noted that the conclusion was an increase in 1RM strength, this is despite 1RM being determined off an equation based off 10RM testing (Nishimura et al., 2010). It is clear here that it was in fact 10RM that improved, which is not truly indicative of maximal strength.

In untrained participants, both a systemic hypoxic group (FiO_2 0.144) and control group improved 1RM by a similar amount using five sets of 10 reps at 70% 1RM (Kon et al., 2014), both groups also had the same increases in lean mass and decreases in fat mass. This would suggest that systemic hypoxia offers no further benefit than a control group. But only the hypoxic group improved muscular endurance as measured by maximal repetitions at 70% 1RM (Kon et al., 2014). Of note, a similar training intensity of 70% 1RM was used throughout the study. As this was the same intensity used during training, it is possible that the strength changes seen through systemic hypoxia were specific to the training stimulus, and accentuated through the hypoxic environment. This is further highlighted as there was no change between groups in 1RM, which is a very different strength quality to that needed for maximal reps at 70% 1RM. The theory of hypoxia adaptations being specific to the training stimulus is supported by another group of researchers using a very similar training intensity and study design (Ho et al., 2014). Using untrained participants, IHRT was undertaken three times per week for six weeks. A load corresponding to a 10RM was used for three sets, at the end of the study, 1RM improved for both groups, with no difference between groups (Ho et al., 2014). The authors concluded that no additive effect was present through the IHRT, however if the participants undertook testing at the same intensity as training (a 10RM test), the conclusions may have been very different. There was also no difference in a maximal isometric contraction (Ho et al., 2014).

Contrary to this, following three session per week for eight weeks at hypoxia (FiO_2 0.127), Kurobe et al. found greater muscle hypertrophy in a hypoxic group compared to a normoxic group, no change in 10RM between groups at post testing (Kurobe et al., 2015). As the hypoxic group increased muscle hypertrophy more than the control group, it is hard to determine why this did not translate into greater performance in the 10RM test compared to the control group. Untrained participants were used for this study, with the authors concluding that the main strength gains were due to neural factors (Kurobe et al., 2015). The hypoxic group increased strength in the first two weeks, while the control group did not, suggesting that hypoxia may increase neural mechanisms more than the same training at sea level. The level of hypoxia was greater in the Kurobe et al. study compared to Kon et al. Higher levels of hypoxia have shown a greater metabolic stress (Scott et al., 2015b), indicating that this level of hypoxia by Kurobe et al. may be too great for optimal training stimulus. To assess the effect of hypoxia on RT intensity, participants performed the same RT session three times while exposed to three different levels of hypoxia, with a FiO_2 of 0.21, 0.16, and 0.13 (Scott et al., 2015b). Participants were blinded to the level of altitude, and performed five sets of five repetitions at 80% 1RM. There were no differences between any of the conditions for power or force variables, indicating that RT performance is not affected through hypoxia. There was a difference between groups in HR response, with the most extreme altitude (FiO2 of 0.13) displaying a higher HR than the other conditions (Scott et al., 2015b).

Once again, a study using a higher altitude showed no difference between an IHRT and control group. Using a low intensity IHRT protocol with untrained participants exposed to a FiO_2 of 0.12 three times per week for four weeks, there was no greater change in strength, muscular endurance or hypertrophy than a control group (Friedmann et al., 2003). Participants were required to perform leg extension exercises at 30% 1RM for 25 reps. It is possible that this lower intensity, combined with a higher altitude was suboptimal in eliciting changes in strength.

In contrasting findings, netball athletes using a low intensity RT protocol (20% 1RM) had greater changes than a control group (Manimmanakorn et al., 2013). The altitude level was not reported in this study, with altitude adjusted to maintain SpO_2 values were kept constant at 80%. With a variety of altitudes used to maintain an SpO_2 of 80%, it is possible that the FiO_2 was within the range allowing for adaptations to occur, although this cannot be determined. This is the only study on IHRT using team-sport athletes.

A possible mechanism behind the increased strength and hypertrophy in some IHRT studies is the hormonal response seen following IHRT. Resistance Training in hypoxia causes an increase in the levels of anabolic hormones (Kurobe et al., 2015). Following a moderate intensity training protocol in systemic hypoxia (3 sets of 10RM to fatigue with one minute rest), growth hormone was higher in the hypoxic group compared to the control group, with a concomitant increase in muscle thickness also occurring in hypoxia in comparison to control (Kurobe et al., 2015). This change in anabolic hormones also occurs following lower intensity RT. Participants in a different study undertook five sets of 14 reps at 50% 1RM with 1 minute break (Kon et al., 2012). There was a greater increase in Growth Hormone only after the IHRT trial, with the control trial showing no change in Growth Hormone (Kon et al., 2012). No other hormone had meaningful changes between groups. There is evidence that anabolic hormones are linked to increased strength and hypertrophy (Takarada et al., 2000a), meaning the greater anabolic hormone response following IHRT may lead to greater adaptation.

In conclusion, with the limited amount of research currently available, it appears for IHRT to be successful a number of factors must be met. Firstly, a moderate altitude appears optimal, with a FiO_2 of 0.14 to 0.16 deemed the optimal level. Secondly, IHRT may merely magnify any expected outcome seen through RT. When designing a training study, correct testing procedures should be used to detect changes in strength. Studies that use a similar intensity during testing as training appear most successful in detecting changes in strength. Studies using a different testing intensity to that used during training have show variable results, while other studies that have shown no change in 1RM have used a 10RM to base the 1RM results off. In essence, rather than showing no change in 1RM, these studies are actually reporting no change in 10RM, and should be reported this way as to not add confusion to the literature. Lastly, no research has looked at loads above 70% 1RM in a training study, however these loads may be most suited to changes seen through IHRT, due to no decrease in training intensity at higher altitudes, unlike high intensity aerobic exercise, which sees a decrease in training intensity at maximal workloads.

Table 2.5. Intermittent hypoxic resistance training studies.

[a]1RM determined off a 10RM test.

Authors	Participants	Altitude	Study length	Reps and sets	Load and exercises	Findings
Kon et al. (2014)	Healthy males	FiO_2 0.144	2 x pw for 8 weeks	5 sets of 10 reps	70% 1RM for Bench Press and Leg Press 90-s rest	No difference between groups for CSA. No difference in1RM
Kurobe et al. (2015)	Healthy males	FiO_2 0.127	3 x pw for 8 weeks	3 sets to failure	10RM of elbow extension	IHRT ↑ muscular endurance compared to control No difference between groups for 10 RM. IHRT ↑ muscle hypertrophy compared to control
Friedmann et al. 2003	Untrained males	FiO_2 0.12	3 x pw for 4 weeks	6 sets of 25 reps	30% 1RM for leg extension	Both groups ↑ muscular endurance No difference between groups
Ho et al. (2014)	Untrained males	FiO_2 0.15	3 x pw for 6 weeks	3 sets of 10 reps	10RM for squats	Both groups ↑ 1RM. No difference between groups
Manimmanakorn et. al (2012)	Female team-sport athletes	SpO_2 of 80%	3 x pw for 5 weeks	5 sets to failure	20% 1RM for leg extension and curl	IHRT ↑ 3-s & 30-s MVC compared to control IHRT ↑ max reps at 20% 1RM compared to control
[a]Nishimura et al. (2010)	Untrained males	FiO_2 0.16	2 x pw for 6 weeks	4 sets of 10 reps	[a]70% 1RM for French press & arm curl	IHRT ↑ 1RM and hypertrophy compared to control

2.13 Critically Analysing the Current Altitude Research

When interpreting any altitude training study, and training studies in general, it is important to take into account any training, and the training status of the athletes at the beginning of the study. Failure to monitor training, inappropriate training that does not match the testing protocol employed, or a mismatch of training between intervention and control groups can all contribute to differences seen in the outcome of altitude training studies. Further, the training status of the participants at the beginning of the study, and any training prior to the study beginning should be documented where possible. The reason for this is that if participants come in a state of fatigue, they may improve simply by decreasing training volume, as a taper may increase endurance performance in endurance trained athletes by approximately 3% (anywhere between 2 and 6%) (Kubukeli et al., 2002, Mujika and Padilla, 2003). As most altitude studies find performance changes in these ranges, it is clear that determining the training status pre study can have large implications on the findings of any intervention. These factors also impact on the ability to determine whether any changes in performance are due to the intervention, differences in training between groups, or training status of the participants at testing periods. Timing of testing post altitude exposure may also affect the results (Brugniaux et al., 2006). With tests immediately after altitude exposure, it is possible that there is still residual fatigue from the hypoxic exposure and training intervention (Gough et al., 2012), therefore the biggest benefit from testing may occur a number of days post exposure after any residual fatigue from the training intervention has dissipated.

The aim of this thesis is to answer some questions relevant to team-sport athletes and exposure to altitude training that are yet to be determined.

2.14 Aims

The primary aim of this thesis is to determine whether altitude training improves team-sport athlete physical performance, with a secondary aim to determine the time course for any altitude-induced adaptation. The following studies were designed with the goal of answering the above primary and secondary aims.

1. ***Intermittent Hypoxic Training and team-sport athlete physical performance***
    a. Does IHT improve time trial performance in team-sport athletes?
    b. Does IHT improve intermittent running performance in team-sport athletes?
    c. What is the minimum time course for any altitude induced adaptation?
    d. How long does any increase in performance last?
    e. Does IHT improve Hb_{mass} in team-sport athletes?
2. ***Live-High Train-Low and team-sport athlete physical performance***
    a. Does LHTL improve time trial performance in team-sport athletes?
    b. Does LHTL improve intermittent running performance in team-sport athletes?
    c. What is the minimum time course for any altitude induced adaptation?
    d. Does LHTL improve Hb_{mass} in team-sport athletes?
    e. Does an intermittent LHTL design that could fit in with the in season schedule improve physical capacity in team-sport athletes.
3. ***The effects of Resistance Training in Hypoxia on Strength, Power and Hypertrophy on strength-trained participants.***
    a. Does Resistance Training in hypoxia increase maximal strength, power and speed more than the same training near sea level?
    b. Does Resistance Training in hypoxia increase lean muscle mass more than the same training near sea level?

3 TEAM-SPORT ATHLETES' IMPROVEMENT OF PERFORMANCE ON THE YO-YO INTERMITTENT RECOVERY TEST LEVEL 2, BUT NOT OF TIME-TRIAL PERFORMANCE, WITH INTERMITTENT HYPOXIC TRAINING.

3.1 Abstract

Purpose:

To determine the time-course for physical capacity adaptations to intermittent hypoxic training (IHT) in team-sport athletes, and time-course for benefits remaining post-IHT.

Methods:

A pre-post parallel-groups design was employed, with twenty-one Australian Footballers assigned to IHT (n=10) or control (CON; n=11) matched for training-load. IHT performed eleven 40-min bike sessions at 2500-m altitude over 4-weeks. Yo-Yo Intermittent recovery test level 2 (Yo-Yo IR2) was performed pre, after 3, 6, and 11 IHT sessions, and 30 and 44 days post IHT. Repeated time-trials (2- and 1-km TT, with 5-min rest) were performed pre, post, and 3 weeks post IHT. Haemoglobin mass (Hb_{mass}) was measured in IHT pre, after 3, 6, 9 and 11 sessions.

Results:

Baseline Yo-Yo IR2 was similar between groups. After 6 sessions, the change in Yo-Yo IR2 in IHT was *very likely* higher than CON (27% greater change, Effect size 0.77, 90% confidence limits 0.20;1.33), and likely higher 1-day post (23%, 0.68, 0.05;1.30). The IHT group change remained likely higher than CON 30-days post (24%, 0.72, 0.12;1.33), but was not meaningfully different 44-d post (12%, 0.36, -0.24;0.97). The change in 2-km TT performance between groups was not different throughout. For 1-km TT, CON improved

more post, but IHT maintained performance better after 3-weeks. Hb_{mass} was higher post (2.7%, 0.40 -0.40;1.19).

Conclusion:

Short-duration IHT increased Yo-Yo IR2, compared to training-load matched control in two weeks. An additional 2 weeks of IHT provided no further benefit. These changes remained until at least 30-d post-training. IHT also protected improvement in 1-km TT.

3.2 Introduction:

Team-sports include extensive low- to moderate-intensity movements interspersed with periods of higher intensity (Aughey, 2010, Aughey, 2011). It is common for these high-intensity efforts to have rest periods of less than 20-s (Aughey, 2011). Phosphocreatine plays a critical role in the work completed during repeated high-intensity efforts. The time required for PCr resynthesis is typically greater than rest periods available in competition (Dawson et al., 1997), so the contribution of the aerobic energy system increases to meet the energy demands with each subsequent effort (Bogdanis et al., 1996). Thus, by promoting muscle oxygenation and accelerating PCr resynthesis during recovery, repeat high-intensity performance is increased (Sperlich et al., 2011, Bogdanis et al., 1996). A high aerobic capacity is important for TS athletes evidenced by better performing teams and individuals covering greater distance, and performing more accelerations during games (Aughey, 2010, Aughey, 2011), and better performance in time trials (TT) (Gastin et al., 2013), and the Yo-Yo IR2 (Young et al., 2005, Mooney et al., 2011). Although inconclusive whether improved physical capacity translates into greater running performance during games or chance of winning, training that increases aerobic and/or anaerobic capacity may potentially improve team-sport athlete running performance.

Intermittent hypoxic training (IHT) involves residing at sea level and training at altitude (Czuba et al., 2011). It is debated, however, as to the effectiveness of IHT on sea-level performance. Performance has increased, stayed the same, or even decreased following IHT. For example, power output in a 30-s Wingate test has both improved (Hamlin et al., 2010b), and not changed (Morton and Cable, 2005). Similarly, 30-km cycling TT $\dot{V}O_{2max}$, oxygen uptake at lactate threshold and time to exhaustion have all improved more than control following IHT (Czuba et al., 2011, Dufour et al., 2006), yet in another, 20-km TT improvements were unclear (Hamlin et al., 2010b). Surprisingly, average power in a cycling TT performed at sea level was actually worse following IHT compared to control, although when performed in hypoxia, the IHT group outperformed the control group (Roels et al., 2007). Muscle oxidative function may decrease with hypoxic training (Bakkman et al., 2007), and due to the short exposure to hypoxia, Hb_{mass} generally does not increase following IHT (Rasmussen et al., 2013). Therefore performance changes with IHT are likely driven by non-haematological mechanisms. Although we don't expect to see changes in Hb_{mass}, we will measure Hb_{mass} to help determine whether any performance changes are through haematological, or non-haematological changes.

It is unknown if IHT improves team-sport athlete running, or how long benefits last. As Yo-Yo IR2 and TT performance are correlated to team-sport athlete performance (Mooney et al., 2011, Young et al., 2005, Gastin et al., 2013), the aim of this study was to determine whether IHT increases Yo-Yo IR2 and aerobic TT performance in team-sport athletes. Repeated aerobic TT's may be more indicative of aerobic capacity than a single effort (Garvican et al., 2011). Therefore the effects of IHT on repeated aerobic TT's will be measured.

Furthermore, studies reporting increased performance following IHT are usually 3 or more weeks in duration (Czuba et al., 2011, Faiss et al., 2013, Dufour et al., 2006), limiting the in-season applicability of IHT for team-sport athletes with a hectic training and competition schedule (Cormack et al., 2008). However, if fewer sessions were effective in eliciting a performance benefit, short exposures become viable in-season. Therefore, secondary aims were to determine the time-course for adaptation, and the time-course for performance benefits remaining post-IHT.

3.3 Methods

3.3.1 Design

A pre-post, parallel groups controlled-trial study design was used. The study was undertaken during pre-season after 12 days of normal squad training. Although participants had only trained for 12-d prior to the study, they were instructed to maintain a reasonable level of fitness in the off-season break; however, training data was not collected during this period. For TS athletes, this is a high-volume period of training, with a primary goal to improve the physical capacity of athletes. Therefore gains in aerobic capacity are expected, however testing the efficacy of IHT in stimulating additional gains was established through a pair matched control group with a similar training load. The study was approved by the Victoria University Human Research Ethics Committee.

3.3.2 Participants

Twenty-two male semi-professional Australian Footballers from the same Victorian Football League (VFL) team volunteered for the study. The VFL is a feeder competition to the elite competition. All subjects were free from injury, living at sea level, with no exposure to high altitude in the previous 12 months. After baseline testing, subjects were pair-matched for Yo-Yo IR2 performance, and assigned to IHT or control (CON). One subject was excluded from IHT due to injury; therefore 21 participants completed the study (IHT n=10, CON n=11). The IHT were supplemented daily with oral iron (305 mg ferrous sulfate, 1000 mg Vitamin C). Iron supplementation was used to ensure athletes had adequate iron levels, as iron deficient athletes may be unable to increase red cell volume in response to altitude exposure (Stray-Gundersen et al., 1992).

3.3.3 Methodology

All IHT sessions were performed in a hypoxic chamber under normobaric hypoxia (FiO_2 15.2%, simulating 2500-m altitude, temperature 21.0°C, humidity 40%). This altitude was chosen as it has increased endurance performance through IHT (Czuba et al., 2011).

The IHT group performed 11 IHT sessions (3 sessions.week^{-1} for weeks 1-3, and 2 sessions in week 4), CON performed 8 interval bike sessions at sea level (2 sessions.week^{-1}). Three less bike interval sessions were undertaken by CON to ensure equal total training load between groups. The rationale for CON performing three less bike sessions compared to the IHT group is to compare traditional team-sport pre-season training, including running, with a condition where portions of normal training were replaced with IHT. All interval sessions for both groups were 40-min and performed on a Velotron bicycle ergometer (www.racermateinc.com. Seattle, Washington, USA). After a 5-min warm-up, participants performed 5-min intervals, with 2.5-min recovery. Self-adjusted workloads were used for all sessions. To aid in pacing, for the first 2-min of each interval, CON was instructed to maintain 3-3.5 W.kg^{-1} (220-350 W), then adjust their pace to complete as much work as possible for the remainder of the interval. For the IHT group, due to decreased power at increased altitudes (Clark et al., 2007), 2.5-3 W.kg^{-1}, (180-280 W) was maintained for the first 2-min, with subjects completing as much work as possible for the remainder of the interval. A total of 3-4 intervals were performed per session. Number of intervals per session per week is described in Table 3.1.

Table 3.1. Details of the number of intervals performed per week. Each session was 40 mins in duration. For IHT group, three sessions for weeks 1-3, and 2 sessions for week 4. Each session was separated by at least 1 day. Where 2 sessions are stated, this session was performed twice for that week.

Week	IHT group session details	Control group session details
1	1 session – 4x5 min intervals, 2.5 min rest 2 sessions – 3x5 min intervals, 2.5 min rest	1 session – 4 x 5 min intervals, 2.5 min rest 1 session – 3 x 5 min intervals, 2.5 min rest
2	2 sessions – 4x5 min intervals, 2.5 min rest 1 session – 3x5 min intervals, 2.5 min rest	2 sessions – 4x5 min intervals, 2.5 min rest
3	3 sessions – 4x5 min intervals, 2.5 min rest	2 sessions – 4x5 min intervals, 2.5 min rest
4	1 session – 4x5 min intervals, 2.5 min rest 1 session – 3x5 min intervals, 2.5 min rest	1 session – 4x5 min intervals, 2.5 min rest 1 session – 3x5 min intervals, 2.5 min rest

At the conclusion of the last interval, participants undertook a cool-down, riding until session duration reached 40-min. There was a minimum of 1-d between IHT sessions. Due to CON performing 3 less bike sessions, IHT was removed from portions of the conditioning component of squad training to ensure groups were matched for training load. Training load was determined from the session rating of perceived exertion method as previously described (Foster et al., 2001b).

The Yo-Yo IR2 is a valid test for determining both aerobic and anaerobic capacity for TS athletes (Krustrup et al., 2006a), and was used to measure intermittent running performance. The Yo-Yo IR2 consists of 2 x 20-m shuttles performed to an audible beep at increasing speeds, interspersed with 10 seconds of active recovery until exhaustion (Bangsbo, 1994). The Yo-Yo IR2 has coefficient of variation of 1.3% when expressed as a total distance, and 12.7% when expressed as a level (Thomas et al., 2006). The Yo-Yo IR2 was performed on the same indoor court on both groups at baseline, after 3, 6, and 11 IHT sessions, and again 30 and 44-d post IHT. It was not possible to perform a familiarization trial for the Yo-Yo IR2. Therefore a learning effect existed. However both groups were unfamiliar with this test, thus the learning effect would likely have been present for both groups.

Time trial performance was measured using a repeated TT design. Firstly, a 2-km running TT was performed, 5 mins following completion of the 2-km TT; a 1-km running TT was performed. These repeated TT's were undertaken pre, post, and 4 weeks post on the same outdoor 400-m running track at the same time of day (18:00). The CV of a 1500 m TT is 2.6 ± 1.8% for time (Laursen et al., 2007), which is similar to that displayed for the Yo-Yo IR2. The TT's were performed two days after the Yo-Yo IR2 and following a recovery week in the training cycle. Participants were instructed to perform both trials maximally and not pace themselves for the 1-km TT. All participants were familiar with this repeated TT, having completed a minimum of 2 of these prior to the study.

Haemoglobin mass (Hb_{mass}) was measured via the carbon monoxide (CO) rebreathing technique (Schmidt and Prommer, 2005). This involves rebreathing a small volume (1.0 $mL.kg^{-1}$) of CO for two mins. A 3-mL venous blood sample was taken before and seven mins post CO inhalation to measure percent carboxyhaemoglobin (OSM-3 Hemoximeter, Radiometer Medical, Copenhagen). Haemoglobin mass was calculated by the change in percent carboxyhaemoglobin from pre to seven mins post CO inhalation. Duplicates were taken pre and post CO rebreathing to increase precision. If duplicates were more than 0.1% different, a third measure was taken, with the average of the two nearest measures used for analysis. This technique has a typical error of 1.7% (Schmidt and Prommer, 2005). Measures were taken from IHT at baseline, after 3, 6, 9 and 11 IHT sessions.

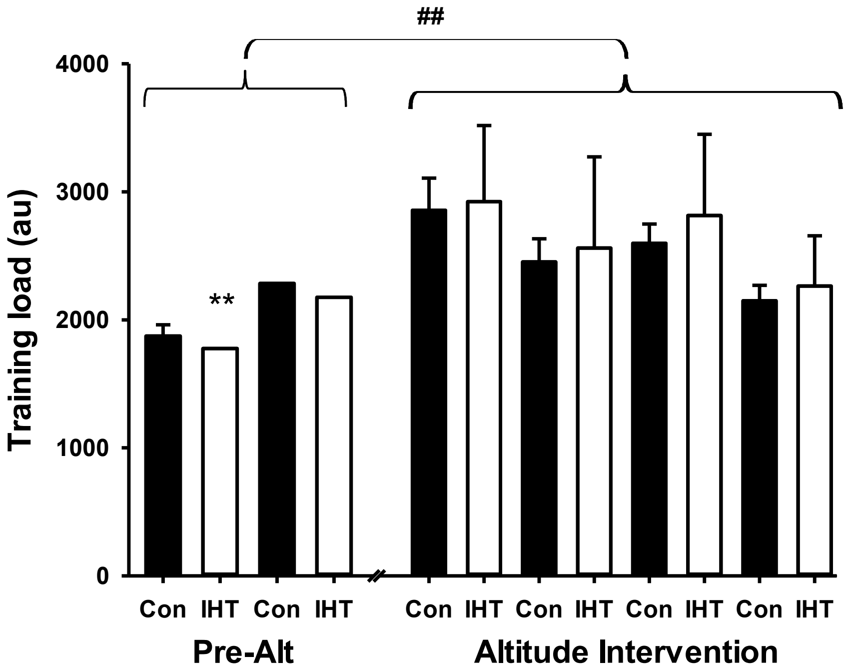
Statistical analysis

All data was analysed using a contemporary statistical approach (Hopkins et al., 2009), and expressed as mean ± SD and effect size (ES) ± 90% confidence limits (CL). Percentage change was determined in comparison to baseline. Magnitude of difference between groups was calculated using both ES and % changes ± 90% CL. In addition, qualitative chances and inferences were determined. Raw data collected was first log transformed to reduce nonuniformity of error, and then back transformed. Standards for measuring ES were as previously described (Hopkins et al., 2009).

3.4 Results

Training load was successfully matched on session RPE and duration between-groups during the intervention. However there was a *likely* moderate difference in training load between groups in Week -2, with CON's training load higher (3.5%, ES -0.8 90% confidence limits for ES [-1.5;0.1], likelihood of change 72/21/7 Figure 3.1). There was a moderate increase in training load from pre to during the intervention for IHT (0.6 [-0.1;1.4], Figure 3.1).

Figure 3.1: Weekly training load from session RPE for control (Con, black bars) and intermittent hypoxic training groups (IHT, open bars). All data is Mean ± SD arbitrary units (au); Con, n=11; IHT, n=10. ** denotes likely moderate effect in the difference between groups; ## denotes moderate effect in the difference in the mean altitude intervention training load compared to the mean pre-intervention training load.



Yo-Yo IR2 results are displayed in figure 3.2a and 3.3a. Differences in the percentage change between groups are presented in Figure 3.2a. The IHT group was *possibly* lower performing at pre testing (IHT 412 ± 136 vs CON 454 ± 113 m). Although both groups improved Yo-Yo IR2 performance throughout, after one week, the greater change for IHT compared to CON was not meaningfully different (15% greater change, 0.44, [-0.19;1.07], 74/21/5). After 2 weeks, change in Yo-Yo IR2 for IHT was moderately greater than CON (27% 0.77 [0.20;1.33], 95/4/1). This greater change in IHT persisted 1-d (23%, 0.68 [0.05; 1.30], 90/9/1), and 30-d post (24%, 0.72 [0.12;1.33], 92/7/1). By 44-d post, the change in Yo-Yo IR2 between groups was not meaningfully different (12%, 0.36 [-0.24;0.97], 68/26/6).

Figure 3.2: Percentage difference in the change in performance from baseline for IHT compared to Con. Figure 3.2A is the between group change in Yo-Yo IR2, figure 3.2B is between group change in 2km TT, and figure 3.2C is between group change in 1km TT. ** denotes likely moderate effect in the difference in the change between groups. '#' denotes likely small effect in the difference in the change between groups.

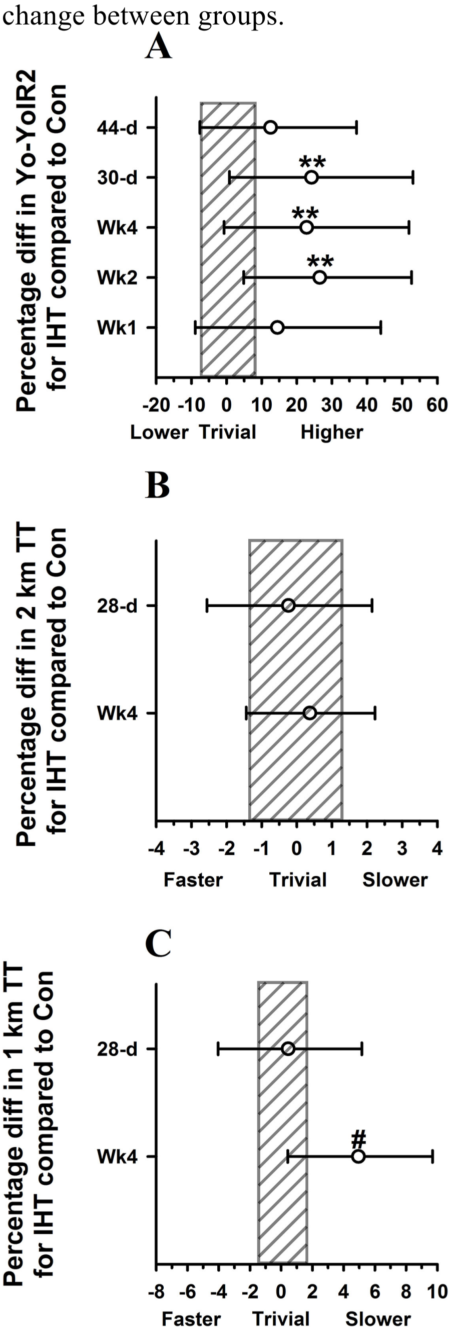
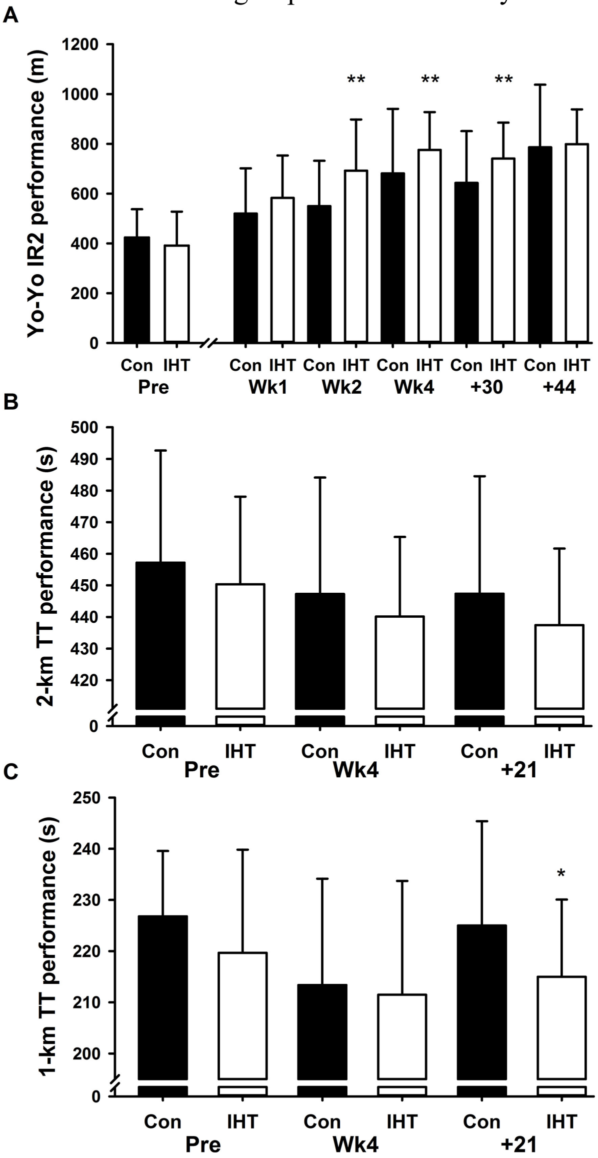


Figure 3.3: Performance changes throughout the study for control (Con, black bars) and intermittent hypoxic training groups (IHT, open bars). All data is Mean ± SD; Figure 3.3A is displayed in metres, while figure 3.3B and 3.3C are in seconds. Con, n=11; IHT, n=10. ** denotes likely moderate difference between groups. * denotes likely small difference between groups.



At baseline, there was no meaningful difference between groups for 2-km TT or 1-km TT (Figures 3.3B and 3.3C respectively).

There was no clear difference for between group change in 2-km TT at any point, (Figure 3.2b). When 1-km TT was performed 5-min after, both groups improved from pre to post (figure 3.3c). However, CON improvement was *likely* greater than IHT at post (figure 3.2c)

(5.0% greater change for CON, 0.56 [0.05:1.07] 89/10/1). However, IHT had a *likely* smaller decrement in performance in 1-km TT from post to 3 weeks post -0.42 [-0.92:0.07] 78/20/2). There was no change in Hb_{mass} after 2 weeks; a *possible* small increase after 3 weeks (2.5%, 0.20, CL [0.24;0.58]), and a *very likely* small increase after 4 weeks (2.7%, 0.40, [0.24;0.63], Table 3.2).

Table 3.2. Hb_{mass} for IHT group at each time point. All data is Mean ± SD (with range values in brackets). * denotes possibly small difference in comparison to pre testing. ** denotes very likely small difference in comparison to pre testing.

	Absolute Hb_{mass} (g)	Range (g)
Pre	965 ± 62.8	846 – 1083
1 week	967 ± 73.2	836 – 1060
2 weeks	973 ± 62.4	889 – 1075
3 weeks	981 ± 64.6*	867 – 1105
4 weeks	987 ± 70.4**	873 – 1124

3.5 Discussion

Two weeks of IHT (six sessions) superimposed on normal training was superior to load-matched sea-level training for enhancing Yo-Yo IR2 performance in moderately-trained team-sport athletes. This 27% greater change after two weeks had a moderate effect of 0.77. An additional two weeks of IHT conferred no additional benefit. In comparison to pre-testing, the greater increase in performance for IHT compared to CON lasted at least 30-d post exposure. Although not meaningfully different after 44-d, IHT change from pre was still 12% higher than CON, with the likelihood of a positive or trivial change being 94%, and only a 6% chance of harm. The early performance enhancement was independent of changes in Hb_{mass}, with no Hb_{mass} change after 2 weeks. An interesting finding was, however, that there was no increase in 2-km TT performance compared to CON, while a subsequent 1-km TT did not improve to the same extent as CON.

Players starting on the field in AF possess superior Yo-Yo IR2 performance than substitutes (Young et al., 2005), and individuals with greater Yo-Yo IR2 performance have more ball disposals than lesser performing athletes (Mooney et al., 2011). Thus, the improved Yo-Yo IR2 performance observed after just 6 IHT sessions may translate into improved match running performance. Our improvements in Yo-Yo IR2 are greater than other non-IHT studies using team-sport athletes; with an 11% increase after 5 weeks in sub-elite soccer players (Gunnarsson et al., 2012), and a 27%-42% improvement for Division 1 Soccer players (Krustrup et al., 2006a). However, these studies were either performed during the season (Gunnarsson et al., 2012), or participants had a higher starting Yo-Yo IR2 than the present study (Krustrup et al., 2006a), which both could have contributed to the lesser change in performance. As the starting Yo-Yo IR2 in the present study was quite low, further examination is required to determine whether these results are applicable to higher trained athletes.

Compared to training near sea-level, IHT can increase the rate of PCr resynthesis when exercising in normoxia (Holliss et al., 2013). This potentially faster PCr resynthesis may improve Yo-Yo IR2, as the Yo-Yo IR2 taxes both aerobic and anaerobic energy systems in athletes (Krustrup et al., 2006a). This is evidenced by PCr concentration at the end of the test being ~38% of resting levels (Krustrup et al., 2006a). This is a similar reduction to the 27% and 44% of resting levels reported 10 and 30-s post five 6-s sprints with 24-s recovery (Dawson et al., 1997). This is also similar to the decreased PCr levels after intense periods of soccer match play, showing that the Yo-Yo IR2 is relevant to high intensity intermittent performance, both in the sporting context and in a more controlled environment (Krustrup et al., 2006b). Intermittent hypoxic training has improved muscle glycolytic enzyme activity and repeat-sprint performance (Faiss et al., 2013). This enhanced enzyme activity was accompanied by an increased number of repeated maximal sprints in the hypoxic, but not the normoxic group (Faiss et al., 2013). Hypoxic training may delay fatigue by enhancing microvascular O_2 delivery to type II fibres, minimizing accumulation of inorganic phosphate and decreased pH (Faiss et al., 2013). As type II fibres are recruited at higher intensities (Fry, 2004), delaying their fatigue is likely to increase high-intensity activity performance.

Repeated high intensity efforts, rather than a single short sprint, may benefit most from IHT. Using a repeat-sprint protocol, both hypoxic and normoxic groups improved a single sprint, but only hypoxic improved the number of cycling sprints completed before exhaustion (Faiss et al., 2013). Our findings of improved Yo-Yo IR2 performance appear to support this, as Yo-Yo IR2 is a repeated, high-intensity effort test.

Contrasting to the increased Yo-Yo IR2 performance, like others (Hamlin et al., 2010b), we observed no additional improvement in TT performance with IHT, with 2-km TT performance change not different to CON. Interestingly, although both groups improved 1km TT, the IHT change was less than CON.

As with Yo-Yo IR2, a 6-min TT displays a positive relationship to match running performance in AF (Gastin et al., 2013). A 6-min TT is similar duration to a 2-km TT, which was chosen in the current study due to its familiarity for the participants. A secondary aerobic TT was undertaken as repeated TT's require a greater reliance on aerobic metabolism than a single effort, and therefore appears more indicative of aerobic capacity.

The aerobic contribution for TT's of 1500-3000 m is high (Duffield et al., 2005), which may have contributed to the lack of further improvement in 2-km TT performance for the IHT group, as improvements in aerobic capacity, as measured through a TT, are less likely following IHT compared to CON (Hamlin et al., 2010b, Roels et al., 2007). What was surprising was the lower increased performance for IHT compared to CON during the 1-km TT post intervention. To our knowledge, this is the first time repeated TT's with a large aerobic component have been used following IHT. There are a number of possible explanations for the poorer TT performance compared to CON. Firstly, due to a lower intensity during the IHT sessions, the training stimulus during these sessions may have been insufficient to provide an additional improvement in aerobic performance. The IHT may have been able to perform a single exercise bout, but as aerobic capacity is important for recovery between maximal bouts (Billaut and Buchheit, 2013), improvements in a second effort were less than CON. While CON was training at a higher intensity throughout the study, this may have led to greater aerobic adaptation. It should be noted though, that 3 weeks after the intervention the CON group had reverted closer to pre-test 1-km TT performance, suggesting maximal IHT-induced aerobic performance enhancement occurred weeks after exposure.

Secondly, although there was a possible small change in Hb_{mass} in the present study for IHT, the magnitude of change may have been insufficient to increase endurance performance beyond that of CON. Further, as CON did not have Hb_{mass} taken, it is not possible to determine whether these Hb_{mass} changes are greater than CON, or a natural adaptation to pre-season training. The low accumulated time at altitude (440-min) is a possible reason for this lack of adaptation, with a minimum exposure for hypoxic induced haematological adaptation of >12 $hrs.d^{-1}$ for 3 weeks suggested (Rusko et al., 2004).

Finally, a possibly faster 1-km TT for IHT at pre may have meant a greater aerobic capacity at baseline for IHT, which would leave less room for an improvement in performance.

In summary, as Yo-Yo IR2 has a high anaerobic contribution, increased anaerobic capacity may have been responsible for the greater change in Yo-Yo IR2 for IHT compared to CON. Improved rate of PCr resynthesis, glycolytic potential, and carbohydrate utilization are potential mechanisms associated with the effectiveness of IHT, which all could have contributed to the change in Yo-Yo IR2 performance.

Regarding the smaller improvement in TT performance for the IHT group, the lower absolute training intensity for IHT during the IHT sessions may have been insufficient to allow maximal aerobic adaptations. The magnitude of change of Hb_{mass} after IHT may also have been insufficient to increase TT performance more than CON. And a possibly greater starting

TT may have indicated a higher aerobic capacity at baseline. Therefore, IHT can improve performance in a short high-intensity task, but not a more sustained aerobic effort.

As intermittent running performance appears more applicable for a team-sport athlete than the ability to hold a steady state TT (Aughey, 2011), the changes in Yo-Yo IR2 appear more beneficial than any possible change in TT performance.

The minimum time-course for enhanced running performance seen in the Yo-Yo IR2 in this study was much shorter than previously reported. In fact, only six sessions of IHT produced benefits larger than CON. Nine sessions for aerobic (Czuba et al., 2011), and eight to ten sessions for anaerobic performance were previously thought of as a minimum for increases in performance through IHT (Faiss et al., 2013, Hamlin et al., 2010b).

The finding of 6 IHT sessions increasing Yo-Yo IR2 performance is extremely important for team-sport athletes. With such a rapid time-course it may be possible to implement a short, in-season block of IHT for intermittent running performance enhancement.

There are some noted limitations to the present study. Firstly, there was no familiarization trial for the Yo-Yo IR2, which may have contributed to the large increase in Yo-Yo IR2 performance in both groups. However, as neither group were familiar with the Yo-Yo IR2, this learning effect would have been present for both groups. Further, due to the nature of the test whereby each shuttle is 40-m, an improvement of a single shuttle equates to a percentage improvement of ~10% from the IHT groups average starting distance of 412-m. Therefore, small changes in physical capacity result in large percentage changes in Yo-Yo IR2 performance. The Yo-Yo IR2 improved 42% across a season (Krustrup et al., 2006a), therefore our large changes in Yo-Yo IR2 are in line with other researchers.

A second limitation is that Hb_{mass} was not taken from CON. However considering there were no changes in Hb_{mass} during the first 2 weeks of IHT, which is when all changes to Yo-Yo IR2 between groups occurred, this is not thought to impact on the findings.

Only supplementing the IHT group with iron is also a limitation. The iron supplementation contained vitamin C can have an interference effect at the cellular level, however this does not translate into an interference in performance adaptation (Paulsen et al., 2014). Thus, this would have had no effect on the current performance outcomes.

Although matched for training load during the intervention, CON had a higher training load pre intervention. Consequently, there was a greater increase in load in IHT vs CON from pre to during. However, this was only a very small difference.

The last limitation is that the training program was undertaking on bikes, whereas the testing protocol undertaken were running based tests. This may have limited the changes in the running based tests. However as both groups undertook the training on a bike, this would have been minimised. Due to the constraints of a large group of athletes, it would have been logistically impossible to undertake the training in a running based environment, due to only a single athlete at a time being able to train.

Tracking performance post-exposure has rarely been performed, and never for the length of time as in this study. This is important for team-sport athletes, as seasons can last for 6 months (Cormack et al., 2008). We determined that IHT group change was likely higher than CON for Yo-Yo IR2 performance 30-d post-intervention. As this study was conducted during pre-season, when increased capacity was a primary goal, the athletes were possibly able to increase the training stimulus, allowing for further adaptation post-exposure. Further research should examine whether these benefits are also apparent in-season, when maintenance, rather than increased capacity, is the primary goal of training, and whether these results can be replicated with a group of more highly trained team-sport athletes.

3.6 Practical applications

Only 6 IHT sessions improved Yo-Yo IR2 performance during pre season, and these improvements remained for at least 30 days. As team-sport athletes play weekly, determining the minimum time-course for adaptation is extremely beneficial. If this can be replicated in season, the present research indicates short blocks of IHT can be implemented in season with almost immediate increases in high intensity intermittent running performance, with possible benefits lasting at least one month. Further research should look to determine whether these changes do in fact occur in season. Repeat, high intensity performance is improved more than a more sustained effort. As repeated high intensity running performance is more important for team-sport athletes than a sustained submaximal effort, these athletes' may benefit from IHT. These changes in Yo-Yo IR2 performance are not caused primarily by increases in Hb_{mass}. Due to the small change in Hb_{mass} and lack of change in TT performance, TS athletes with lower aerobic capacity may be better advised to undertake other altitude modalities. Following altitude exposure, the quality of training may increase due to enhanced capacity, increasing the training stimulus of subsequent sessions therefore providing further improvement in performance (Rusko et al., 2004). Further, as IHT also participated in normal squad training in normoxia during the study, this may have provided adequate stimulus to protect gains through higher intensity exercise more so than if all sessions were performed in hypoxia.

3.7 Acknowledgements

The authors thank the participants from Williamstown Football Club for their participation in the study and those that helped with data collection, analysis and lab preparation: Dr Aaron Peterson, Alice Sweeting, Amber Rowell, Brad Gatt, Emily Walker, Dr George Elias, Jess Meilak, Dr Matt Varley, Ramon Rodriguez and Robert Inness. The authors have no competing interests, and no funding from external sources was provided to complete this project.

4 LIVE-HIGH TRAIN-LOW IMPROVES REPEATED TIME-TRIAL PERFORMANCE IN SUB-ELITE TEAM-SPORT ATHLETES

4.1 Abstract

Objectives:

To determine the efficacy of live-high train-low on team-sport athlete physical capacity and the time-course for adaptation.

Design:

Pre-post parallel-groups.

Methods:

Fifteen Australian footballers were matched for Yo-YoIR2 performance and assigned to LHTL (n=7) or CON; (n=8). LHTL spent 19 nights (3x5 nights, 1x4 nights, each block separated by 2 nights at sea level) at 3000-m simulated altitude (F_IO_2: 0.142). Yo-Yo IR2 was performed pre and after 5, 15, and 19 nights. A 2- and 1-km time-trial (TT) were performed pre and post intervention. Haemoglobin mass (Hb_{mass}) was measured in LHTL after 5, 10, 15 and 19 nights. A contemporary statistical approach using effect size, confidence limits and magnitude-based inferences was used to measure changes between groups.

Results:

Compared to pre, Hb_{mass} was *possibly* higher after 15 (3.8%, ES 0.19, 90% confidence limits 0.05 to 0.33) and *very likely* higher after 19 nights (6.7%, 0.35, 0.10;0.52).

For Yo-Yo IR2, LHTL group change was not meaningfully different to CON after 5 nights, *possibly* greater after 15 (10.2%, 0.37, -0.29;1.04), and *likely* greater after 19 nights (13.5%, 0.49, -0.16;1.14).

Both groups improved 2-km TT, with LHTL improvement *possibly* higher than CON (1.9%, 0.22, -0.18;0.62). Only LHTL improved 1-km TT, with LHTL improvement *likely* greater than CON (4.6%, 0.56, -0.08;1.04).

Conclusions:

Fifteen nights of LHTL was *possibly* effective, while nineteen nights was effective at increasing Hb_{mass}, Yo-Yo IR2 and repeated TT performance more than sea-level training.

4.2 Introduction

Australian Football (AF) athletes cover high distances (Johnston et al., 2012), often at high-velocities (>4.17 $m \cdot s^{-1}$) (Aughey, 2010), suggesting a high physical capacity is important for these athletes.

Despite this, higher aerobic capacity may not translate into improved match running (Aughey, 2010, Sullivan et al., 2014, Gastin et al., 2013), with physical capacity not always related to match running performance (Sullivan et al., 2014). However, better performing teams and individuals cover more distance in matches (Aughey, 2010, Aughey, 2011), and have superior TT (Gastin et al., 2013), and Yo-Yo IR2 performance (Krustrup et al., 2006a, Ingebrigtsen et al., 2012). The resynthesis of PCr is oxygen-dependent (Harris et al., 1976), with the rate of muscle re-oxygenation after a maximal effort critical for subsequent performance (Billaut and Buchheit, 2013). Therefore, a highly developed aerobic system is crucial for performing both the lower-intensity movements and repeated high-intensity activities during matches. As increased fatigue reduces technical skill performance (Kempton et al., 2013), minimizing fatigue may help maintain skill efficiency. Therefore, altitude training that increases aerobic capacity can potentially improve team-sport athlete running performance and skill efficiency. Intermittent hypoxic training has been used to good effect as highlighted in chapter three, however there is very little research on LHTL and team-sport athletes.

With LHTL altitude training, participants live at real or simulated altitude (2,000 to 3,000 m) for more than 12 hours per day and train at or near sea level (Siebenmann et al., 2012). Although not unanimous, the majority of literature points to improved sea-level performance or haematological changes following LHTL. For example, elite endurance athletes have improved running economy (Saunders et al., 2004b), and Hb_{mass} (Robertson et al., 2010a), compared to groups living and training at sea-level (Saunders et al., 2004b).

An increased Hb_{mass} appears beneficial for performance in repeated aerobic efforts. In elite female cyclists following LHTL, Hb_{mass} was clamped in one group and free to adapt in a second (Garvican et al., 2011). Both groups improved 4-min mean power, although the clamp group could not match the group with improved Hb_{mass} for performance during a subsequent aerobic effort (Garvican et al., 2011). This indicated Hb_{mass} is important not only to improve oxygen carrying capacity during sustained efforts, but also to improve the rate of recovery, allowing greater performance in subsequent efforts. This has critical relevance to team-sport athletes, and thus a repeated TT performance test should be used to ascertain team-sport specific performance changes through LHTL (Garvican et al., 2011).

Twelve to 14-h.night^{-1} is recommended to increase Hb_{mass} and performance (Pottgiesser et al., 2012) (Clark et al., 2009). Thus, bouts of LHTL of less than 12-hrs may be insufficient to increase Hb_{mass} (Rusko et al., 2004), due to the break between altitude bouts being too long to allow a sustained release of erythropoietin to stimulate Hb_{mass} changes. As an increase in Hb_{mass} of 1-1.5% per week has been shown, exposure of more than 14 nights is required to see meaningful changes (Pottgiesser et al., 2012, Clark et al., 2009). Many team-sport athletes play competition matches each week, so an unbroken block of >14 nights in-season is difficult to administer. Blocks of five nights of LHTL separated by two days at sea level have been successfully used in elite runners to improve running economy and race performance (Saunders et al., 2004b), and are more realistic for team-sport athletes due to matches and training in-season. Therefore, investigation is required to determine whether intermittent LHTL is effective for team-sport athletes and the minimum time course for adaptation.

This study therefore investigated the effects of LHTL on aerobic performance measures that correlate to team-sport athlete running performance (Yo-Yo IR2 and short-duration time trials) (Ingebrigtsen et al., 2012), and the time-course of adaptation using sub-elite team-sport athletes.

4.3 Methods

A pre-post, parallel-groups controlled trial study design was undertaken during the latter stages of pre-season immediately before practice matches. For these athletes, this is a medium- to high-volume period of pre-season training, with the primary focus on skill and tactical development, with a secondary goal of continuing to improve physical capacity (Helgerud et al., 2011). As such, small gains in aerobic capacity are expected during this period; therefore, testing the efficacy of LHTL in producing additional gains was established through a pair-matched control group with matched internal training load. Ethical approval was obtained through the institutional Human Research Ethics Committee.

Sixteen male semi-professional Australian Footballers from the same Victorian Football League (VFL) team volunteered for the study. The VFL is a sub-elite AF competition; it is a feeder league to the AFL. At the beginning of the study, all participants were injury free, living at sea level, and had not been exposed to high altitude for at least 12 months. After baseline testing, the eight participants from LHTL were pair-matched with another squad member with similar Yo-Yo IR2 performance who acted as a CON. One subject from LHTL did not reach the required minimum altitude exposure, with his data removed from analysis; therefore 15 participants completed the study (LHTL n=7, 20.1 ± 1.2 years, 83.2 ± 6.8 kg, 182.7 ± 7.8 cm, CON n=8, 20.2 ± 1.4 years, 83.6 ± 11.7 kg and 184.2 ± 8.5 cm). All LHTL subjects were given a single daily oral iron supplementation (305 mg ferrous sulfate, 1000 mg Vitamin C) throughout the study.

The LHTL group lived in an altitude hotel for 19 nights (3 x 5 nights, and 1 x 4 night block) of simulated altitude exposure (F_IO_2 0.142 simulating 3,000 m altitude, humidity 40%, temperature 21°C). Each altitude block was separated by two nights at sea level. Participants were required to spend 12-h.night^{-1} at altitude (average of 12-h 10 mins.night^{-1}).

The Yo-Yo IR2 was used to test intermittent running performance of the participants. This test consists of 2 x 20-m shuttles performed to an audible beep at increasing speeds, interspersed with 10 seconds of active recovery, performed until exhaustion (Bangsbo, 1994). It is a valid test for determining aerobic and anaerobic capacity for team-sport athletes (Castagna et al., 2008). The Yo-Yo IR2 was performed on the same indoor court on both groups at baseline, after 5, 15, and 19 nights LHTL. Due to participant availability, not all athletes performed the Yo-Yo IR2 weekly, however all subjects performed the Yo-Yo IR2 pre and post.

Both groups performed the 2- and 1-km TT two days following the pre and post Yo-Yo IR2. On the same outdoor 400-m running track, participants first performed a 2-km TT, after a 5-minute break, a 1-km TT was undertaken. Two maximal aerobic efforts were used as multiple efforts require a greater reliance on aerobic metabolism (Garvican et al., 2011). This is both for enhanced oxygen transport and improved recovery rates, through the removal of metabolic by-products accumulated from the first effort (Garvican et al., 2011). Further, due to the intermittent nature of many team-sports, repeated efforts may be more important for team-sport athletes than a single TT. This repeated aerobic test, combined with the Yo-Yo IR2 helps determine the running capacities that are important for team-sport athletes. Both tests were performed at the same time of day, after a standardized warm up before training, with participants instructed to maintain a consistent diet before each test. Apart from the iron supplementation, participant were instructed not to begin taking supplements, or those on supplements were asked to maintain the same dosage as prior to the study.

Haemoglobin mass was measured by the same experienced assessor using the carbon monoxide (CO) rebreathing technique (Schmidt and Prommer, 2005). This involves rebreathing 1.0 $mL.kg^{-1}$. of CO for two-mins. A 3 mL venous blood sample was taken before and seven mins post initial CO inhalation, to measure percent carboxyhaemoglobin (OSM-3 Hemoximeter, Radiometer Medical, Copenhagen). Haemoglobin mass was calculated by the change in percent carboxyhaemoglobin from these two measures. Duplicates were taken to increase precision. If duplicates were more than 0.1% different, a third measure was taken, with the average of the two nearest measures used for analysis. This technique has a typical error of 1.7% (Schmidt and Prommer, 2005).

Haemoglobin mass was measured in LHTL at baseline, after 5, 10, 15 and 19 nights. All seven participants from LHTL had Hb_{mass} measured pre and post LHTL, although due to participant availability, only five participants had Hb_{mass} measured after 5, 10, and 15 nights.

Training load was determined using the product of session duration and rating of perceived exertion (RPE) following each session (Foster et al., 2001a). Weekly load was determined using the sum of daily load. As both groups performed the same training throughout the study, the CON group is a true control, with the LHTL intervention being the only difference between groups. Training load was also gathered on participants in the seven weeks prior to LHTL to ensure all participants presented in the same training state at the beginning of the study. This prior monitoring of training load ensured we were able to determine the effects of LHTL on the performance tests undertaken confident it was not due to a difference in training between groups.

Means, standard deviations and percentage changes were calculated at each testing session. A contemporary statistical approach (Hopkins et al., 2009, Batterham and Hopkins, 2005), using ES and Confidence Limits was used to measure changes between groups. Differences between, and within groups were determined, with an ES of 0.20 set to evaluate the smallest worthwhile change (Aughey, 2011). Standardised effects were classified as small (0.2-0.59), or moderate (0.6-1.2). 90% CL were expressed for changes compared to pre for all measures.

4.4 Results

There were no meaningful differences in training load prior to, or throughout the study (LHTL 1.2% greater load, ES 0.44 90% CL -0.43;1.31) Fig. 4.1).

Figure 4.1: Weekly training load shown in arbitrary units for CON (black bars) and LHTL (clear bars) for the 7 weeks prior to (pre-intervention), and the 4 weeks of intervention phase of the study.

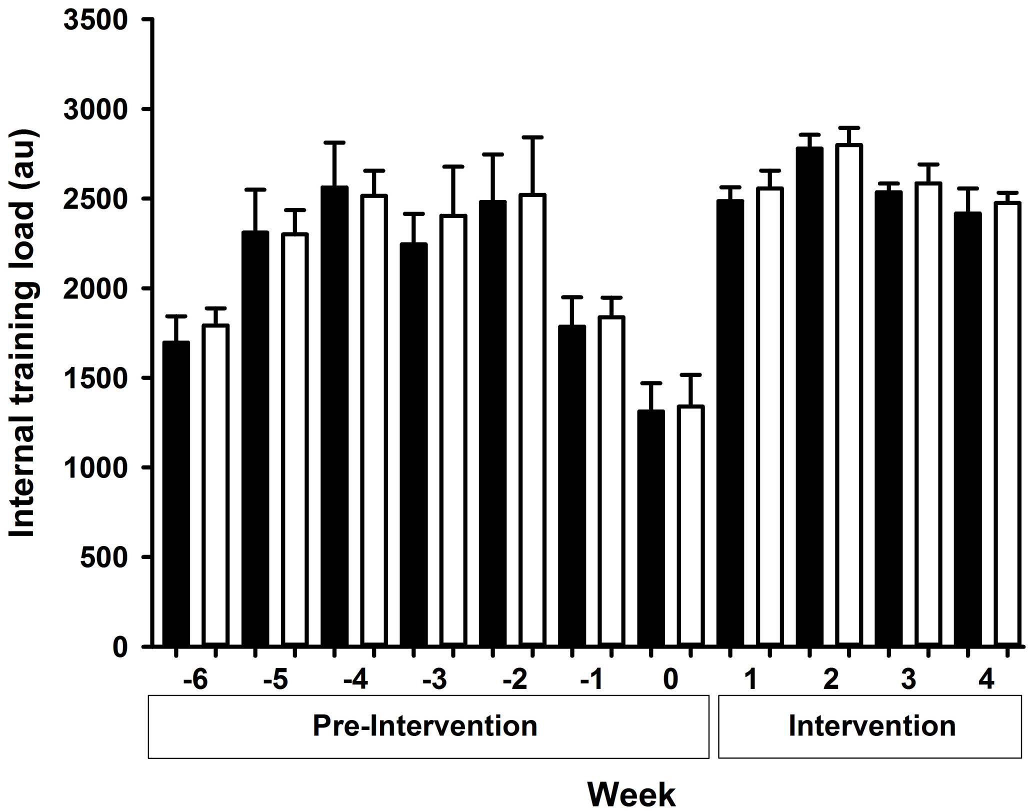
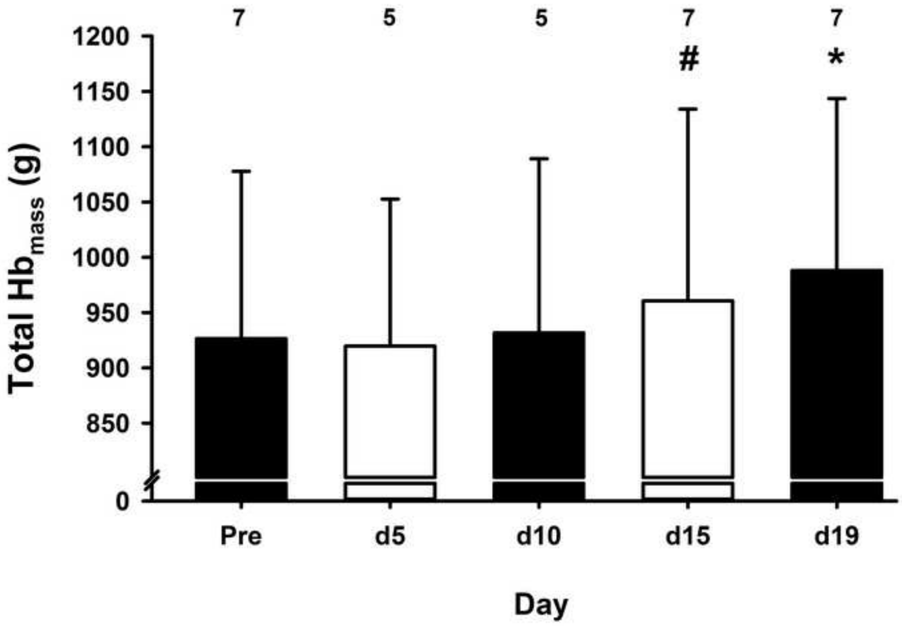


Figure 4.2 displays Hb_{mass} in LHTL at each time point. In comparison to pre, change in absolute Hb_{mass} was not meaningfully different after 5 (0.2% change, ES 0.01, 90% CL -0.03;0.05) or 10 nights (1.6%, 0.08, -0.16;0.32), *possibly* higher after 15 nights (3.8%, 0.19, 0.05;0.33), and a *likely* small effect after 19 nights (6.7%, 0.35, 0.19;0.52).

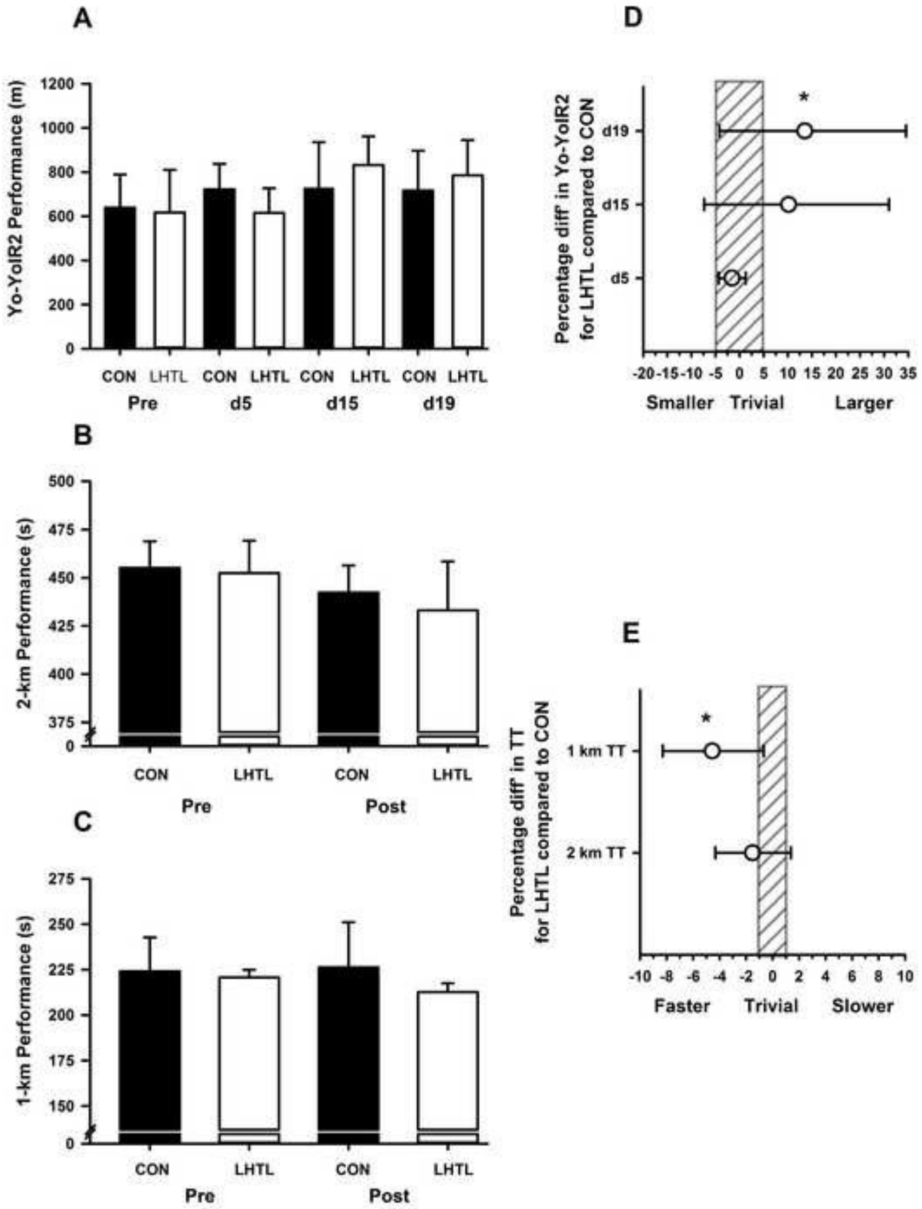
Figure 4.2: Average total Hb_{mass} for the LHTL group throughout the hypoxic exposure. # indicates possibly greater than pre testing. * Indicates very likely greater than pre testing. Number of participants tested at each time point are displayed. Data expressed as mean, with standard deviation bars.



Group means and the number of athletes tested at each time point for Yo-Yo IR2 are displayed in Figure 4.3a. Differences in the change between groups compared to baseline at each time point are shown in Figure 4.3. Groups were not different for Yo-Yo IR2 performance at baseline (LHTL 3.0% lower, -0.12, -1.18;0.94). The LHTL change compared to CON was not clearly different after 5 nights, *possibly* greater after 15 nights, and *likely* greater after 19 nights (5.5%, 0.21, -0.26;0.67, 10.2%, 0.37, -0.29;1.04, and 13.5%, 0.49, -0.16;1.14 after 5, 15 and 19 nights respectively).

At pre, LHTL was not meaningfully different to CON for either 2-km, (0.9% faster, 0.09, -0.76;0.93, Figure 4.3b) or 1-km TT (1.9% faster, 0.21, -0.64;1.07, Figure 4.3c). At post, both groups improved 2-km TT, with LHTL improvement *possibly* greater than CON (1.9%, 0.22, -0.18;0.62, figure 4.3e). Only LHTL improved 1-km TT from pre to post, with LHTL change greater than CON (4.6%, 0.56, -0.08;1.04, Fig 4.3e).

Figure 4.3: Figures A, B, and C represents performance at each testing session for CON (black bars) and LHTL (clear bars) for Yo-Yo IR2, 2 km TT, and 1 km TT respectively. Data is expressed in metres (Yo-Yo IR2) or seconds (2 and 1 km TT) with standard deviation bars. Figures D and E represent the percentage difference in the change in performance from pre for LHTL compared to CON. Figure D is the between group change in Yo-Yo IR2, figure E is between group change in 2 and 1km TT. * denotes likely greater change than CON.



4.5 Discussion:

The main finding was that 19 nights of LHTL broken up into 3 x 5 nights, and 1 x 4 nights with 2 nights between blocks implemented during pre-season training increased intermittent running performance in sub-elite team-sport athletes more than sea-level training alone. While both groups improved 2-km TT performance at post, only LHTL improved 1-km TT when performed 5-min post 2-km TT. Therefore, increased performance after LHTL appears to be more evident in a second aerobic challenge.

As the study was undertaken in pre-season, it is expected that changes in physical performance will occur through normal training. As expected, both groups improved Yo-Yo IR2 performance; however changes in Yo-Yo IR2 were likely greater in LHTL compared to CON. Therefore LHTL on top of normal pre-season training can increase physical performance. This change in Yo-Yo IR2 for LHTL became more apparent the greater the time spent at altitude. As there were increases in Hb_{mass}, improved aerobic capacity may have contributed to a greater Yo-Yo IR2 performance.

The increased Yo-Yo IR2 after LHTL may be important for team-sport athlete match running performance. Yo-Yo IR2 performance can discriminate between playing levels in team-sport athletes, with International level soccer players outperforming division 1 and 2 players (Krustrup et al., 2006a), while elite players performed 41% better than sub elite (Ingebrigtsen et al., 2012). Therefore, a higher Yo-Yo IR2 performance appears important to team-sport athletes. However, despite the high aerobic demand of team-sport matches and the relationship between Yo-Yo IR2 performance and playing level, it is yet to be determined if changes in Yo-Yo IR2 performance translate directly into better match-running performance. Therefore, caution should be taken to assume the change in Yo-Yo IR2 in the LHTL group translates into better running performance and chances of success in matches. Even though improved Yo-Yo IR2 may not relate directly to better match-running performance, improved aerobic capacity results in a decreased relative running intensity when running at the same absolute speed. In turn decreasing peripheral muscle fatigue, possibly negating any decrease in skill efficiency seen through fatigue (Kempton et al., 2013).

Increased Yo-Yo IR2 has occurred in hypoxic studies. Combining heat and hypoxia in elite AF athletes increased Yo-Yo IR2 by 25% after six, and 44% after 14 days of LHTL (Buchheit et al., 2013). However this was in combination with heat and IHT training making it difficult to isolate the effect of LHTL on Yo-Yo IR2. As IHT has improved Yo-Yo IR2 by 27% more than a control group after only six sessions, it is possible that this greater change in Yo-Yo IR2 in the LHTL + Heat study was through the IHT component of training. Further, both groups completed IHT, and there was no difference between the LHTL group and the control group for change in Yo-Yo IR2, again supporting the thought that IHT may be more beneficial than LHTL for increasing Yo-Yo IR2. However, in a separate study there was no difference in the change in Yo-Yo IR2 performance between a LHTL+IHT and a LHTL only group (Brocherie et al., 2015), with both groups improving more than a control.

Although 2-km TT improved in both groups at post, importantly only LHTL improved subsequent 1-km TT, with a likely greater improvement from baseline compared to CON. It is possible that LHTL was able to increase 1-km TT performance through increased aerobic capacity, as shown through increased Hb_{mass}. Alternative mechanisms, including increased contribution of anaerobic metabolism may be why CON still improved 2-km TT. However, fatigue doesn't allow improved performance during the 1-km TT. The increased Hb_{mass} not only enhances oxygen delivery during the 2-km TT, but may also improve the rate of recovery, allowing improved performance during the subsequent 1-km TT through decreased accumulated fatigue (Garvican et al., 2011).

The finding of a greater performance in a second effort is novel for team-sport athletes, but as stated earlier is not unique among elite endurance athletes (Garvican et al., 2011).

Considering team-sport competition can last up to 120 mins, with breaks in play, repeated aerobic efforts are required by team-sport athletes. Therefore, the finding of LHTL improving repeated efforts more than a single bout is extremely relevant for team-sport athletes.

As with Yo-Yo IR2, the change in Hb_{mass} was greater with more nights spent at altitude. This is consistent with findings of a gradual increase in Hb_{mass} with consecutive nights at altitude (Clark et al., 2009). With a change in Hb_{mass} of 1% per week typically occurring in well-trained endurance cyclists through LHTL. This change in Hb_{mass} (6.7%) is greater than reported in elite endurance athletes (Garvican et al., 2011, Saunders et al., 2004b, Pottgiesser et al., 2012). In elite runners a similar altitude exposure to the present study did not change Hb_{mass} (Saunders et al., 2004b, Siebenmann et al., 2012, Clark et al., 2009).

It is important to ensure the testing protocol is designed to detect any changes seen through the altitude exposure employed. As the repeated TT design used is predominantly an aerobic test, and there is a large anaerobic contribution to the Yo-Yo IR2, it is likely that different mechanisms are at play for each of these tests. Therefore, study design is crucial to determine the performance outcomes from an altitude intervention, with the testing protocol needing to match the intended findings. It is possible that true changes in performance in altitude studies are missed due to the design and selection of tests being unable to detect these performance changes. Therefore the conflicting findings between LHTL studies are perhaps in part due to differences in testing protocol (Siebenmann et al., 2012, Martin et al., 2002)'

An important factor often overlooked with training studies is the training status prior to the commencement of the study. Most training studies only have the participants for the duration of the study; making it difficult to monitor activity prior to the study. However it is important to do this to determine whether athletes present at the beginning of the study in the same training state. For example, if an athlete begins the study during a high training load period, the result of a performance test may be sub-optimal. Knowing that changes in performance after altitude can be similar to that seen in a taper (Pyne et al., 2009), determining the training load prior to a LHTL intervention is crucial. By using a single team in the present study, we were in the unique position to be able to monitor training for seven weeks prior to the study commencing. Therefore participants were matched, not only for testing performance at the start of the study, but also on pre-study training load.

It appears that if increased aerobic capacity and Hb_{mass} are the aim for team-sport athletes, LHTL offers a viable option to achieve this.

A limitation was not taking Hb_{mass} from CON. This made it impossible to determine if CON also increased Hb_{mass}, and if the clear changes in Hb_{mass} in LHTL were induced through the altitude or adaptations to normal training. However, team-sport athletes with a similar Yo-Yo IR2 performance showed no changes in Hb_{mass} through normal training alone (Brocherie et al., 2015), indicating large increases in Hb_{mass} from CON would be unlikely.

4.6 Conclusions

In team-sport athletes, 19 nights of *intermittent* LHTL is effective at increasing Hb_{mass}. Further, LHTL improves Yo-Yo IR2 and repeated TT performance more than sea-level training alone. Importantly, this alternate design allows sub-elite team-sport athletes to partake in effective altitude training during the season. Before LHTL is undertaken in season, further research is required to determine the optimal timing for LHTL to finish prior to matches.

4.7 Practical Applications

- Live-High Train-Low improves aerobic running performance in sub-elite team-sport athletes.
- Live-High Train-Low can be used to increase Hb_{mass} in sub elite TS athletes.

- Appropriate selection of tests is crucial for detecting performance changes seen through altitude training, with a repeated time-trial design important for detecting aerobic changes through altitude.

4.8 Acknowledgements

The authors thank the participants from Williamstown Football Club for their participation in the study and those that helped with data collection, analysis, altitude hotel monitoring and lab preparation:, Alice Sweeting, Amber Rowell, Brad Gatt, Dr Cedric Lamboley, Dr Chris Stathis, Emily Walker, Jackson Fyfe, Jessica Meilak, Karen Hill, Lewan Parker, Dr Matt Varley, Ramon Rodriguez, Dr Raul Bescos and Robert Inness. The authors have no competing interests, and no funding from external sources was provided to complete this project.

5 INTERMITTENT HYPOXIC RESISTANCE TRAINING AND SQUAT PERFORMANCE

5.1 Abstract

Purpose:

To determine if heavy resistance training in hypoxia (IHRT) is more effective at improving strength, power and increasing lean mass than the same training in normoxia.

Methods:

A pair-matched, placebo-controlled study design included 20 resistance-trained participants assigned to IHRT (F_IO_2 0.143) or placebo (F_IO_2 0.20), (n=10 per group). Participants were matched for strength and training. Both groups performed 20 sessions over 7 weeks either with IHRT or placebo. All participants were tested for 1RM, 20-m sprint, body composition and countermovement jump pre-, mid- and post-training and compared via magnitude-based inferences.

Presentation of Results:

Groups were not clearly different for any test at baseline. Training improved both absolute (IHRT: 13.1 ± 3.9%, effect size (ES) 0.60, placebo 9.8 ± 4.7%, ES 0.31) and relative 1RM (IHRT: 13.4 ± 5.1%, ES 0.76, placebo 9.7 ± 5.3%, ES 0.48) at mid. Similarly, at post both groups increased absolute (IHRT: 20.7 ± 7.6%, ES 0.74, placebo 14.1 ± 6.0%, ES 0.58) and relative 1RM (IHRT: 21.6 ± 8.5%, ES 1.08, placebo 13.2 ± 6.4%, ES 0.78).

Importantly, the change in IHRT was greater than placebo at mid for both absolute (4.4% greater change, 90% Confidence Interval (CI) 1.0:8.0%, ES 0.21, and relative strength (5.6% greater change, 90% CI 1.0:9.4%, ES 0.31 (relative)). There was also a greater change for IHRT at post for both absolute (7.0% greater change, 90% CI 1.3:13%, ES 0.33), and relative 1RM (9.2% greater change, 90% CI 1.6:14.9%, ES 0.49). Only IHRT increased countermovement jump peak power at Post (4.9%, ES 0.35), however the difference between

IHRT and placebo was unclear (2.7%, 90% CI -2.0:7.6%, ES 0.20) with no clear differences in speed or body composition throughout.

Conclusion:

Heavy resistance training in hypoxia is more effective than placebo for improving absolute and relative strength.

5.2 Introduction:

Hypoxia has long been used in combination with endurance training (Terrados et al., 1988). The benefits of endurance training in hypoxia include increased intermittent running performance (chapter 3), glycolytic enzyme activity (Faiss et al., 2013), and rates of PCr regeneration (Holliss et al., 2013). Hypoxia may also improve performance in time trials (Czuba et al., 2011), although this is less conclusive (chapter 3). These benefits are potentially important to enhance team-sport athlete performance.

The development of strength and power is also important for team-sport athletes due to the physical involvements in collision sports including Australian football and the Rugby codes (Dawson et al., 2004, Roberts et al., 2008). Therefore resistance training plays an integral part in the physical preparation of team-sport athletes. The positive effects of resistance training in hypoxia are becoming evident (Takarada et al., 2000b). When used in combination with resistance training, hypoxia is commonly achieved in two ways, blood flow restriction and intermittent hypoxic resistance training (IHRT). With blood flow restriction, a pressure cuff is applied to the limb, restricting blood flow, participants then perform resistance training exercises (Takarada et al., 2000b). Blood flow restriction causes many perturbations in the muscle, only one of which is hypoxia. Restricting blood flow to the muscle places the restricted tissue in an ischemic state, leading to hypoxia. Some of the possible mechanisms behind increased strength and hypertrophy through blood flow restriction include increased type ii fibre type recruitment (Yasuda et al., 2010), accumulation of metabolites (Loenneke et al., 2010), increases in plasma growth hormone (Takarada et al., 2000a), and muscle cell swelling (Loenneke et al., 2012).

There are practical limitations to blood flow restriction when using traditional resistance training exercises such as squats, deadlifts and bench press. Firstly, it is only possible to restrict blood flow to the limbs; therefore a large proportion of musculature used during these exercises is not in a hypoxic state. This causes a disassociation in muscle hypertrophy between the muscles of the limb, which is exposed to blood flow restriction, and the muscles of the trunk, which is not exposed to blood flow restriction (Yasuda et al., 2011). Since blood flow restriction is usually matched with low intensity resistance training, the changes in cross sectional area and strength may not be accompanied by a concomitant increase in connective tissue strength. This is due to decreased mechanical loading through low intensity resistance training used with blood flow restriction (Scott et al., 2015a), therefore the strength of muscles and connective tissue will adapt disproportionately. Increased tensile strength of the tendon might be expected to maintain the safety of the tendon under increasing loads (Buchanan and Marsh, 2002). Although currently unknown, there is a possibility that increasing the strength of the muscle without allowing the tendons time to adapt to this increased force production of the muscle may result in an increased risk of musculotendinous injuries. Due to these limitations in blood flow restriction, it is possible IHRT may be more suited for athletes and strength-trained individuals, as it allows high force production during training that also strengthens connective tissue to aid in injury prevention.

With IHRT, participants perform resistance training in hypoxia, induced by either a normobaric reduction of oxygen content in the mixture (Friedmann et al., 2003, Nishimura et al., 2010), or decreased partial pressure of air as evident at moderate to high altitude (Feriche et al., 2014). There is very little research on IHRT, with conflicting findings on its the effectiveness for increasing 1RM. One of the earliest studies using IHRT showed increased strength and hypertrophy compared to the same training in normoxia (Nishimura et al., 2010). For two sessions per week for six weeks, French press and arm curls were performed at 70% 1RM. The IHRT group showed greater hypertrophy and strength than the control group. Further to this, lower intensity IHRT (50% 1RM for 15 reps) may be just as effective as high intensity IHRT (80% 1RM) at improving 1 RM in team-sport athletes (Thuwakum et al., 2017). After 3 sessions per week for 5 weeks of leg extension and leg curl, a lower intensity IHRT group had the same improvement in 1RM as a higher intensity group in normoxia. This may have relevance for team-sport athletes returning from injury who cannot lift the same absolute load as when uninjured.

To further support the use of IHRT, netball athletes undertaking low intensity IHRT had a greater improvement in maximal voluntary contraction than a control group (Manimmanakorn et al., 2013). Similarly, in previously untrained participants, using a moderate intensity resistance training protocol, only the IHRT group improved muscular endurance as measured by maximal repetitions at 70% 1RM (Kon et al., 2014). However the IHRT group showed no greater improvement in 1RM compared to control (Kon et al., 2014). This is interesting considering a moderate training intensity of 70% 1RM, using 5 sets of 10 reps was used throughout the study. It is possible that the lack of an increase in 1RM is due to the moderate intensity training protocol used, rather than heavy RT of greater than 85%1RM which is more likely to see changes in 1RM.

In the aforementioned study, both groups had similar increases in lean mass and decreases in fat mass (Kon et al., 2014). A low intensity IHRT protocol with previously untrained participants did not have the same effect on muscular endurance (Friedmann et al., 2003), while maximal strength, as measured through a maximal voluntary contraction, did not increase (Friedmann et al., 2003).

It is clear the current research is conflicting, and further investigations are required to deduce the best training combinations.

There is currently no training study using a high intensity resistance training protocol, using a load of greater than 80% 1RM. The effects of IHRT on strength-trained participants have also not been determined. This study will therefore investigate if heavy IHRT is more effective at developing maximal strength in resistance-trained participants. A secondary aim is to determine whether IHRT aids changes in body composition, sprint performance and power production during the countermovement jump.

5.3 Methods

5.3.1 Participants:

Twenty strength-trained male participants aged between 18 and 34 volunteered as participants. Participants were required to record a training diary, and qualified as strength trained by achieving at least 12 months continuous resistance training history immediately prior to the study. Resistance training prior to the study needed to include squats and deadlifts as part of their regular training program. The study was approved by the University Human Research Ethics Committee and conformed to the Declaration of Helsinki. All participants provided written informed consent. Participants completed a training log of their current resistance training, including frequency, exercises, sets, repetitions and intensity to ensure they qualified as strength trained for the purpose of the study. Participants were then pair-matched on absolute 1RM squat strength and training history, and assigned to either the hypoxic (IHRT) or placebo groups.

5.3.2 Testing:

Pre-, mid- and post-study, participants were scanned using dual energy x-ray absorptiometry (DXA) to assess changes in body composition, tested for 1RM squat strength, countermovement jump, and 20-m sprint time with 5 and 10-m splits.

All participants were familiar with the 1RM squat, a warm up set of 5 repetitions at 50% predicted 1RM was performed, followed by 3 repetitions at 80% predicted 1RM, then a single repetition at 90% predicted 1RM. The weight was then increased in small increments until failure, with the goal of achieving a 1RM in a further 3-4 attempts. For the lift to be successful, a depth was required whereby the crease of the hips was below the top of the patella. The same Australian Strength and Conditioning Association Level 3 qualified coach assessed 1RM depth throughout the study. A linear position transducer was connected to the bar, and during the warm-up sets, participants were instructed as to the required depth for 1RM testing by the assessor. This depth was recorded via minimum displacement from the linear position transducer. A failed attempt was recorded if the participant failed to lift the weight, or if adequate depth was not achieved.

The 20-m sprint was performed pre- and post-intervention on the same indoor basketball court using Swift timing gates (Swift, www.spe.com.au. Wacol, Queensland, Australia). Participants were instructed to place their toe on a line between the two starting gates, with their weight over their front foot to ensure acceleration occurs from a stationary start with no rock back. Timing gates were placed at 0, 5, 10 and 20-m to record split times. A minimum of three attempts was allowed, with a fourth attempt given if the third trial was the fastest. Participants were offered as much rest as required to ensure each effort was maximal, with a minimum of three mins given.

A countermovement jump using a force plate, linear position transducer and corresponding Ballistic Measurement System Software (Fitness Technologies, www.fittech.com.au, Adelaide, South Australia, Australia) was used to assess jump qualities. The force plate and linear position transducer were calibrated prior to each testing session according to manufacturer's instructions. Participants performed a familiarization session for the countermovement jump prior to baseline testing. At each testing session, participants performed four single jumps with approximately 30 seconds between each jump, with the jump that achieved the highest power output being used for analysis.

Body mass was measured on calibrated scales and height was measured on a calibrated stadiometer. A DXA scan was performed to assess change in body composition measures including fat mass, lean tissue and bone mass. The DXA scanner used was a Discovery W version 13.4.2. It was calibrated prior to each testing session according to manufacturer's instructions. A standard scanning protocol was used to ensure measurement reliability (Nana et al., 2013). Two experienced technicians performed the scans throughout the study, however each participant was scanned and analysed by the same technician at pre, mid and post to remove any inter-tester differences. The protocol for the DXA scan is described in detail elsewhere (Nana et al., 2013). Briefly, participants were positioned on their back in the supine position with hands pronated and legs positioned slightly apart with the femur rotated inwards.

Participants were instructed to maintain a food diary for the first week of the study, and told to replicate this eating plan as closely as possible for the duration of the study. This was followed up with a subsequent weekly food diary after 6 weeks. This was to minimise the likelihood that any changes in body composition were due to a change in diet. Participants were instructed not to start taking any supplements, and maintain any current supplement regime.

5.3.3 Training:

During the training sessions, all participants wore a face-mask connected to a hypoxic simulator (Altitude Training Systems, www.ats-altitude.com, Lidcombe, NSW, 2141). The hypoxic simulator exposed the participants to simulated altitude by increasing the percentage of nitrogen in the inspired air. The simulator was set at one of two altitudes. The placebo group was exposed to air with an FiO_2 of 0.20, simulating an altitude of 400-m above sea level, while the hypoxic group was exposed to air with an FiO_2 of 0.145 for the first four weeks, simulating an altitude of 3,100-m, and FiO_2 of 0.141 for the last three weeks, simulating 3,400-m above sea level. Groups were blinded to their group allocation until the completion of all testing post-study. Participants completed seven weeks of heavy resistance training 3 times per week, with sessions performed on non-consecutive days. Each session consisted of squats, deadlifts and lunges, with repetitions ranging from 3 to 6, and sets ranging from 2 to 4 (Table 5.3). Rest periods were set at 3 mins throughout the study. For squats, starting weight was 75% 1RM for session 1. This weight was chosen after pilot testing, as it was the heaviest weight that could be lifted whereby participants remained blinded to the simulated altitude. During pilot testing, when loads above 75% were used for 6 repetitions participants were able to correctly guess whether they were in the IHRT or placebo trial. We wanted to ensure participants remained blinded to their groups while still using heavy loads. The placebo effect may play a part in determining endurance changes due to altitude (Lundby et al., 2012), however it is unknown if the placebo effect plays a part in resistance training strength changes through altitude. To control for a possible placebo effect, it was important participants remained blinded to the group allocation. The starting weight for deadlift was the same as squat, while lunge started at 50% squat 1RM. If participants lifted the weight to the predetermined repetition goal, they were encouraged to increase the weight. Participants were asked for a rating of perceived exertion (RPE, Borg 6-20 scale) immediately post-set, and this, combined with the judgement of the researcher was used to determine whether the participant should increase the weight for the next set. This method of increasing the load each session was chosen over a set increase per session or week to allow for individual variations in adaptation over time. For squats and lunges, the bar was positioned on the back across the superior trapezius, with participants instructed to achieve a depth of crease of hips below the top of the patella, as for 1RM testing. For deadlift, the weight was lowered to the ground between each rep. As participants were experienced in these exercises, a degree of flexibility was allowed regarding placement of feet, with some choosing a wider stance, and others a narrower stance.

The hypoxic mask was worn for the last warm up set and all working sets. Once applied, the hypoxic mask was not removed until the completion of the session (approximately 45 mins). Prior to hypoxic exposure, baseline SpO_2 and heart rate were taken via pulse-oximetry. These values were also taken pre- and post- each working set, with the values immediately prior to the set used as the pre-set value, and the lowest value of SpO_2 and highest value for heart rate used as the post-set value. Post-set values were usually achieved 15 to 30 seconds post-set. As well as the 6 to 20 Borg scale post each working set, the Borg 1 to 10 RPE scale was used post session. After the first session, and regularly throughout the seven weeks, participants were asked which group they thought they were in.

5.3.4 Statistical analysis:

A contemporary statistical approach was used to analyse all data, and expressed as mean ± SD and effect size (ES ± 90% confidence limits (CL)). Percentage change was determined in comparison to baseline. The difference in the change between groups was determined using both ES and % changes ± 90% CL. Where the difference in between group change for 90% CL crossed from positive to negative (across 0%), this was interpreted as unclear at 90% CL. Standards for measuring ES were as previously described (Hopkins et al., 2009).

5.4 Results:

Participants were blinded to condition, with only one participant guessing their group allocation. Table 5.1 gives details of the participants. Of the 20 volunteers, 18 completed the study (9 per group), while the other two completed the mid testing. One participant withdrew due to illness, and the other through injury, both unrelated to the training study. Only the 18 who finished the study were included for post analysis, while all 20 participants were included in the mid testing analysis. Groups were not clearly different for any of the testing procedures at baseline.

Training data: Pre-training SpO_2 values were not different between groups (98.3 ± 1.3% for IHRT and 98.4 ± 1.3% for placebo) (Table 5.2). During the session, oxygen desaturation occurred in IHRT only, with a *likely* large effect in the difference between groups pre set (90.0 ± 2.5% for IHRT vs 97.3 ± 1.3% for placebo. ES -5.61, 90% CL for ES -5.7 to -5.5). There was also greater desaturation post-set for IHRT with a *most likely* large effect in the difference between groups (84.1 ± 3.5% for IHRT vs 96.5 ± 1.7% for placebo, ES -7.3, CL for ES -7.4 to -7.2) (Table 5.2). Neither session RPE (IHRT 7.5 ± 1.3 vs placebo 7.3 ± 1.6), nor post-set RPE (IHRT 15.4 ± 2.5 vs placebo 15.2 ± 2.3) were different between groups.

Heart rate was higher post set compared to pre in both groups (pre to post set HR 103.7 ± 19.6 bpm to 144.8 ± 19.0 bpm for IHRT, and 104.0 ± 18.3 bpm to 144.9 ± 18.2 bpm for placebo), with no clear difference between groups (Table 5.2). Load lifted when reported as percentage of squat 1RM was not different between groups during week one (77.5. ± 3.7% for IHRT vs 78.2 ± 3.9 for placebo) For squat, there was a trend towards IHRT lifting a greater percentage of baseline 1RM compared to placebo throughout the study (Table 5.3). By week 3, IHRT was lifting a greater percentage of starting 1RM for squat compared to placebo, with a *likely* large effect (3.9%, ES 0.94, 90% CL 0.65 to 1.24). This greater percentage of starting 1RM lifted in training for IHRT compared to placebo remained through to week 7 (5.4%, ES 0.91, 90% CL 0.61 to 1.20.

Table 5.1: Testing results for all performance tests for both IHRT and Placebo groups. All data is Mean ± SD

	IHRT Group			**Placebo Group**		
Test	**Pre (n=10)**	**Mid (n=10)**	**Post (n=9)**	**Pre (n=10)**	**Mid (n=10)**	**Post (n=9)**
Height (cm)	183.1 ± 4.5	183.1 ± 4.5	184.1 ± 4.5	181.0 ± 5.8	181.0 ± 5.8	180.8 ± 5.8
Body mass (kg)	83.1 ± 7.5	83.0 ± 7.5	83.7 ± 7.9	80.2 ± 12.0	80.5 ± 11.2	78.7 ± 9.8
Total lean mass (kg)	67.88 ± 5.4kg	67.61 ± 4.6 kg	67.60 ± 5.2 kg	64.54 ± 4.8 kg	65.24 ± 5.3 kg	64.83 ± 3.9 kg
Absolute 1RM strength (kg)	121.4 ± 22.1	138.2 ± 27.8	148.4 ± 32.7**	125.5 ± 30.7	135.7 ± 29.5	141.8 ± 28.8#
Relative squat strength ($kg.bm^{-1}$)	1.46 ± 0.19	1.66 ± 0.22	1.76 ± 0.26**	1.56 ± 0.30	1.69 ± 0.29	1.80 ± 0.25#
5 metre split time (s)	1.17 ± 0.08		1.17 ± 0.03	1.13 ± 0.08		1.12 ± 0.07
10 metre split time (s)	1.94 ± 0.11		1.94 ± 0.06	1.89 ± 0.09		1.88 ± 0.08
20 metre split time (s)	3.25 ± 0.15		3.27 ± 0.10	3.21 ± 0.14		3.18 ± 0.09
Absolute Peak Power (W)	4,360 ± 602		4,676 ± 463*	4,333 ± 656		4,299 ± 527

* *Possibly* greater pre-post change than placebo. ** *Likely* greater change than placebo. #*Likely* greater than pre.

Table 5.2: Average SpO_2 and Heart Rate values pre and post all sets for the duration of the training study and post-set RPE for each group. All Data is Mean ± SD

	IHRT Pre session	IHRT Pre set	IHRT Post set	Placebo Pre session	Placebo Pre set	Placebo Post set
SpO_2%	98.29 ± 1.3	89.97 ± 2.5*	84.13 ± 3.5*[#]	98.38 ± 1.3	97.26 ± 1.3	96.51 ± 1.7
Heart Rate (BPM)	93.8 ± 19.1	103.7 ± 19.6	144.8 ± 19.0**	93.8 ± 17.2	104.0 ± 18.3	144.9 ± 18.2**
RPE (au)			15.43 ± 2.5			15.16 ± 2.3
Post session RPE (au)			7.53 ± 1.28			7.27 ± 1.61

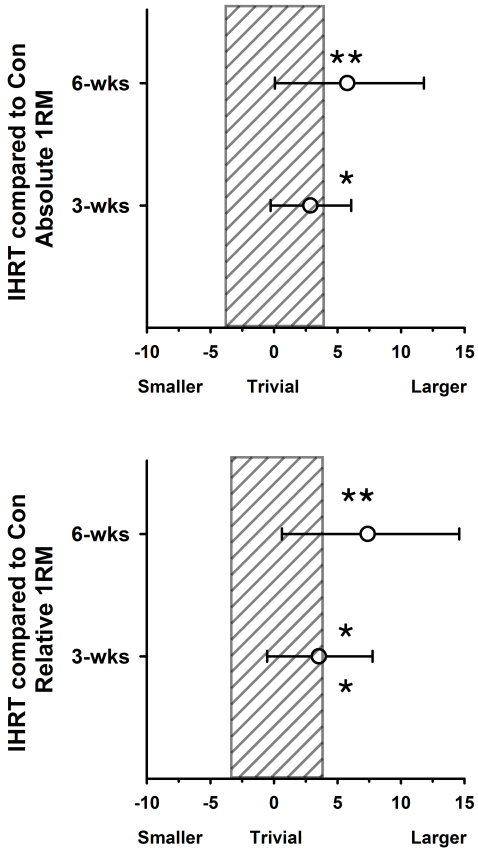
**Most likely* less than placebo. [#]*Most likely* less than pre. ***Most likely* greater than pre-set.

Table 5.3: Repetitions (Reps) and sets each week for squats, deadlifts and lunges (3 lunges each leg per set) and percentage 1RM for squat lifted and post-set RPE for each group each week. All data is Mean ± SD.

Week	Sets	Squat Reps	Deadlift reps	Lunge Reps	Squat %1RM IHRT load	Squat %1RM Placebo load	Post set IHRT RPE	Post set Placebo RPE
1	3	6	6	6	77.5 ± 3.7	78.2 ± 3.9	6.74 ± 1.63	6.02 ± 2.19
2	3	5	5	6	85.4 ± 5.3	83.8 ± 4.0	7.39 ± 2.14	7.03 ± 1.90
3	3	4	4	6	94.4 ± 5.6#	90.5 ± 4.1	7.80 ± 2.28	7.38 ± 2.13
4	2	4	4	6	99.2 ± 5.4#	94.2 ± 4.5	6.98 ± 2.44	6.71 ± 2.16
5	3	5	5	6	100.4 ± 6.5#	94.7 ± 5.9	8.14 ± 2.49	7.66 ± 2.10
6	4	4	4	6	104.2 ± 7.8#	98.6 ± 6.5	7.86 ± 2.80	7.71 ± 1.87
7	4	3	3	6	109.9 ± 8.2#	104.5 ± 5.9	7.60 ± 2.80	7.83 ± 2.15

#*Likely* Large effect in the difference of 1RM lifted between group.

Figure 5.1: Percentage difference in the change in performance from baseline for intermittent hypoxic resistance training (IHRT) compared with placebo with 90% CI. (A) Between-groups change in Absolute 1RM strength. (B) Between-groups change in Relative 1RM strength. Shaded bar represents uncertainty in the measure. * *Possibly* small effect in the difference in change between groups, ***Likely* moderate effect in the difference in the change between groups



Baseline: Absolute strength was 121.4 ± 22.1 kg for IHRT and 125.5 ± 30.7 kg for placebo. Relative strength was 1.46 ± 0.19 $kg.bm^{-1}$ for IHRT and 1.56 ± 0.30 $kg.bm^{-1}$ for placebo. Differences between groups for strength, or any other testing parameter at baseline were unclear (Table 5.1).

Mid: Compared to baseline, both groups improved both absolute (12.7 ± 3.9% for IHRT vs 8.7 ± 4.7% for placebo) and relative (12.9 ± 5.1% for IHRT vs 8.2 ± 5.3% for placebo) 1RM squat (Figure 4.1). Compared to placebo, the IHRT group had a *possibly* greater change for absolute (4.4% greater change, CL 1.0 to 8.0%, ES 0.21, 90% CL 0.05 to 0.37) and a *likely* greater change for relative 1RM (5.1% greater change, CL 1.0 to 9.4%, ES 0.31, 90% CL 0.06 to 0.57). There was no change for lean mass or countermovement jump parameters either between or within groups.

Post: Compared to baseline both groups improved both absolute (22.2 ± 7.6% for IHRT vs 14.2 ± 6.0% for placebo) and relative 1RM (20.5 ± 8.5% for IHRT vs 13.6 ± 6.4% for placebo). The IHRT group had a *likely* greater change than placebo from pre to post for both absolute (7.0% greater change, CL 1.3 to 13.0%, ES 0.33, 90% CL 0.06 to 0.59) and relative (8.0% greater change, 90% CL 1.6 to 14.9%, ES 0.49, 90% CL 0.10 to 0.87) 1RM. At post, only IHRT improved countermovement jump peak power, however this change was unclear in comparison to placebo (2.7% greater change, 90% CL -2.0 to 7.6%, ES 0.20, 90% CL -0.15 to 0.54). There was no difference between or within groups compared to pre for 20-m sprint or body composition.

5.5 Discussion:

Hypoxia improved both absolute and relative 1RM compared to the same training using a placebo despite no change in lean mass. The placebo group also improved 1RM strength, however the IHRT change was 5.8% and 9.2% greater than placebo in absolute and relative 1RM strength, respectively. Considering participants were already strength trained with a moderate to high level of strength, this is a meaningful change between groups after only seven weeks.

This is the first study to use heavy resistance training combined with hypoxia. Only an acute resistance exercise bout has been previously used (Scott et al., 2015b), therefore the present study reports original findings using heavy resistance training and hypoxia in a training study. The majority of resistance and systemic hypoxia studies used low to moderate intensity resistance training of approximately 30 to 70% 1RM. However, the present study used 75% 1RM for the first session, increasing to 104% of starting 1RM for placebo and 109% for IHRT.

Unlike high-intensity interval training in hypoxia, which shows a decrease in maximal work (Balsom et al., 1994), hypoxia does not appear to impact on physical performance during high-load resistance exercise. This is shown by no differences in RPE and heart rate between groups, and is in agreement with the only other research using heavy resistance exercise and hypoxia. Using five repetitions of squat and deadlift in three different conditions (FiO_2 of 0.21, 0.16 and 0.13), heart rate and post set RPE were not different in the conditions with an FiO_2 of 0.21 and 0.16 despite using the same load. However at the more extreme hypoxia, heart rate was higher than the other two conditions (Scott et al., 2015b). This, combined with our findings, confirms resistance training exercise intensity is not affected by moderate hypoxia, at least in trained individuals.

While increased strength and hypertrophy is consistently achieved through resistance training combined with blood flow restriction (Takarada et al., 2000b, Scott et al., 2014), there are conflicting findings whether systemic hypoxia increases strength to a greater extent than resistance training alone. The inconsistent findings can be partly attributed to differences in study design. For example, studies of moderate volume and intensity (3 to 4 sets of approximately 70% 1RM) generally show greater changes in muscle hypertrophy using hypoxia (Nishimura et al., 2010, Kurobe et al., 2015), although one showed no difference between groups (Kon et al., 2014). There are also inconsistent results regarding changes in 1RM between groups when using IHRT with submaximal loads. Studies show increases in 1RM using both moderate (Nishimura et al., 2010) and very light loads (Manimmanakorn et al., 2013), while others show no benefit on 1RM through hypoxia compared to control (Kon et al., 2014). Unfortunately, the study by Nishimura et al. used a predictive equation to determine 1RM from a 10RM test. Therefore, although authors concluded an increase in muscular strength, it is rather likely that, because of the non-specific testing (Reynolds et al., 2006, Tanner and Gore, 2013), an increase in muscular endurance explained the change in predicted 1RM.

Two studies have used tests of moderate intensities to test for muscular endurance, similar to the load used during training, with hypoxic groups showing both a benefit (Kon et al., 2014), and no change in performance (Kurobe et al., 2015). In the Kon et al. study, systemic hypoxia showed no greater change in 1RM compared to control, however when testing using the same intensity as training, muscular endurance improved more in the hypoxic group (Kon et al., 2014), showing the importance of the testing protocol matching the training protocol.

As all hypoxia and resistance training studies to date have used moderate intensities more suited to hypertrophy and muscular endurance gains (Fleck and Kraemer, 2014), combined with the differences in methodology for determining 1RM, it is not surprising that changes in

1RM through systemic hypoxia are conflicting. Therefore it is important to ensure the testing battery is appropriate to reflect the nature of the training intervention (Tanner and Gore, 2013). Systemic hypoxia may merely magnify the expected outcome from a given training program, with specificity of the stimulus and testing protocol important to test the outcome of training.

It is possible there were no increases in lean mass due to our study employing a lower volume, high intensity program designed to increase maximal strength more so than muscle hypertrophy. This type of protocol is more likely to see changes in strength as opposed to muscle hypertrophy (Kraemer and Ratamess, 2004). This change in strength despite a lack of change in lean mass is an important finding, as many athletes, including team-sport athletes with a high running demand in their sport, athletes competing in weight classes, and many endurance athletes want to increase strength without an increase in mass.

Other researchers have concluded that the placebo effect may be at least partly responsible for performance changes through hypoxia (Siebenmann et al., 2012), however this was not the case in our study. As participants were successfully blinded to the environmental condition, the greater changes in strength observed in IHRT in the present study cannot be attributed to a placebo effect. Due to no placebo effect, and no changes in lean mass, we cannot fully explain the mechanisms responsible for the differences between groups. When beginning strength training, most of the early strength changes can be attributed to neural adaptations (Moritani and deVries, 1979). Such early changes include adaptations in agonist, antagonist and stabilizer muscle activation, increased firing frequency, motor unit synchronization, and agonist co-activation (Folland and Williams, 2007). As all participants were strength trained, matched for training status and 1RM, any neural adaptations could be expected to be minimal.

The decreases in SpO_2 in IHRT are similar to other systemic hypoxic studies (Scott et al., 2015b, Kon et al., 2010). A decrease in SpO_2 occurs with hypoxia, and this activates a cascade of events that eventually lead to changes in endurance performance (Rusko et al., 2004). It is yet to be determined what effect a decrease in SpO_2 has on changes seen through IHRT. There is reduced central fatigue following adaptation to hypoxia through low intensity endurance training (Amann et al., 2013). Enhanced cerebral O_2 delivery to compensate for hypoxia could enhance neurotransmitter turnover, thus enhancing skeletal muscle fibre firing rate (Amann et al., 2013), which is a typical neural adaptation seen through resistance training. However as stated above, this was through aerobic training, so it is speculation only that this may also occur through IHRT. The heavy resistance training used in the current study increases the level of neural activity (Tan, 1999). Whether these changes are evident following IHRT is unknown, however if apparent, this would possibly explain an adaptation to hypoxia that may increase strength through neural changes including muscle fibre firing rate. Although there are possible neural changes that could explain increases in 1RM through IHRT, most changes in neural adaptation occur quite early in a resistance-training program (Moritani and deVries, 1979). As we used resistance-trained participants, most of the neural changes would have already occurred. Further, a low intensity knee flexion and extension protocol combined with either using BFR or hypoxia had no further increases in EMG compared to a control group (Manimmanakorn et al., 2013). Therefore it is quite surprising that there were changes in 1RM despite no change in muscle mass. Because of this, the mechanisms behind increased 1RM are not known. Neural changes should be analysed in further IHRT studies to determine whether neural changes are responsible for the change in performance following IHRT. Although the above study showed no increases in EMG over those in a control group, this should also be examined in a higher intensity IHRT protocol like the one used in the current thesis.

We found no change in 20m-sprint performance for either group, despite a change in 1RM. Although only IHRT improved CMJ peak power, the difference in the change between groups was unclear. There is a strong correlation between maximal squat strength and sprint performance (Wisløff et al., 2004, McBride et al., 2009), this correlation is also apparent between maximal squat strength and CMJ performance (Wisløff et al., 2004). It is also generally believed that improving 1RM directly increases sprint performance. In soccer athletes, there was a small change in 20-m sprint times after improvements in 1RM squat strength (Styles et al., 2016). A low volume, heavy resistance training protocol was used. Although not stated, the Styles et al. study was performed during the competition season and it is assumed these athletes would have been exposed to maximal running velocity during training and matches. Therefore strength changes through resistance training, combined with the sprint training during the on pitch training may have combined to increase 20-m sprint performance. To support this, strength training only, and sprint training only displayed the same changes in 30-m sprint times, while a combination of strength and sprint training had a greater enhancement in 30-m sprint times (Marques Má et al., 2015).

As our study was heavy resistance training only, and the participants were not performing sprint training as part of their normal activity outside of the study, a possible reason for the lack of change in 20-m sprint times and CMJ performance in our study is due to no explosive training being performed as part of training. In a study on team-sport athletes, a group that performed plyometric exercises improved sprint times, while a control group showed no change (Marques Má et al., 2013), however it should be noted that neither group performed resistance training as part of the study. The addition of sprint or plyometric training combined with maximal strength training may therefore be important to improve sprint times, with resistance training alone insufficient to increase speed and power.

In a normal periodised resistance-training program for athletes, high velocity resistance training either follows, or is completed in conjunction with heavy strength training. This change in strength could well be transferred into changes in power with appropriate subsequent training.

5.6 Practical Applications

- IHRT increases relative and absolute 1RM in comparison to a strength and training matched control group.
- Increases in 1RM occurred despite no changes in muscle mass, 20 m sprint or CMJ parameters.
- Athletes wanting to increase strength without increasing muscle mass are advised to undertake heavy resistance training in systemic hypoxia.

5.7 Acknowledgements:

The authors would like to acknowledge the help of all the lab staff and participants. We would also like to thank, Amber Rowell, Brendan Lazarus, James McMahon, Jan Lemon, Kristal Hammond and Raku Shimakawa for supervising the training sessions.

6 GENERAL DISCUSSION, CONCLUSIONS AND FUTURE RESEARCH

6.1 Introduction

This thesis aimed to determine the efficacy of altitude training to enhance team-sport athlete physical performance, and the time course of any altitude induced adaptation. There are a number of factors influencing team-sport performance, of which physical capacity is only one. Technical, tactical and mental aspects are also important in determining overall team-sport performance; therefore it is important to distinguish between team-sport physical performance, which this thesis focuses on, and overall team-sport performance, which has a much wider context, and is outside the scope of this thesis.

Team-sport athletes need a unique mixture of strength, power, endurance and intermittent running capability. To truly determine the efficacy of any training intervention on team-sport athlete physical performance, the effects on all of these physical qualities must be examined. As well as the unique factors involved in team-sport competition, the length of the season, combined with the training and match schedule presents challenges not taken into account in the current altitude training literature. The three studies in this thesis were designed with the specific goals of determining the effects of altitude on the physical qualities highlighted above, and also how any intervention could be applied considering an extended team-sport training and competition schedule.

6.1.1 Intermittent Hypoxic Training and Team-sport Physical Performance

This thesis determined that IHT improved intermittent running performance as measured through the Yo-Yo IR2, with a 27% change after only six sessions in sub elite team-sport athletes. This time course is more rapid than originally thought. Prior to this thesis, a minimum of eight to 10 sessions were thought to be required to elicit gains in physical capacity through IHT (Czuba et al., 2011, Hamlin et al., 2010b, Faiss et al., 2013). Repeated TT performance failed to show any change post IHT in either group.

Studies on team-sport athletes generally take place in the pre-season (McLean et al., 2015). This is in part due to the thought that an extended block of IHT was needed to offer any benefit. With the packed training schedule, it is difficult to add a block of eight to 10 sessions throughout the season. As this thesis shows that six sessions may increase intermittent running performance, a short block of IHT could prove beneficial if performed in season, ensuring the benefits on intermittent running performance are maintained for sustained periods throughout the competitive season, and not just for a single peak at the start of competition. This makes IHT a much more attractive training modality to team-sport athletes throughout the season.

As well as the importance of the minimum time course, determining how long the benefits last is important for team-sport athletes, due to the extended seasons of most professional competitions (www.afl.com.au, 2016, www.premierleague.com, 2016). No study has tracked athletes for the length of time post IHT as the current thesis. The benefits of the IHT intervention in comparison to the control group remained for at least 30 days post exposure, with the IHT group change compared to pre still 24% greater than the control.

The combined findings of the minimum time course for IHT induced adaptation of only six sessions, and the benefits remaining at least 30 days has great practical importance for team-sport athletes. These combined time courses can help shape altitude dosage throughout a competitive season. From this thesis, practical applications for IHT on team-sport athletes may be a six session dose administered over two weeks, with a period of four to six weeks without IHT, followed by another two week dose administered to “top up” the adaptation, ensuring the beneficial effects on intermittent running performance last for the course of a full season.

Due to the importance of intermittent running performance for team-sport athlete physical performance, the relatively short exposure required to achieve a meaningful change in intermittent running performance, and the length of time these adaptations remain, this thesis has determined that IHT is a viable option for improving TS athlete physical performance.

6.1.2 Live High Train Low and Team-Sport Physical Performance

As with IHT, this thesis also determined that LHTL is a viable option for improving team-sport athlete running performance. Although both the control and LHTL groups improved Yo-Yo IR2, the LHTL group improved to a greater extent. This change occurred more slowly than that seen through IHT, but unlike IHT where all the benefits were evident in the first six sessions, the LHTL group change became more apparent the longer the time spent at altitude. A major difference to that seen in the IHT study was that the LHTL group improved TT performance to a greater extent than the control group. Interestingly, this was clearer in the second aerobic effort. As a second aerobic effort has a greater reliance on aerobic pathways (Garvican et al., 2011), it is possible that the change in Hb_{mass} mediated in part by LHTL resulted in greater aerobic adaptation. The study design allowed for two days break between each block of five days exposure, this was to test the efficacy of the type of exposure that could be undertaken during a team-sport season, where games regularly occur on weekends.

This study was able to track the athletes training load for up to seven weeks prior to the LHTL intervention. Therefore the training status of the participants leading into the study was well known, with athletes matched for training history and fitness capacity. As the altitude-induced changes are similar in magnitude to those with a taper (Pyne et al., 2009), it is important to ensure that athlete training status at the beginning of the study is determined, otherwise changes in performance could simply be put down to a change in training, rather than any intervention as part of the study. This may be a reason for many altitude studies being unable to find a change in performance, or conversely, why some find improvements.

As participants were matched for training history, it is much clearer that these changes were due to the intervention. Due to the intermittent exposure of the study design, LHTL can be used in season on team-sport athletes for great benefit to both TT and intermittent running performance. A practical application would be to identify a period in season where the athletes can spend four blocks of five nights with short breaks between exposures for matches and recovery. As with IHT, this would ensure that the benefits are not confined to the first couple of weeks of the season, but can have effect throughout the season. Further research should focus on how long the benefits of such an intervention last, which would then allow periodic exposures throughout the season to maintain the benefit throughout.

It is clear that the changes with LHTL are different than those with IHT. In a practical sense, this shows the importance for sport scientists working with team-sport athletes to determine the adaptation the athlete is requiring before applying certain methods of altitude exposure for team-sport running performance.

6.1.3 Intermittent Hypoxic Resistance Training and Squat Performance

Most research using altitude on team-sport athletes and physical performance has focused on the effects on running ability. However when judging physical capacity, neglecting effects on strength and power of any intervention misses important physical qualities. As strength and power are important for team-sport performance due to the physical involvements (Dawson et al., 2004), and RT is common among most team-sport athletes (Helgerud et al., 2011), determining the effects of altitude exposure combined with RT is important for any true holistic look at the effects of altitude on team-sport athlete physical performance. In the present thesis, IHRT was more effective than placebo for improving both absolute and relative 1RM squat strength in resistance trained participants. After four weeks, this change was only meaningful for relative 1RM (5.1% greater change for IHRT). After seven weeks, this change was greater for both absolute (7.0% greater change) and relative (8.0% greater change) 1RM squat strength. This greater change for IHRT occurred despite no change in lean mass, power or speed.

This thesis provides the first training study using IHRT combined with heavy RT. The starting load used was 75% 1RM, progressing to 104% starting 1RM for the placebo group, and 109% for the IHRT group. Unlike endurance training, where a decrease in exercise intensity occurs at maximal work rates (Clark et al., 2007), exercise intensity is maintained through IHRT, with no differences in RPE and heart rate between groups despite a similar load being used, which supports research using moderate hypoxia and similar load (Scott et al., 2015b). As heavy RT generally does not exhibit the same changes in lean mass compared to moderate intensity RT (Kraemer and Ratamess, 2004), the lack of change in lean mass is not unexpected. It was concluded that IHRT merely magnifies any expected RT-derived outcome.

Team-sport athletes cover large amounts of distance at high velocities (Aughey, 2011), therefore carrying excessive body weight may be counterproductive to a team-sport athletes running performance during games. Increasing strength without the added muscle mass may be important to maintain running capacity, therefore the finding of increased strength with no meaningful change in lean mass is important for team-sport athletes. As there were no changes in speed and power, heavy strength training alone appears insufficient to increase power and speed, which has been shown in similar team-sport athletes following resistance training (Marques Má et al., 2013). To increase these physical qualities, high velocity training should be employed to transfer the changes in strength seen through IHRT into changes in speed and power (Marques Má et al., 2015). The findings from this thesis show that IHRT has clear benefits to team-sport athlete physical performance, in that there are changes in strength independent of changes in lean muscle mass, however it should be noted that this is in contrast to most research using IHRT. The practical applications of this finding are that athletes looking to increase strength without the risk of compromising running performance through added weight may be better advised to undertake IHRT with a heavy resistance training protocol. If added lean muscle mass is the goal, a lower intensity protocol may be preferred.

6.2 Conclusions

This thesis produced a number of novel findings. Of particular interest is that the type of altitude training undertaken should not be a one size fits all approach. Depending on the type of adaptation a particular team-sport athlete requires will determine the most appropriate method of altitude exposure. For example, a team-sport athlete who has a large aerobic capacity but is relatively poor at repeated high intensity efforts would best be suited to IHT, whereas an athlete who has excellent strength and power, but poor aerobic capacity could benefit most from LHTL. The limiting factor to each athlete's physical performance should be determined, and appropriate training stimulus given to achieve the desired outcome. This individual approach to altitude exposure is an important consideration for all sport scientists working with team-sport athletes. The main findings from the thesis are summarised below:

- Team-Sport athletes looking to improve intermittent running capacity are best advised to undertake IHT
- IHT is unlikely to increase Hb_{mass} due to the small accumulated time spent at altitude
- The benefits of IHT are apparent after only six IHT sessions in team-sport athletes.
- The benefits of IHT remain for at least 30 days in team-sport athletes.
- Team-Sport athletes that are looking to improve aerobic capacity are recommended to undertake LHTL.
- LHTL increases Hb_{mass} in team-sport athletes to a similar degree to that seen in elite endurance athletes.

- The more nights spent at altitude, the greater the change in running performance and Hb_{mass} following LHTL
- Strength trained participants looking to improve strength without large increases in muscle hypertrophy can benefit from heavy strength training combined with systemic hypoxia.
- Heavy strength training alone is insufficient to improve speed and power in strength trained participants.
- There are no differences in perceived exertion from heavy resistance training in systemic hypoxia compared to normoxia.
- IHRT may magnify expected outcomes through RT, therefore training specificity and correct testing protocols are important in determining outcomes through IHRT.

6.3 Future Research

It has been determined that different methods of altitude exposure are effective at increasing physical performance in sub elite team-sport athletes, however a number of questions still remain, with the current thesis opening up windows for future research. A single IHT study found only six sessions were effective at increasing Yo-Yo IR2 performance, with the benefits of 11 sessions lasting at least 30 days. Future research on IHT in team-sport athletes should look at the following:

- Can undertaking the altitude dose found to be effective in this thesis at regular intervals have the same repeated benefit? If so, a small dose could be administered sporadically throughout a competitive season to ensure the benefits remain for the duration of a team-sport season.
- Although the last five IHT sessions did not offer any further benefit, are these extra five sessions responsible for allowing the benefits to remain for the 30 days, or are

they unnecessary? Therefore further research should compare how long the benefits of 6 sessions of IHT last compared to 11 sessions of IHT.

Further research surrounding LHTL should focus on the time course the benefits remain. Testing should be undertaken post LHTL at regular intervals to determine how long any benefit remains. As with IHT, this has practical importance when determining the optimal time to administer the intervention around important periods of competition, therefore testing should continue for a number of weeks post LHTL exposure.

Intermittent hypoxic resistance training is the least researched area of this thesis. This is the first training study of its kind using heavy RT. For this reason, there are many potential areas for future research in IHRT. Future research should determine the following:

- What is the optimal load for increases in strength and/or hypertrophy through IHRT.
- Future studies should add explosive training to future IHRT studies to determine whether explosive training is needed to improve power production through IHRT.
- Heat combined with hypoxia could be a potent mix, and should be investigated to determine whether combining these methods can increase adaptation.

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