
The Acute Physiological, Physical and Perceptual Responses to Intermittent Hypoxic Resistance Training



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Doctor of Philosophy
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Statement of Originality

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Acknowledgement of Authorship

I hereby certify that the work embodied in this thesis contains a published paper/s/scholarly work of which I am a joint author. I have included as part of the thesis a written statement, endorsed by my supervisor, attesting to my contribution to the joint publication/s/scholarly work.

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Table of Contents

STATEMENT OF ORIGINALITY	I
ACKNOWLEDGEMENT OF COLLABORATION	II
ACKNOWLEDGEMENT OF AUTHORSHIP	III
ACKNOWLEDGEMENTS	IV
LIST OF PUBLICATIONS ARISING FROM THIS THESIS	VI
TABLE OF CONTENTS	IX
LIST OF FIGURES	XIII
LIST OF TABLES	XVI
LIST OF ABBREVIATIONS	XVII
ABSTRACT	XXI

CHAPTER 1

Introduction	1
Background Information	2
Statement of the Problem	6
Purpose of the Thesis	7
Significance of the Study	8
Limitations and Assumptions	9
Delimitations	10

CHAPTER 2

Review of the Literature	12
Abstract	13
Introduction	14
Resistance Exercise with Blood Flow Restriction	15
Adaptive and Perceptual Responses to Blood Flow Restriction Training	16
Potential Mechanisms of Blood Flow Restriction for Hypertrophy and Strength	20
Practical Applications and Limitations of Blood Flow Restriction	32
Resistance Exercise with Systemic Hypoxia	35
Adaptive and Perceptual Responses to Intermittent Hypoxic Resistance Training	43
Potential Mechanisms of Intermittent Hypoxic Resistance Training for Hypertrophy and Strength	47
Differences Between Blood Flow Restriction and Intermittent Hypoxic Resistance Training Methods	54
Conclusions	56

CHAPTER 3

Study 1	58
<i>Reliability of Telemetric Electromyography and Near-Infrared Spectroscopy during High-Load Resistance Exercise</i>	58
Abstract	59
Introduction	60
Methods	63
Results	72
Discussion	77
Conclusions	82
Practical Applications	83

CHAPTER 4

Study 2	84
<i>Physical Performance during High-load Resistance Exercise in Normoxic and Hypoxic Conditions</i>	84
Abstract	85
Introduction	86
Methods	90
Results	94
Discussion	101
Conclusions	105
Practical Applications	106

CHAPTER 5

Study 3	107
<i>Systemic Hypoxia does not Enhance Acute Responses to High-Load Resistance Exercise</i>	107
Abstract	108
Introduction	109
Methods	111
Results	116
Discussion	122
Conclusions	126
Practical Applications	127

CHAPTER 6

Study 4	128
<i>Acute Physiological Responses to Moderate-Load Resistance Exercise in Systemic Hypoxia</i>	128
Abstract	129
Introduction	130

Methods.....	132
Results.....	137
Discussion	143
Conclusions	148
Practical Applications	149
 CHAPTER 7	
Study 5	150
<i>Resistance Exercise in Hypoxia does not Affect Markers of Physical Performance, Training Stress or Neuromuscular Recovery</i>	150
Abstract	151
Introduction.....	152
Methods.....	154
Results.....	161
Discussion	169
Conclusions	173
Practical Applications	173
 CHAPTER 8	
General Discussion	175
Overview of Thesis	176
Reliability of Methods to Monitor Muscle during Resistance Exercise ...	177
Physical Performance and Neuromuscular Recovery during Hypoxic Resistance Training.....	178
Physiological Responses to Resistance Exercise in Hypoxia	180
Perceptual Responses to Resistance Exercise in Hypoxia	183
Conclusions	184
 CHAPTER 9	
Summary and Practical Applications	185
Summary of the Major Findings.....	186
Practical Applications	188
Recommendations for Future Research.....	189
 CHAPTER 10	
References	191
 CHAPTER 11	
Appendices	230
Appendix A	231
Information Statement (Study 1).....	231

Appendix B	236
Consent Form (Study 1)	236
Appendix C	239
Information Statement (Study 2-5)	239
Appendix D	245
Consent Form (Study 2-5)	245
Appendix E	248
Expedited Approval (Study 2-5)	248
Appendix F	250
Pre-Exercise Health Screening Questionnaire	250
Appendix G	252
<i>Intermittent Hypoxic Resistance Training: Does it Provide Added Benefit?</i>	252
Introduction	253
Findings from Intermittent Hypoxic Resistance Training Studies	254
Level of Hypoxia	255
Metabolic Stress	257
Conclusions	260
Appendix H	262
<i>Intermittent Hypoxic Resistance Training: Is Metabolic Stress the Key Moderator?</i>	262
Abstract	263
Introduction	264
Conflicting Results of Intermittent Hypoxic Resistance Training Studies	266
Effects of Inter-Set Rest Periods on Energetic Metabolism	268
Hypoxia-Mediated Challenges for Energetic Metabolism	270
Anabolic Effects of Metabolic Stress	272
Considerations for Training Programs	276
Conclusions	278

List of Figures

Figure 2.1. Simplified schematic of the proposed interplay between potential mechanisms that may mediate the adaptive responses to BFR training and IHRT.....	36
Figure 3.1. Example of a subject performing the harness back squat exercise, highlighting the squat position at the end of the eccentric/beginning of the concentric phase (A), and at the end of the concentric phase (B).	64
Figure 3.2. Placement positions the NIRS device on the right <i>vastus lateralis</i> (1), and EMG electrodes on the left <i>vastus lateralis</i> (2), <i>vastus medialis</i> (3), <i>gluteus maximus</i> (4) and <i>biceps femoris</i> (5) from an anterior (A) and posterior (B) view.	68
Figure 3.3. Example of the accelerometry trace from the VL electrode and typical raw EMG traces from the <i>gluteus maximus</i> (GM), <i>biceps femoris</i> (BF), <i>vastus lateralis</i> (VL) and <i>vastus medialis</i> (VM) muscles during three repetitions of the harness back squat exercise.....	69
Figure 3.4. The ICC and CV of RMS, MDF and iEMG data between identical repeated sets of harness back squat exercise within a single testing session from the (A) <i>gluteus maximus</i> , (B) <i>biceps femoris</i> , (C) <i>vastus lateralis</i> and (D) <i>vastus medialis</i> muscles.....	73
Figure 3.5. The ICC and CV of RMS, MDF and iEMG data between identical matched sets of harness back squat exercise in separate testing sessions from the (A) <i>gluteus maximus</i> , (B) <i>biceps femoris</i> , (C) <i>vastus lateralis</i> and (D) <i>vastus medialis</i> muscles.....	74
Figure 3.6. The ICC and CV of HbO ₂ (%), HHb (%) and TSI (%) data between identical repeated sets of harness back squat within a single testing session from the <i>vastus lateralis</i>	76
Figure 3.7. The ICC and CV of HbO ₂ (%), HHb (%) and TSI (%) data between identical matched sets of harness back squat in separate testing sessions from the <i>vastus lateralis</i>	76
Figure 4.1. Pooled data for (A) peak and (C) mean force as well as (B) peak and (D) mean power during the concentric phase of each repetition across five sets of the back squat.....	96
Figure 4.2. Pooled data for (A) peak and (C) mean force as well as (B) peak and (D) mean power during the concentric phase of each repetition across five sets of the deadlift.....	97

Figure 4.3. Percentage change in concentric force and power from the first to the fifth set of the back squat (A and C) and the deadlift (B and D) in NORM, MH and HH.	99
Figure 4.4. Pooled data for SpO ₂ , HR and RPE immediately following each set of 5 repetitions for the back squat and deadlift exercises.	100
Figure 5.1. Mean relative values for minimum HbO ₂ (A and B) and maximum HHb (C and D), during high-load back squat exercise (A and C) and deadlift exercise (B and D).	117
Figure 5.2. Blood lactate (BLa ⁻) concentrations and pH levels prior to exercise, and following the final sets of back squat and deadlift exercises. ...	118
Figure 5.3. Blood oxygen saturation (sO ₂) and partial pressure of oxygen (PO ₂) prior to exercise, and following the final sets of back squats and deadlifts.	119
Figure 5.4. Mean iEMG during the concentric phase of the back squat (A-D) and deadlift (E-G) exercises in normoxia (NORM), moderate-level hypoxia (MH) and high-level hypoxia (HH) conditions.	121
Figure 5.5. Physical fatigue and muscle soreness scores prior to and for up to 40 minutes (fatigue) or 24 h (soreness) post-exercise.	122
Figure 6.1. Blood lactate (BLa ⁻) concentrations expressed relative to pre-exercise values immediately following the final set of back squats and deadlifts.	138
Figure 6.2. Arterial oxygen saturation (SpO ₂) and heart rate (HR) immediately following each set of back squats and deadlifts.	139
Figure 6.3. Mean integrated electromyography (iEMG) values during the back squat for the <i>gluteus maximus</i> (GM; A), <i>biceps femoris</i> (BF; B), <i>vastus lateralis</i> (VL; C) and <i>vastus medialis</i> (VM; D).	141
Figure 6.4. Mean integrated electromyography (iEMG) values during the deadlift for the <i>gluteus maximus</i> (GM; A), <i>biceps femoris</i> (BF; B) and <i>vastus lateralis</i> (VL; C).	142
Figure 6.5. Mean relative values for minimum HbO ₂ (A and B) and maximum HHb (C and D), during back squat (A and C) and deadlift (B and D) exercise.	143
Figure 7.1. Isometric mid-thigh pull using a customised power rack and force platform.	160
Figure 7.2. Mean concentric velocity (A and B) and power (C and D) for repetitions 1-10 during the back squat (A and C) and deadlift (B and D).	163

Figure 7.3. RPE values for sets of back squats and deadlifts in normoxia and hypoxia.....	164
Figure 7.4. Perceived levels of physical fatigue and muscle soreness prior to and following experimental trials measured via visual analogue scales.	165
Figure 7.5. Jump height (A and B) and peak relative concentric power (C and D) prior to, immediately following and at 24 h and 48 h after experimental trials during the countermovement jump (A and C) and squat jump (B and D).	167
Figure 7.6. Peak force and rate of force development (RFD) prior to, immediately following and at 24 h and 48 h after experimental trials.	168
Figure 10.1. Theoretical time-course changes of intramuscular metabolic stress following a set of moderate-load traditional resistance exercise, moderate-load IHRT and low-load BFR exercise.....	273

List of Tables

Table 2.1. Summary of the current understanding of physiological responses to resistance exercise with BFR, and factors influencing the magnitude of these responses.	33
Table 2.2. Summary of research examining the acute responses to resistance exercise with systemic hypoxia.....	38
Table 2.3. Summary of research examining the morphological and strength responses to resistance training programs with systemic hypoxia.	40
Table 3.1. Summary of the resistance exercise protocol used during experimental trials.....	66
Table 7.1. Dynamic stretching protocol used prior to assessment of neuromuscular function.....	158
Table 7.2. Overall wellbeing scores prior to exercise and at 24 and 48 h following trials.....	166
Table 9.1. Summary of the investigations conducted as part of this thesis....	187
Table 10.1. Summary of research examining the morphological and strength responses to IHRT programs.	267

List of Abbreviations

~	Approximately
>	Greater than
≥	Greater than or equal to
<	Less than
≤	Less than or equal to
↑	Increase
↓	Decrease
↔	No change
?	Equivocal or unclear findings
±	Plus/minus
%	Percent
°	Degree/s
°·s ⁻¹	Degrees per second
°C	Degrees Celsius
μL	Microlitre
η ²	eta squared
Δ	Delta
1RM	1-Repetition maximum
10RM	10-Repetition maximum
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
AU	Arbitrary units
BF	Biceps femoris
BFR	Blood flow restriction
BLa ⁻	Blood lactate
[BLa]	Blood lactate concentration

bpm	Beats per minute
CI	Confidence intervals
cm	Centimetre
CMJ	Countermovement jump
CR-10	Category-Ratio 10 scale
CSA	Cross-sectional area
CV	Coefficient of variation
EMG	Electromyography
ES	Effect size
<i>F</i>	<i>F</i> statistic
F _I O ₂	Fraction of inspired oxygen
GH	Growth hormone
GM	Gluteus maximus
h	Hour/s
H ⁺	Hydrogen ion
HbO ₂	Oxyhaemoglobin
HbO _{2min}	Relative minimum oxyhaemoglobin value
[HbO ₂]	Oxyhaemoglobin concentration
HBS	Harness back squat
HH	High-level hypoxia
HHb	Deoxyhaemoglobin
HHb _{max}	Relative maximum deoxyhaemoglobin value
[HHb]	Deoxyhaemoglobin concentration
HIF-1 α	Hypoxia-inducible factor-1 α
HR	Heart rate
Hz	Hertz
ICC	Intra-class correlation coefficient
iEMG	Integrated electromyography

IGF-1	Insulin-like growth factor-1
IHRT	Intermittent hypoxic resistance training
kg	Kilogram/s
m	Metre/s
MAPK	Mitogen-activated protein kinase
MDF	Median frequency of the electromyography signal
MH	Moderate-level hypoxia
min	Minute/s
mm	Millimetre/s
mmHg	Millimetres of mercury
mmol·L ⁻¹	Millimole per litre
MPS	Muscle protein synthesis
mRNA	Messenger ribonucleic acid
m·s ⁻¹	Metres per second
mTOR	Mammalian target of rapamycin
MTP	Mid-thigh pull
MVC	Maximum voluntary contraction
MVC ₃	Maximum voluntary contraction for 3 seconds
MVC ₃₀	Maximum voluntary contraction for 30 seconds
<i>n</i>	Number
N	Newtons
NIRS	Near-infrared spectroscopy
nm	nanometer
NORM	Normoxia
O ₂	Oxygen
<i>p</i>	Alpha
PCr	Phosphocreatine
pH	Potential hydrogen

P_i	Inorganic phosphate
PO_2	Partial pressure of oxygen
r	Pearson's correlation coefficient
r^2	Pearson's r squared
reps	Repetitions
RFD	Rate of force development
RMS	Root mean square of electromyography signal
RNA	Ribonucleic acid
ROS	Reactive oxygen species
RPE	Rating of perceived exertion
RT	Resistance training without BFR in normoxia
s	Second/s
SD	Standard deviation of the mean
SENIAM	Surface EMG for non-invasive assessment of muscles
SJ	Squat jump
sO_2	Oxygen saturation
SpO_2	Arterial oxygen saturation (%)
sRPE	Session rating of perceived exertion
S6K1	Ribosomal S6 kinase 1
TSI	Tissue saturation index
TSI_{min}	Relative minimum tissue saturation index
VEGF	Vascular endothelial growth factor
VL	Vastus lateralis
VM	Vastus medialis
W	Watts
$W \cdot kg^{-1}$	Watts per kilogram
WU	Warm-up set
yr	Year/s

Abstract

Recent evidence suggests that supplemental hypoxia during resistance training can enhance muscular adaptation. However, the mechanisms underpinning augmented muscular responses to intermittent hypoxic resistance training (IHRT) and how they can be optimised remain largely unknown. Therefore, the aim of this thesis was to examine the acute physiological, physical and perceptual responses to IHRT in well-trained participants.

Study 1 quantified the inter- and intra-test reliability of electromyography (EMG) and near-infrared spectroscopy (NIRS) technologies during resistance exercise. Twelve well-trained young men (age: 24.8 ± 3.4 yr; height: 178.6 ± 6.0 cm; body mass: 84.8 ± 11.0 kg) performed high-load back squat exercise (12 sets at 70-90% of 1-repetition maximum [1RM]) on two occasions, with thigh muscle activation and oxygenation being monitored by EMG and NIRS, respectively. Intra-test reliability for EMG and NIRS variables was generally higher than inter-test reliability. NIRS-derived measures of muscle oxygenation were generally more reliable during single-repetition sets than multiple-repetition sets at the same load. Although the reliability of EMG and NIRS varied across the exercise protocol, the biological variation during multi-joint isoinertial resistance exercise may account for the fluctuations in the observed results.

Study 2 aimed to determine whether different levels of hypoxia affect physical performance during high-load resistance exercise. Using a randomised single

blind cross-over design, 12 resistance-trained males (age: 25.3 ± 4.3 yr; height: 179.0 ± 4.5 cm; body mass: 83.4 ± 9.1 kg) completed three trials of 5 x 5 repetitions of back squats and deadlifts at 80% 1RM with 180 s inter-set rest. Trials took place in normoxia (NORM; fraction of inspired oxygen [$F_{I}O_2$] = 21%), moderate-level hypoxia (MH; $F_{I}O_2$ = 16%), and high-level hypoxia (HH; $F_{I}O_2$ = 13%). Physical performance was monitored during repetitions (force and power variables), and arterial oxygen saturation (SpO_2), heart rate (HR), and a rating of perceived exertion (RPE) were obtained following each set. No differences in performance were evident between conditions. HR was higher following sets in HH than NORM ($p = 0.009$), while SpO_2 was lower in hypoxic conditions than in NORM ($p < 0.001$). There were no differences in RPE between conditions. These findings suggest that physical performance and perceived effort during high-load resistance exercise is not affected by supplemental hypoxia.

Study 3 assessed whether hypoxia during high-load resistance exercise could enhance the acute responses thought to underpin IHRT adaptation. Twelve well-trained males (age: 25.3 ± 4.3 yr; height: 179.0 ± 4.5 cm; body mass: 83.4 ± 9.1 kg) performed the same high-load resistance exercise protocol described for Study 2 in NORM, MH and HH. Muscle oxygenation and activation were monitored via NIRS and EMG, respectively. Blood lactate (BLa^-) concentration and pH levels were assessed to quantify metabolic stress. Perceived fatigue and soreness were also quantified following the exercise. HH appeared to cause the lowest levels of muscle oxygenation during exercise, though significant differences between conditions were only observed for maximal

deoxyhaemoglobin in the deadlift ($p = 0.009$). Metabolic stress increased from baseline following exercise ($p \leq 0.004$), however there were no consistent between-condition differences. Muscle activation, perceived fatigue and soreness also did not differ between conditions. These data suggest that high-load IHRT may not provide added benefit over the equivalent normoxic training, possibly because of its inherent design with long inter-set rest periods.

Study 4 assessed whether moderate-load IHRT with short rest periods could augment acute anabolic responses. Using a randomised single blind cross-over design, 14 well-trained male subjects (age: 24.6 ± 2.7 yr; height: 179.7 ± 5.9 cm; body mass: 84.6 ± 11.6 kg) performed resistance exercise trials in NORM and MH (3 x 10 repetitions of back squats and deadlifts at 60% 1RM with 60 s rest). SpO_2 and HR were assessed following each set, and BLa^- concentration was quantified after each exercise. Thigh circumference was measured as a marker of muscle swelling. Muscle activation and oxygenation were monitored via EMG and NIRS, respectively. Relative BLa^- concentrations were significantly higher following both squats ($p = 0.041$) and deadlifts ($p = 0.002$) in MH than NORM. SpO_2 was lower following each set in MH ($p < 0.001$), though there were no between-condition differences for HR or thigh circumference. Integrated EMG was higher in the MH trial at several time points for the back squat ($p < 0.001$), but not the deadlift. Muscle oxygenation did not differ between conditions. These data demonstrate that hypoxia during moderate-load resistance exercise with brief rest periods between sets can enhance metabolic stress in concert with increased muscle activation.

Lastly, Study 5 aimed to determine whether hypoxia can affect markers of physical performance, training stress and neuromuscular recovery during moderate-load resistance exercise. Fourteen well-trained male subjects (age: 24.6 ± 2.7 yr; height: 179.7 ± 5.9 cm; body mass: 84.6 ± 11.6 kg) performed the same moderate-load resistance exercise protocol as for Study 4 in NORM and MH. Physical performance was quantified during repetitions (velocity and power). Perceived exertion, fatigue, soreness and wellbeing were assessed during and following exercise. Neuromuscular performance was monitored using vertical jump and isometric mid-thigh pull (MTP) tasks for up to 48 h following exercise. Performance declined across sets ($p \leq 0.010$), though this was not different between conditions. Perceptual responses were also not different between conditions. Jump height and MTP peak force were decreased from pre-exercise values immediately after all trials ($p \leq 0.026$), but returned to pre-exercise values at 24 h. Despite increases in metabolic stress and muscle activation (Study 4), physical performance and markers of training stress were not impacted by hypoxia during moderate-load resistance exercise.

This collective work has highlighted the importance of structuring exercise using sufficient repetition volume and brief inter-set rest periods to elicit hypoxia-mediated benefits. Moderate-load IHRT with short rest in hypoxia was shown to enhance metabolic stress and muscle activation, which may maximise adaptation to resistance training. Importantly, supplementary hypoxia did not affect markers of training stress or recovery of neuromuscular function, making this an attractive strategy for already well-trained individuals.