
ATHLETE MONITORING IN CANADIAN FOOTBALL

A thesis submitted to the College of Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

in

EXERCISE SCIENCE

at the

University of Saskatchewan

By

Nick Clarke

Supervisor: Jonathan P. Farthing, PhD

Committee: Stephen R. Norris, PhD

Philip Chilibeck, PhD

Carol D. Rodgers, PhD

© Copyright by Nick Clarke, March 2017

TITLE: Athlete Monitoring in Canadian Football

AUTHOR: Nick Clarke, Master of Science in Kinesiology (Uni. Of Saskatchewan)

SUPERVISOR: Jonathan P. Farthing, PhD

NUMBER OF PAGES: 166

PERMISSION TO USE

In presenting this thesis/dissertation in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis/dissertation in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis/dissertation work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis/dissertation or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis/dissertation.

DISCLAIMER

Reference in this thesis/dissertation to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the University of Saskatchewan. The views and opinions of the author expressed herein do not state or reflect those of the University of Saskatchewan, and shall not be used for advertising or product endorsement purposes.

Requests for permission to copy or to make other uses of materials in this thesis/dissertation in whole or part should be addressed to:

Dean of Kinesiology
PAC, 87 Campus Drive
University of Saskatchewan
Saskatoon, Saskatchewan, S7N 5B2
Canada

ABSTRACT

INTRODUCTION: Sports performance optimization relies heavily on the balance between increasing training load (TL) and appropriate recovery. In high performance settings, the crucial role that athlete monitoring plays in this intricate balancing act is widely recognized. *PURPOSE:* Due to the violent and unique demands of Canadian football, minimal research and few practical monitoring tools are available for coaches and practitioners. The thesis aim therefore, is to provide a body of research that begins to address athlete monitoring challenges in Canadian football. *CHAPTER III:* Study 1 was designed to validate the Session-Ratings of Perceived Exertion (sRPE) method of quantifying internal TL in football players. Statistically significant correlations for all individual players between sRPE and two criterion heart rate-based measures were found. Results confirm that sRPE is a highly practical and valid tool for Canadian football application. *CHAPTER IV:* Despite frequent use in other sports, the high injury occurrence in football often prevents consistent neuromuscular fatigue (NMF) monitoring using a maximal countermovement jump (CMJ). Further, little direct evidence exists supporting the relationship between athlete CMJ performance and NMF. Study 2 addressed these issues by assessing the acute-fatiguing effects of a game simulation (G-Sim) on postural sway (PS), CMJ performance and lab-based NMF measures in football players. Congruency between all measures post G-Sim suggests that submaximal PS monitoring has the potential to supplement CMJ in NMF tracking of football players hampered by minor injuries. *CHAPTER V:* Recognizing that acute-fatiguing effects may misrepresent fatigue across extended training periods, study 3 applied previous methodology (study 1 & 2) to evaluate PS as a valid NMF indicator over a competitive 11-week season. Significant associations between both CMJ and PS performance with weekly Global TL fluctuations provided evidence of NMF assessments valid across a football season. There was no evidence of differences in NMF status between starters and non-starters of the weekly game. *CONCLUSION:* Thesis findings confirm the validity and practicality of sRPE and the NMF monitoring tools of CMJ and PS across a competitive football season. This initial work provides a spring-board for future research as it has broadened our knowledge of athlete responses to- and monitoring in- Canadian football.

PUBLISHED WORK & CONTRIBUTION OF AUTHORS

Due to the nature of a manuscript style thesis, chapters III & IV of this thesis have been published as multi-authored papers in peer reviewed journals. Chapter V is ready for publication. All manuscripts were prepared for publication by myself. Co-author contribution is stated below.

1. **Chapter III - Clarke, N**, Farthing, JP, Norris, SR, Arnold, BE, and Lanovaz, JL. Quantification of training load in Canadian football: application of Session-RPE in collision-based team sports. *J Strength Cond Res* 27(8); 2198-2205, 2013.

Author's roles: *Study Design:* JF, NC, SN and BA. *Study conduct:* NC and JF. *Data collection:* NC. *Data Analysis:* JL, NC and JF. *Drafting manuscript:* NC. *Revising manuscript content:* SN, BA, and JF. *Approving final version of manuscript:* All authors.

2. **Chapter IV - Clarke, N**, Farthing, JP, Lanovaz, JL, and Krentz, JR. Direct and indirect measurement of neuromuscular fatigue in Canadian football players. *Appl Physiol Nutr Metabol* 40(5); 464-473, 2015.

Author's roles: *Study Design:* NC, and JF. *Study conduct:* NC and JF. *Data collection:* NC and JK. *Data Analysis:* JL, NC and JF. *Drafting manuscript:* NC. *Revising manuscript content:* NC and JF. *Approving final version of manuscript:* All authors.

MANUSCRIPT READY FOR PUBLICATION

3. **Chapter V - Clarke, N**, Farthing, JP, Norris, SR, Arnold, BE, Chilibeck, PD, Rodgers, CD, Lanovaz, JL, and Brodie, R. Novel approach to neuromuscular fatigue monitoring of a competitive collegiate season in Canadian football players.

Author's roles: *Study Design:* NC, JF, SN, PC, CR, and BA. *Study conduct:* NC, JF and BA. *Data collection:* NC. *Data Analysis:* JL, RB, NC and JF. *Drafting manuscript:* NC. *Revising manuscript content:* NC and JF. *Approving final version of manuscript:* All authors.

CONFERENCE PRESENTATIONS

American College of Sports Medicine (ACSM) International Conference, Podium Presentation, Orlando, FL May 2014. **Clarke, N.** *Effect of an Acute Bout of High Intensity Game Simulation Exercise on Direct and Indirect measures of Neuromuscular Fatigue in Canadian Football Players*

CONFERENCE POSTERS

Canadian Society for Exercise Physiology (CSEP), Regina 2012 - **Clarke, N,** Farthing, JP, Norris, SR, Arnold, BE, and Lanovaz, JL. *Quantification of training load in Canadian football: Application of Session-RPE in collision-based team sports.*

Canadian Society for Exercise Physiology (CSEP), Victoria 2016 - **Clarke, N,** Farthing, JP, Norris, SR, Arnold, BE, and Lanovaz, JL, Brodie, R, and Arnold, BE. *Novel approach to neuromuscular fatigue monitoring of a competitive collegiate season in Canadian football players.*

ACKNOWLEDGEMENTS

I've been contemplating the most appropriate way to write these acknowledgements for the best part of 3 years and decided that authenticity is the only option. Apologizes for momentarily slipping out of the traditional academic writing style.

Wow, what a journey! I never envisioned that it would take this long. I never dreamt it would be this hard; but I can honestly say that there hasn't been a piece that I haven't enjoyed (well, maybe not the comprehensive exams). The patience and support of all my academic advisors, work colleagues, family and friends has been nothing less than monumental. I will never forget everyone who helped me on the way. And I will never be able to write enough, or be able to thank people enough...but I will try.

To Phil, Steve and Carol – the Avengers of committees. I bet you were getting pretty fed up of me? Sorry for dragging this out for almost a decade but thank you for all the guidance, patience and unwavering support. I could not ask for a more knowledgeable and understanding group of mentors.

Joel Lanovaz - Thanks for teaching us all how remarkably average our computer skills are. You are truly an asset to the project and I would still be typing numbers in my excel sheet right now if it wasn't for you.

Bart Arnold - You're a legend and the real Governor. A legend in the football world, a legend in the college and a legendary role model. Thanks for always being sarcastic and being instrumental in getting the football team on-board.

Coach Towriss & the University of Saskatchewan Football Team – Gents, it was emotional. Thanks for the buy-in, thanks for believing in me and thanks for being conned into sitting in that electric chair 4 TIMES!! No picnic.

To Shane Schwanbeck, Trevor Barss, Professor Weber, Joel Krentz, Scott McCubbing, Mike Smith and all my other U of S and Saskatoon friends - You didn't really help but what a ride.

The Van Dunn's - Thanks for being my surrogate Saskatoon family and supporting me through the tough times. When I have a family my own, if I can emulate just one iota of your warmth, laughter and generosity I will be a happy man. You are a very special group of humans. I can never repay you for all the Thanksgiving's, Christmas's and lazy Sunday's watching the Riders. "Kates!!"

Bryce Chapman & University of Saskatchewan Soccer team – The most important thing to Bryce is his family; a very very close second is winning. Bryce is a winner. The team he assembled during my time was special and I want to thank them all for providing me with perspective and a balance in my life during this project. But mostly I want to thank Bryce for believing in an old washed up Centre half. Without Bryce I would have got through the dark days (of which there were a few) and I would not be the person or the professional that I am today. TMF.

Canadian Sports Institute Pacific – For hiring a foreigner and providing me with my dream job even without a completed PhD, I thank you! More importantly, I will be forever grateful to all my work colleagues, who over the last Olympic cycle, never let me forget what a laughing stock I would be if I didn't finish this PhD. in 10 years. The motivation was inspired.

Jon Farthing – O man, where to begin...when I grow up I want to be Jon.

He's not only one of the smartest people I know, but he's been the rock from which this whole project was anchored. He can grow beards that would be the envy of any Canadian, represented U of S as a QB, he's a proud father of 5, dedicated husband, plays guitar like a boss in a band that has an EP on iTunes (*The Banisters*), and has achieved all this while remaining one of the most grounded and humble humans ever. Jon; thank you is not strong enough. Without you this would have all faded away. Thanks for believing in me at the start, thanks for opportunity to take this research in a direction that is not "typical" and thanks for keeping me on track over the 7 or 8 years since I pestered you into taking me on as a student. I hope this is not our last journey together.

The Clarke's – I miss you more than you'll ever know. Family is everything. There is not a day that goes by where I don't struggle with my decision to move countries. But I just want to make you proud. You are my why.

DEDICATION

Dedicated to Danya Douglas Hunt.

Since the instant your welcome invasion first set foot in the unclaimed territory of my heart, you've been my favorite. I end where you start.

Champion of my now, and every moment after.

I know it doesn't sound like much but in the long line of *everything*, you are first.

You are water to my thirst.

You, are my favorite.

I love you X

CONTENTS

PERMISSION TO USE.....	i
ABSTRACT.....	ii
PUBLISHED WORK & CONTRIBUTION FROM AUTHORS.....	iii
ACKNOWLEDGEMENTS.....	v
DEDICATION.....	vii
CONTENTS.....	viii
LIST OF TABLES.....	xiii
LIST OF FIGURES.....	xvi
LIST OF ABBREVIATIONS.....	xx
LIST OF APPENDICES.....	xxiii

CHAPTER I: THESIS INTRODUCTION & OBJECTIVES

1.1 INTRODUCTION.....	1
1.2 THESIS RATIONALE.....	1
1.3 THESIS AIMS & OBJECTIVES.....	2
1.4. THESIS STRUCTURE.....	3
1.5. REFERENCES.....	5

CHAPTER II: LITERATURE REVIEW

2.1 SYNOPSIS.....	6
2.2 TRAINING ADAPTATION & THE ROLE OF FATIGUE.....	6
2.2.1 Systems Approach to Training – Fitness Fatigue Model	9
2.3 AETIOLOGIES OF FATIGUE: AN OVERVIEW.....	11
2.3.1 Acute Muscle Fatigue.....	12
2.3.2 Sub-Acute Muscle Fatigue.....	14
2.3.3 Accumulated Fatigue: Repetitive Bouts.....	19
2.3.4 Accumulated Fatigue: Overtraining Syndrome.....	20
2.3.5 Fatigue Summary.....	21
2.4 ATHLETE MONITORING.....	22

2.4.1	Training Load or “Dose” Quantification.....	22
2.4.1.1	<i>External Training Load</i>	22
2.4.1.2	<i>Internal Training Load</i>	23
2.4.2	Performance or “Response” Quantification.....	26
2.4.2.1	<i>Performance Indicators</i>	26
2.4.2.2	<i>Heart Rate Response</i>	28
2.4.2.3	<i>Athlete Self-Report Measures</i>	29
2.4.3	Monitoring Summary.....	30
2.5	ATHLETE MONITORING IN CANADIAN FOOTBALL	30
2.5.1	Demands of Football.....	31
2.5.2	Monitoring Challenges in Canadian Football.....	33
2.5.2.1	<i>Postural Control</i>	34
2.6	SUMMARY & IMPLICATIONS	36
2.7	REFERENCES	37

**CHAPTER III: QUANTIFICATION OF TRAINING LOAD IN CANADIAN FOOTBALL:
APPLICATION OF SESSION-RPE IN COLLISION-BASED TEAM SPORTS**

3.1	ABSTRACT	49
3.2	INTRODUCTION	49
3.3	METHODS	52
3.3.1	Experimental Approach to the Problem.....	52
3.3.2	Subjects.....	52
3.3.3	CIS Football Season structure and training.....	53
3.3.4	Procedures - Measures of Internal Load.....	53
3.3.5	Statistical Analyses.....	56
3.4	RESULTS	56
3.5	DISCUSSION	59
3.5.1	Practical Application.....	62
3.6	REFERENCES	63

**CHAPTER IV: DIRECT & INDIRECT MEASUREMENT OF NEUROMUSCULAR
FATIGUE IN CANADIAN FOOTBALL PLAYERS**

4.1 ABSTRACT	66
4.2 INTRODUCTION	66
4.3 METHODS	68
4.3.1 Experimental Approach to the Problem.....	68
4.3.2 Participants.....	69
4.3.3 Experimental Design.....	69
4.3.4 High Intensity Game Simulation.....	70
4.3.5 Exercise Characteristics.....	71
4.3.6 Direct Neuromuscular Fatigue Measures.....	72
4.3.7 Indirect Neuromuscular Fatigue Measures.....	74
4.3.8 Reliability.....	75
4.3.9 Statistical Analyses.....	76
4.4 RESULTS	78
4.4.1 Exercise Characteristics.....	78
4.4.2 Direct Neuromuscular Fatigue Measures.....	79
4.4.3 Indirect Neuromuscular Fatigue Measures.....	80
4.5 DISCUSSION	82
4.5.1 Direct Measures: Torque Reduction.....	82
4.5.2 Indirect Measures.....	83
4.6 REFERENCES	87

**CHAPTER V: NOVEL APPROACH TO NEUROMUSCULAR FATIGUE
MONITORING OF A COMPETITIVE COLLEGIATE SEASON IN CANADIAN
FOOTBALL PLAYERS**

5.1 ABSTRACT	91
5.2 INTRODUCTION	92
5.3 METHODS	94

5.3.1 Experimental Approach to the Problem.....	94
5.3.2 Participants.....	96
5.3.3 CIS Football Season structure and training.....	96
5.3.4 Procedures - Measures of Internal Load.....	97
5.3.5 Reliability.....	98
5.3.6 Statistical Analyses.....	99
5.4 RESULTS.....	101
5.5 DISCUSSION.....	104
5.5.1 Mechanisms of Fatigue.....	104
5.5.2 Recovery time-course of Neuromuscular Fatigue measures.....	105
5.5.3 Global Training Load Composition: Starters vs. Non-Starters.....	107
5.5.4 Conclusion.....	108
5.5.5 Practical Application.....	109
5.6 REFERENCES.....	110

CHAPTER VI: SUMMARY, RECOMMENDATIONS & CONCLUSIONS

6.1 SUMMARY OF FINDINGS.....	113
6.1.1 Study1 - Application of Session-RPE in collision-based team sports.....	113
6.1.2 Study 2 - Direct and Indirect measures of Neuromuscular fatigue.....	114
6.1.3 Study 3 - Neuromuscular fatigue of competitive Canadian football season.....	115
6.2 PRACTICAL APPLICATION & RECOMMENDATIONS.....	116
6.2.1 Monitoring Systems.....	116
6.2.2 Training Load or “Dose” Monitoring.....	117
6.2.3 Neuromuscular fatigue or “Response” Monitoring.....	118
6.2.4 Athlete Self-Reported Measures.....	120
6.2.5 Matching Training Loads.....	123
6.3 LIMITATIONS & FUTURE RESEARCH.....	124
6.4 CONCLUSION.....	126
6.4.1 Theoretical synopsis.....	126
6.4.2 Applied synopsis.....	127

6.5. REFERENCES.....128

LIST OF TABLES

TABLE 2-1	17
Investigations showing acute fatigue-induced force responses of maximal voluntary contractions as well as high- and low- frequency stimulation of the knee extensor muscles.	
TABLE 2-2	18
Investigations assessing delayed recovery after acute fatigue-induced interventions or sports using functional performance tests.	
TABLE 2-3	31
Key rule differences between Canadian and American football.	
TABLE 3-1	54
Player details, number of practice session for which both Session-RPE and HR-Based TL data was collected and games played during 2011 CIS Season.	
TABLE 3-2	55
Foster’s modified Borg scale.	
TABLE 3-3	58
Individual correlation coefficients (r) between Session-RPE and two HR-based training load methods. Each player contributed an average 36 practice sessions of data to the analysis. All individual correlations were statistically significant (p <0.01).	
TABLE 4-1	77
Test-retest reliability of direct and indirect variables assessed using time points 24 hours before (T _{Base}) and immediately before (T _{Pre}) game simulation. All 15 participants data was analyzed using the intra-class correlation coefficient (ICC), technical error of the measurement (TEM), and a one sample t-test of percent change from T _{Base} ran against zero.	

TABLE 4-2	78
Direct and indirect neuromuscular fatigue (NMF) measures 24 hours before (T_{Base}), immediately before (T_{Pre}), immediately (T_{Post}), 24 hours (T_{24}) and 48 hours after (T_{48}) a high intensity Canadian football game simulation.	
TABLE 5-1	99
Test-retest reliability of indirect neuromuscular fatigue variables assessed using time points 24 hours before (T_0) and immediately before (T_{24}) pre-season commencement. Data from all 40 participants was analyzed using the intra-class correlation coefficient (ICC), technical error of the measurement (TEM), and a one sample t-test of percent change from T_0 ran against zero.	
TABLE 5-2	100
Week-by-week player status, training week length (days) and game descriptors of the 2012 CIS football season.	
TABLE 5-3	101
Average individual correlation coefficients (r) between weekly Global Training Load (GTL) and two neuromuscular fatigue (NMF) metrics. Across 10 weeks of the season an average of 30 players per week (15 starters & 15 non-starters) contributed 286 data points.	
TABLE 6-1	122
Individual correlation coefficients (r) between seven modified Recovery-Cue components with Global Training Load (TL) and two neuromuscular fatigue indicators (CMJ and Postural Sway). 286 comparisons were analyzed. CoP_A = Adjusted Center of Pressure; CMJ = Countermovement Jump; W = Watts * statistically significant ($p < 0.01$).	
TABLE A-1	132
Methodological considerations for using objective and subjective training load monitoring tools.	
TABLE A-2	133
Methodological considerations for monitoring functional performance in athletes.	

TABLE A-3134
Methodological considerations for monitoring athletes using heart rate metrics.

TABLE A-4135
Methodological considerations for using athlete self-report measures.

TABLE C-1.....139
Test-retest reliability of indirect neuromuscular fatigue variables assessed using time points 24 hours before (T_0) and immediately before (T_{24}) pre-season commencement. Data from all 55 participants was analyzed using the intra-class correlation coefficient (ICC), technical error of the measurement (TEM), and a one sample t-test of percent change from T_0 ran against zero.

LIST OF FIGURES

FIGURE 2-1	7
Visual representation of the supercompensation model of training adaptation following single exercise bout.	
FIGURE 2-2	8
Visual representation of theoretical effects of optimal, insufficient and excessive recovery between subsequent exercise bouts on training adaptation.	
FIGURE 2-3	10
Banister’s fitness-fatigue model. Illustration how a single exercise stimulus results in 2-factors; a fitness after-effect (+ve) and a fatigue after-effect (-ve). Interaction between fitness and fatigue predicts change in performance change.	
FIGURE 2-4	11
Revised fitness-fatigue model. Illustration of how multiple specific fitness (+ve) and fatigue (-ve) after-effects respond from a single exercise stimulus and exert a cumulative effect to form a main fitness and fatigue after effect. Interaction between main fitness and fatigue predicts change in performance change.	
FIGURE 3-1	56
Bespoke HR monitor protector. Protector was trimmed to fit each player’s normal clothing and equipment.	
FIGURE 3-2	57
Daily team internal training load (TL) for A) 2010 and B) 2011 CIS preseason camp (Days 0 to Pre. 1) and regular competitive football season. 3-Day average represents the average TL of the previous 3 practise days and can be indicative of rested state.	

FIGURE 3-358

Representative comparison of one player’s (Player 8) practice training load patterns calculated using the Session-RPE, Edwards’ TL and Polar TRIMP methods.

FIGURE 4-171

A) Experimental set-up for day of Game simulation. Set-up for all other testing sessions was identical but ended after the first direct neuromuscular tests (e.g. 40 mins in length). B) Direct neuromuscular test set-up.

FIGURE 4-279

Mechanical response of **A**) Maximal isometric voluntary contraction (MVC) and MVC/80-Hz tetanus contraction (80Hz) ratio as well as **B**) 80-Hz tetanus (80Hz), 20-Hz tetanus (20Hz) and 20Hz/80Hz ratio contraction of the right knee extensor muscles 24 hours before (T_{Base}), immediately before (T_{Pre}), immediately (T_{Post}) and 48 hours after (T_{48}) a high intensity Canadian football game simulation. Values are means \pm SE. *significantly different from T_{Base} $P < 0.016$.

FIGURE 4-380

Percent change of **A**) Take-off velocity and **B**) Peak Power during execution of a maximal CMJ from 24 hours before (T_{Base}) to immediately before (T_{Pre}), immediately (T_{Post}), 24 hours (T_{24}) and 48 hours after (T_{48}) a high intensity Canadian football game simulation. Values are means \pm SE. $n = 12$. *Percent change was significantly different from T_{Base} $P < 0.016$.

FIGURE 4-481

A) Representative trace of center of pressure displacement (mm) in Anterior / Posterior (CoP_y) and Medio / Lateral (CoP_x) direction during 60 secs of the Sharpened Tandem static balance task and **B**) postural sway assessed by total area covered by center of pressure (CoP) 24 hours before (T_{Base}), immediately before (T_{Pre}), immediately (T_{Post}), 24 hours (T_{24}) and 48 hours after (T_{48}) a high intensity Canadian football game simulation. CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Therefore the adjusted CoP data (CoP_A) included 95% of the original data points. Values are means \pm SE. $n = 10$ *Percent change was significantly different from T_{Base} $P < 0.016$.

FIGURE 5-190

A typical regular season football week in terms of global training load (GTL) and structure. One week consists of four football practice sessions (Mon, Tue, Wed & Thu), a competitive CIS game (Fri) and two recovery days (Sat, Sun). (↑) are representations of collision intensity/frequency.

FIGURE 5-2102

Fluctuation of weekly Global Training Load (GTL) and percent change from baseline of neuromuscular fatigue indicators **A**) postural sway and **B**) countermovement jump variables. CoP_A = Adjusted area covered by center of pressure trajectory; TOV = Takeoff velocity; PP = Peak Power. Values are means ± SE. Effect size boundaries (16); CoP_A= Small (16.2%), Mod (48.8%), Large (86.8%). CMJ = Small (0.7%), Mod (2.1%), Lrg (3.9%). * Significantly different than all 10 weeks (p<0.05). ** Significantly different from 9 out of 10 weeks (p<0.05). *** Significantly different from 7 out of 10 weeks (p<0.05).

FIGURE 5-3103

Starters (S) vs. non-starters (NS) comparison of weekly Global Training Load (GTL) and percent change from baseline of neuromuscular fatigue indicators **A**) postural sway and countermovement jump variables, **B**) Peak power (PP), **C**) Takeoff Velocity (TOV). CoP_A = Adjusted area covered by center of pressure trajectory; Values are means ± SE.

FIGURE 6-1121

Weekly athlete self-reported measures of **A**) Sleep Quality, Self-Regulation; **B**) Recovery Efforts, Physical Recovery, Social Recovery; **C**) Perceived Effort and Perceived Recovery compared with **D**) fluctuation of weekly Global Training Load (GTL) across an 11 week competitive Canadian football season. H = Home game; A = Away game; W = Game Win; L = Game loss; Bye = No game; S = Starter; NS = Non-Starter; D) Numbers in columns represent days in that training week defined as game day to game day. Values are means ± SE.

FIGURE D-1140

The Recovery Stress questionnaire for athletes was modified and administered weekly before neuromuscular fatigue monitoring.

LIST OF ABBREVIATIONS

A	<i>away</i>
A/P	<i>anterior/posterior</i>
ANOVA	<i>Analysis of Variance</i>
ANS	<i>autonomic nervous system</i>
AP	<i>action potential</i>
ASRM	<i>athlete self-report measures</i>
AU	<i>arbitrary units</i>
CIS	<i>Canadian Interuniversity</i>
CI	<i>confidence interval</i>
cm	<i>centimetre</i>
CMJ	<i>countermovement jump</i>
CoP	<i>center of pressure displacement (mm)</i>
CoP_A	<i>adjusted total area covered by CoP</i>
CoP_x	<i>CoP in M/L direction</i>
CoP_y	<i>CoP in A/P direction</i>
CR	<i>category ratio</i>
CR-10	<i>Borg's Category-Ratio</i>
CV	<i>coefficient of variation</i>
DALDA	<i>Daily Analysis of Life Demands for Athletes</i>
DJ	<i>drop jump</i>
dRPE	<i>Differential-RPE</i>
E-C	<i>excitation-contraction</i>
EMG	<i>electromyography</i>
ES	<i>effect size</i>
FMB	<i>Foster's Modified Borg</i>
FOR	<i>functional overreaching</i>
g	<i>grams</i>
GPS	<i>Global Positioning System</i>
GRF	<i>ground reaction force</i>

G-Sim	<i>game simulation</i>
GTL	<i>global training load</i>
h	<i>hour</i>
H	<i>home</i>
HR	<i>heart rate</i>
HRmax	<i>maximal heart rate</i>
HRR	<i>heart rate recovery</i>
HRrest	<i>resting heart rate</i>
HRV	<i>heart rate variability</i>
ICC	<i>Interclass correlation coefficient</i>
ITT	<i>interpolated-twitch technique</i>
KE	<i>knee extensor</i>
L	<i>game loss</i>
LFF	<i>low frequency fatigue</i>
LSCT	<i>Lamberts and Lambert submaximal cycle test</i>
M/L	<i>medio/lateral</i>
mm	<i>millimeters</i>
MVC	<i>maximal voluntary contraction</i>
na	<i>not reported</i>
NMF	<i>neuromuscular fatigue</i>
NOR	<i>non-functional overreaching</i>
NS	<i>non-starters</i>
ns	<i>not statistically significant</i>
OR	<i>overreaching</i>
OT	<i>overtraining</i>
OTS	<i>overtraining syndrome</i>
P20	<i>PT from electrically evoked tetani at 20Hz</i>
P80	<i>PT from electrically evoked tetani at 80Hz</i>
PF	<i>peak force</i>
plyo	<i>plyometric</i>
PP	<i>peak power</i>

PRFD	<i>peak rate of force development</i>
PS	<i>postural sway</i>
PT	<i>peak torque</i>
<i>r</i>	<i>Individual correlation coefficients</i>
RESTQ-Sport	<i>Recovery-Stress Questionnaire for athletes</i>
RM	<i>repetition maximum</i>
RPE	<i>Ratings of Perceived Exertion</i>
S	<i>starters</i>
S&C	<i>strength and conditioning</i>
SJ	<i>squat jump</i>
sRPE	<i>Session-Ratings of Perceived Exertion</i>
sRPE-B	<i>dRPE for breathlessness</i>
sRPE-L	<i>dRPE leg muscle exertion</i>
sRPE-T	<i>dRPE cognitive/technical demands</i>
sRPE-U	<i>dRPE upper body muscle exertion</i>
SSC	<i>stretch-shortening cycle</i>
TEM	<i>technical error of the measurement</i>
TL	<i>training load</i>
TOV	<i>takeoff velocity</i>
TRIMP	<i>Training Impulse</i>
U of S	<i>University of Saskatchewan</i>
VA	<i>voluntary activation</i>
W	<i>game win</i>

LIST OF APPENDICES

APPENDIX A: METHODOLOGICAL CONSIDERATIONS	132
A.1 Training Load.....	132
A.2 Functional Performance Tests.....	133
A.3 Heart Rate.....	134
A.4 Athlete Self-Report Measures.....	135
APPENDIX B: CHAPTER V; STATISTICS	138
APPENDIX C: COMBINED TEST-RETEST RELIABILITY	139
APPENDIX D: MODIFIED RECOVERY STRESS QUESTIONNAIRE	140

CHAPTER I

THESIS INTRODUCTION & OBJECTIVES

1-1. INTRODUCTION

With the ever increasing performance expectations of top level sport, the nature of training has become increasingly more demanding and aggressive. This aggression is borne from the acceptance that increasing training load (TL) will result in a performance improvement; however, this assumption of positive adaptation relies heavily on an appropriate balance between training and recovery (1,3). For this reason, scientific research plays a significant role in high performance settings with more coaches applying an evidence-based systematic approach to the prescription of optimal training regimes (5).

A central issue in the theory and scientific approach to programming training is the connection between TL, the physiological response to training and performance (3). In solution, Lambert and Borresen (4) suggested a reductionist approach to the principle of training describing it as a simple “*dose-response*” relationship. The “*response*” in this relationship can be measured as a change in performance or the adaptation of a physiological system. The “*dose*” of training or physiological stress is associated with the TL. Accurate assessment of this training dose-response relationship requires implementation of a comprehensive and valid athlete monitoring system. Owing to growing popularity, numerous subjective and objective measures have been well described but a single definitive monitoring tool is not yet evident. Furthermore, the nature of a monitoring system as well as the number of measures adopted may vary greatly depending on the unique demands of the sport.

1-2. THESIS RATIONALE

Athlete monitoring in Canadian football is often perceived to be more challenging than individual and other team sports. Similar to most team sports, a number of challenges arise from the large variation in positional demands as well as the diverse range of training modalities (e.g.

conditioning, resistance training, interval training, skill-based training etc. [5]). However, the real practical shortcomings for monitoring in football emanate from collision. The inherent violence within the sport has implications for consistent athlete monitoring that range from high injury rates to the practicality of wearable technology. While monitoring within elite and professional football is often extensive, much of the data remains protected and unpublished (2). Therefore, the methodological challenges to athlete monitoring within Canadian football warrant investigation and the scientific knowledge available to coaches and practitioners working at all levels also requires addressing.

While this thesis focuses on Canadian football, it is highly feasible that other collision-based sports that face similar challenges will benefit from the investigations proposed and subsequent knowledge gained. Furthermore, it is not only the coaches or trainers who need to measure the training dose-response relationship in collision-based team sports. Researchers investigating various aspects of training, such as relationships between injury and TL, overtraining, concussion, efficacies of various training strategies, to name but a few, also need a valid and reliable method of quantifying training.

1-3. THESIS AIMS & OBJECTIVES

The overarching aim of the thesis is to further the monitoring research in collision-based team sports and begin investigating the neuromuscular fatigue (NMF) responses of players exposed to extensive training and competitive periods associated with a high performance Canadian football program. The specific aims of the thesis are as follows:

- 1) Validate the use of Session-Ratings of Perceived Exertion (sRPE) as a reliable method for quantifying internal TL in Canadian football players (Chapter III)
- 2) Describe the response of direct and indirect measures of NMF pre-post an acute bout of simulated Canadian football exercise (Chapter IV)
 - (a) Introduce a novel method of assessing NMF in the form of postural sway and present results for reliability
 - (b) Further investigate the association between functional performance tests and mechanisms of NMF

- 3) Describe the relationship between postural sway and the typical weekly TL fluctuations seen in a competitive collegiate Canadian football season (Chapter V)
 - (a) Further our understanding of fatigue in the applied sport setting where players are exposed to a high frequency of TLs and competitive games
 - (b) Investigate any potential differences in NMF status between players who are exposed to competitive games (*starters*) versus those who are not (*non-starters*).

1-4. THESIS STRUCTURE

This thesis is submitted in the form of a series of publishable papers. The intention of each chapter is to sequentially add to current understanding of monitoring in football players as well as systematically build knowledge of effective tools that can be used to help begin identifying the training dose-response relationship in a high performance setting of this unique sport.

The current chapter along with the literature review in Chapter II, introduces the topic area and forms the rationale behind the thesis. Chapter III describes a season long comparison of heart rate (HR) and RPE based TL indices aimed at validating the sRPE method for quantifying internal TL of Canadian football players during practice. Due to the limitations associated with players wearing HR monitors when exposed to collision, validation of sRPE affords us the ability to easily and effectively collect accurate TL with an entire football team through the remainder of the thesis (e.g. increase sample size). While the sRPE study was underway, a season long CMJ pilot study ran in parallel as to gain more interpretive jump data but also to familiarize the players with regular functional performance testing. During this pilot it became very apparent that in order to regularly monitor football players a submaximal NMF test was needed as a large number of missing data points occurred due to minor injuries (sprains, strains and bruising). Based on this need, Chapter IV introduces a novel approach to monitoring NMF in collision-based sports with the examination of fatigued induced changes in postural sway following a Canadian football game simulation. Chapter V involves the amalgamation of the previous two studies (Chapters III & IV) over an entire Canadian football season. The primary goal was to assess postural sway as an alternative or supplementary tool for tracking NMF over extensive training and competitive periods. By concurrently collecting CMJ and TL data, the secondary aim was to examine the usefulness of

CMJ in this sport specific context but also to provide further insight into the fatigue time-course response of players over a Canadian football season. The final chapter of this thesis will provide a discussion and synopsis of the thesis findings, recommendations for future research and practical applications of knowledge gained.

Chapters III and IV have been published within the period of candidacy; Chapter V has also been submitted for publication and is presently in the peer-review process. These chapters (Chapters III to V) are presented in a standardized thesis format.

1-5. REFERENCES

1. Coutts, AJ, Slattery, KM, and Wallace, LK. Practical tests for monitoring performance, fatigue and recovery in triathletes. *J Sci Med Sport* 10(6): 372-381, 2007.
2. Halson, S. Monitoring training load to understand fatigue in athletes. *Sports Med* 44(S2): S139-S147, 2014.
3. Halson, S, Bridge, M, Meeusen, R, et al. Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* 93: 947-956, 2002.
4. Lambert, MI, and Borresen, J. Measuring training load in sports. *Int J Sports Physiol Perform* 5:406-411, 2010.
5. Siff, MC. *Supertraining - 6th Ed.* Denver, CO: Supertraining Institute, 2003.
6. Taylor, KL, Chapman, DW, Cronin, JB, Newton, MJ, and Gill ND. Fatigue monitoring in high performance sport: A survey of current trends. *J Aus Strength Cond* 20(1): 12-23, 2012.

CHAPTER II

LITERATURE REVIEW

2-1. SYNOPSIS

This review begins by examining the role of fatigue in stimulating training adaptations as well as the candidate mechanisms and contributing factors responsible for the inter-individual variation in response to single and repetitive bouts of varying exercise interventions. The subsequent section presents a selection of fatigue monitoring tools available to coaches and sport scientists in their quest to establish the training dose-response relationship for athletes, along with methodological considerations. Finally, a brief outline of the physical demands of Canadian football is presented, along with discussion and future direction of monitoring athletes in these prolonged intermittent high-intensity collision-based team sports.

2-2. TRAINING ADAPTATION & THE ROLE OF FATIGUE

Optimization of physical performance is achieved through the process of training. The objective of training is to provide successive strain (fatigue) that will displace homeostasis of an athlete and provide a stimulus to initiate superior adaptation (101). In an attempt to increase awareness of the training adaptation process, general training models have been proposed. The most straightforward of which is the supercompensation model, which is described simply as the relationship between work and regeneration that leads to greater physical adaptation (68). Supercompensation is a concept ingrained in the philosophy of almost all coaches, sport scientists, health professionals and fitness enthusiasts responsible for training program design, and underpins the functional increase of an athlete's performance. Theory states that if recovery from a fatigue producing training stimulus is adequate, the body can dissipate this fatigue and rebound through supercompensation (174,175,177,187; Fig. 2-1). Therefore, if the rest intervals between consecutive workouts are of optimal duration, the next training session will coincide with the supercompensation phase. A succession of optimally timed training stimuli - which occur when the maximum training effect from previous stimulus has been realized - establishes a new, increased homeostatic level resulting

in positive training and performance gains (20,174). Replication of the process results in predicted accumulation of positive training effects; however as illustrated in Figure 2-2, if the rest intervals between training stimuli are too short, fatigue can accrue and lead to maladaptation or a reduction in performance capacity (102).

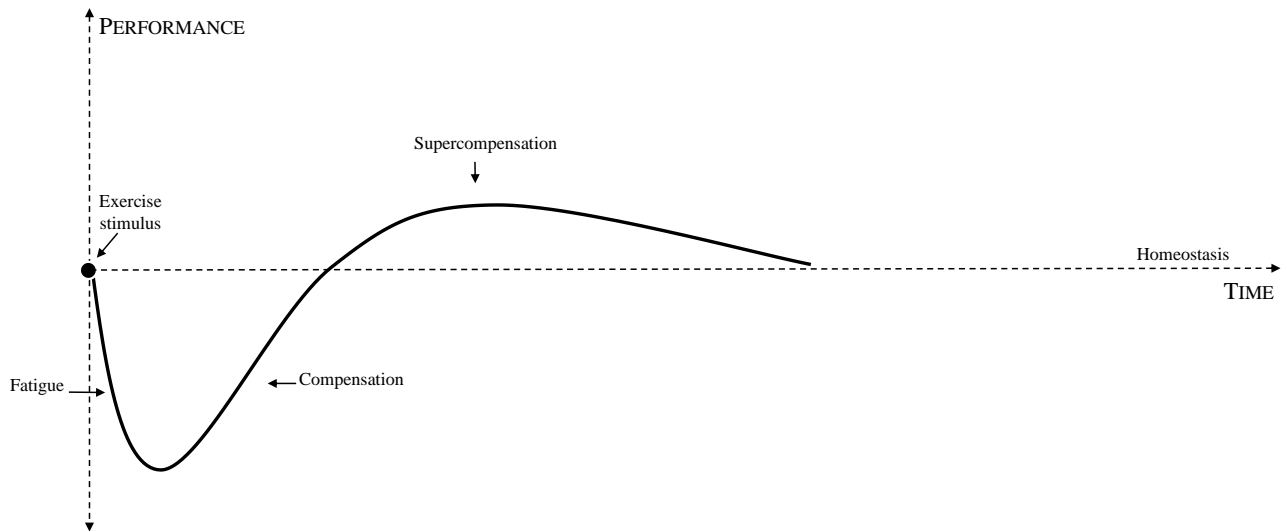


Figure 2-1. Visual representation of the supercompensation model of training adaptation following single exercise bout (Adapted from 20).

Importantly, not all elite athletes experience supercompensation following every session due to the proximity of the second training bout. Consequently, there are limitations to this basic approach. Based on higher improvement rates observed in athletes who participate in more frequent training sessions, other theories advocate systematic loading that does not allow full recovery (153). This is an example of training accumulation or summation and has led to the advancement of the supercompensation theory to the microcycle level where several training sessions of high training load (TL) are conducted with insufficient recovery time between each session (i.e. conjugated successive system [176]). After this ‘impact’ microcycle a sufficient recovery period is introduced with a final supercompensation being produced that is greater than normal (176,180). The resultant enhancement of TL tolerance permits even greater TLs to be implemented in the following microcycle with the promise of further performance gains. This type of training, which involves days and weeks of accumulate stress, requires careful planning and continual monitoring of an athlete response. Each athlete has a certain stress tolerance or a critical

threshold to be able to cope with accumulated fatigue. Once surpassed this can lead to maladaptation, performance decrements and eventually a state of overtraining (102).

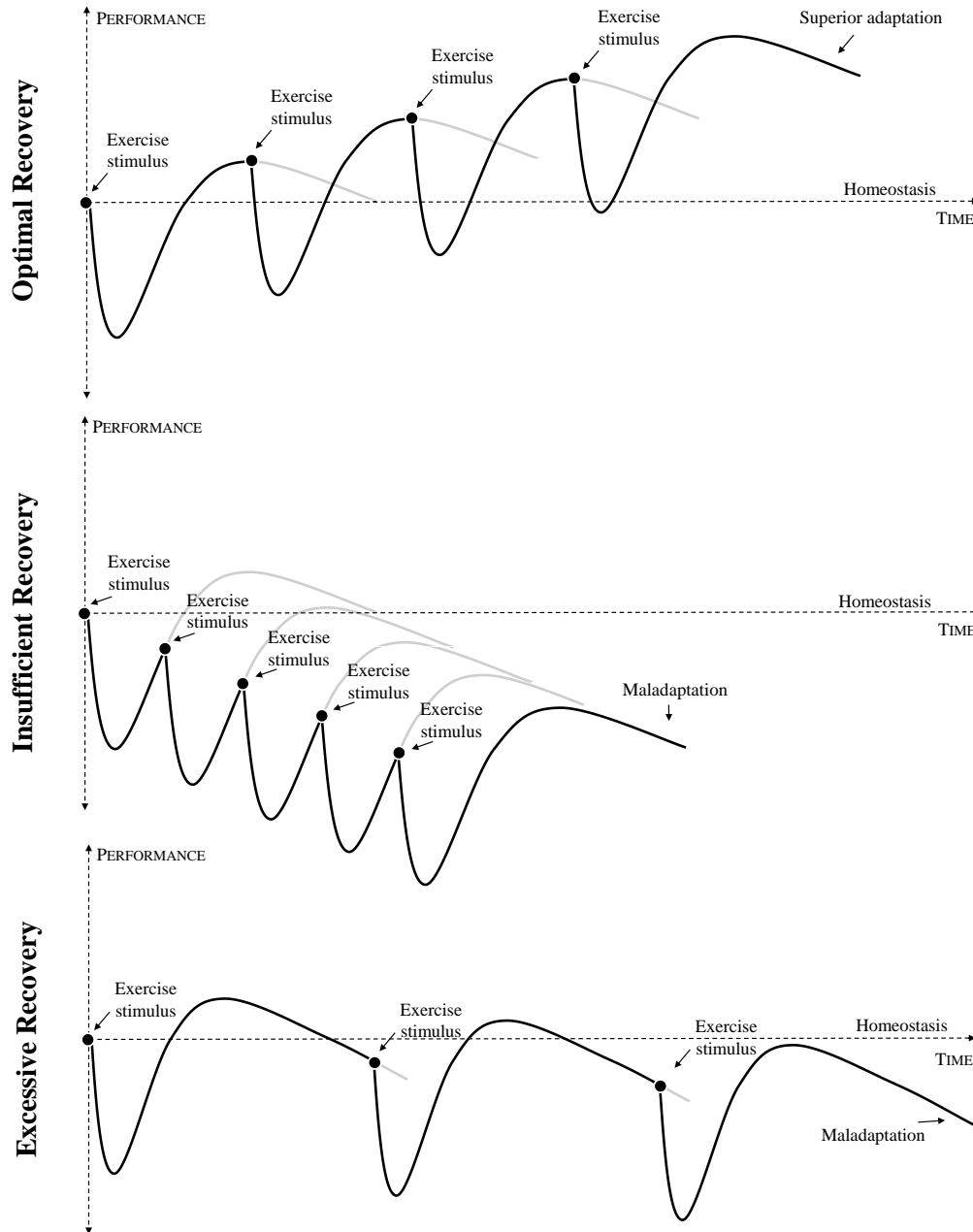


Figure 2-2. Visual representation of theoretical effects of optimal, insufficient and excessive recovery between subsequent exercise bouts on training adaptation (Adapted from 20).

2-2-1. Systems Approach to Training - Fitness Fatigue Model

In further recognition that the one-factor supercompensation model over simplifies the training process, researchers turned to more advanced mathematical modeling. To capture the complexity of the biological adaptive process, seminal models linking training and performance considered the athlete as a system in which the TL is the input and performance the system output (166). This complexity is highlighted through the adaptive protein synthesis variations associated with endurance and strength training. For example, endurance training increases the activity of oxidative enzymes in mitochondria in the overload muscle, while strength training increases the myofibrillar proteins (36). The process of the training effect can be monitored through blood samples and muscle biopsies; however, the actual performance level can only be plotted theoretically since the other component confounding performance is the degree of fatigue produced by the TL.

The first published attempts to mathematically quantify training and its relationship to performance resulted in a four component model (cardiovascular, strength, skill and psychological [10]). System modeling was not expanded upon until the 1990s where Banister et al. (11) proposed a more streamlined three component equation (performance, fitness and fatigue; equation 2-1). Presented as a two-factor model, the authors argued that training results in both a fitness and fatigue after-effect, which can positively or negatively influence performance (Fig. 2-3). On this basis, change in performance or “preparedness” following a training stimulus can be predicted through the interaction between the fitness after-effect, which is a positive physiological response, and the fatigue after-effect, which is a negative physiological response (11). In addition, the fitness and fatigue components were suggested to decline exponentially at different rates. The fatigue after-effect is large in magnitude but short in duration leading to an initial decline in performance. In contrast, the fitness component has a less prominent magnitude but the decay time is longer, estimated at approximately 45 days compared with 15 days for fatigue effects, manifesting in a long-term performance improvement (11). Acknowledging the fact that endocrinological, peripheral and hypertrophic alterations all play a role in positive adaptation as training programs endure, it appears that fitness after-effects are principally neural in nature as evident through observations of both peripheral and central nervous system facilitation (36). Fatigue after-effects on the other hand, comprise of primarily of both neural and metabolic

components. While the classic model depicts a single curve for fatigue-after effects and one for fitness after-effects, in reality multiple fitness and fatigue effects are most likely to exist in response to training (Fig. 2-4). As explained by Chiu and colleagues (36) these specific after-effects are interdependent and exert a cumulative main fitness and fatigue effect.

$$Performance = Fitness - Fatigue$$

(Equation 2-1)

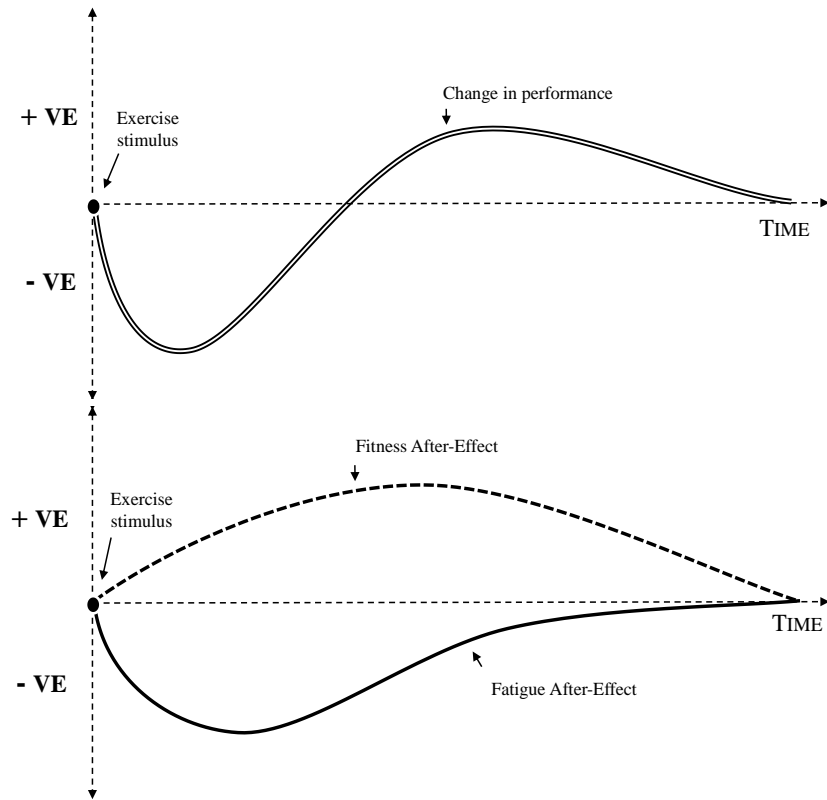


Figure 2-3. Banister's fitness-fatigue model (11). Illustration how a single exercise stimulus results in 2-factors; a fitness after-effect (+ve) and a fatigue after-effect (-ve). Interaction between fitness and fatigue predicts change in performance change (Adapted from 36).

Despite a few initial problems, the concept of mathematically predicting the effect of training bouts on performance remains highly attractive and a number of modifications to the

original fitness-fatigue equation as well as indices of training stress have been proposed and applied to a variety of training modes including cycling (28), running (114,127,165), swimming (10,128), weight lifting (29) and hammer throwing (30). While the limiting factor of using such models in real-world team sports is the definition of performance, it remains abundantly clear that understanding an individual athlete's fatigue response to training is vital for the design and implementation of an optimal training paradigm.

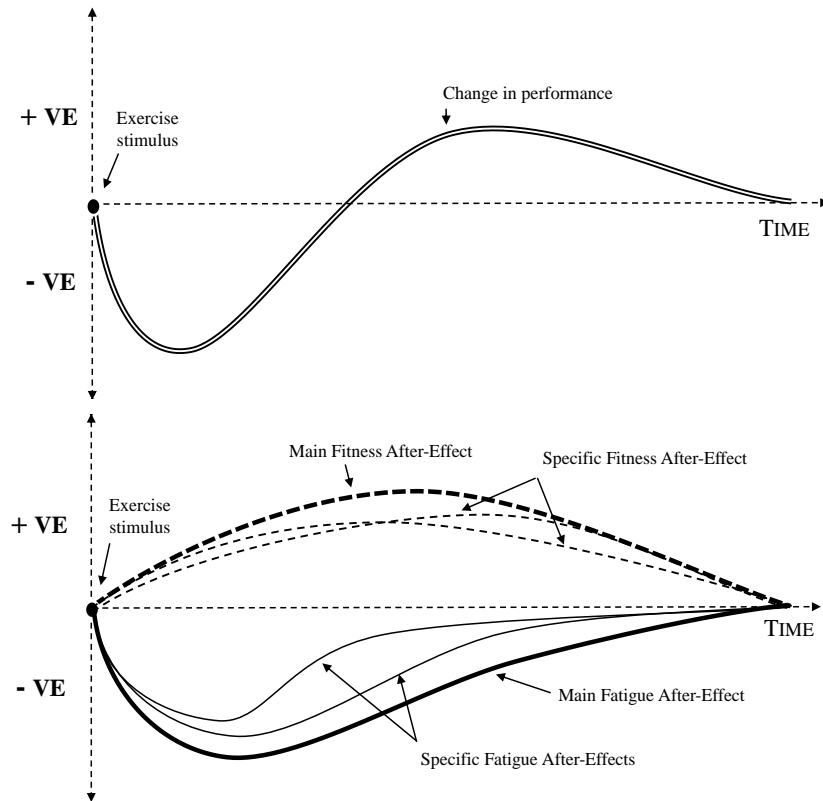


Figure 2-4. Revised fitness-fatigue model. Illustration of how multiple specific fitness (+ve) and fatigue (-ve) after-effects respond from a single exercise stimulus and exert a cumulative effect to form a main fitness and fatigue after effect. Interaction between main fitness and fatigue predicts change in performance change (Adapted from 36).

2-3. AETIOLOGIES OF FATIGUE: AN OVERVIEW

A reduced performance capacity following training is often the definition of fatigue provided in the coaching literature of theoretical program design. Multiple interpretations of the term fatigue exist in the literature. Abiss and Laursen (1) suggested that the definitions of fatigue have been manipulated in order to best suit the diverse research questions in different sports science disciplines. For example, a physiologist may view fatigue as a limitation of a specific physiological

system, such as the inability of the heart to supply ample blood flow to working tissues. A biomechanist may see fatigue as a reduction in force output of a muscle and a neurologist might view it as simply a decline in motor control or central drive. Conversely, psychologists may define fatigue as a decrease in cognitive function or a perception of tiredness (1). Due to this reductionist approach of the sport science disciplines, a vast array of theories and models that explain fatigue-induced performance degradation exist. While this review will be mostly limited to theories explaining the neuromuscular fatigue (NMF) responses to exercise, even within this context it is apparent that contention remains in the way that fatigue is described, defined and subsequently investigated.

Neuromuscular fatigue (NMF) refers to a transient reduction in the maximal force capacity of the muscle, and is measured objectively by an acute reduction in performance during exercise (70,162). Behm and St.Pierre (15) suggested that NMF may also be experienced during prolonged submaximal contractions without an apparent reduction in the targeted force. Limiting the characterization of NMF relative to only maximal contractions may be too simplistic. Therefore, fatigue has also been defined as an acute impairment of performance accompanied by a heightened perceived effort to exert a desired force (15). Based on origin, a distinction between central and peripheral causes of NMF has emerged (162). Defined as a decrease in the force generation capacity of skeletal muscle in the presence of unchanged or increasing neural drive, *peripheral fatigue* largely occurs within the muscle but may have components related to the neuromuscular junction or terminal branches of the motor axon (56). Equally, *central fatigue* is associated with exercise-induced changes occurring upstream or proximal to motor axons and leads to failure of voluntary activation, alterations in firing frequency, synchronization and recruitment resulting in declined voluntary force production (12, 56,162).

2-3-1. Acute Muscle Fatigue

The division of centrally and peripherally mediated fatigue responses is generally drawn at the level of the neuromuscular junction. To date the vast majority of research investigating acute fatigue-induced neuromuscular alterations has been targeted at the periphery, possibly due to the prevalence of peripheral factors in intense exercise bouts (89,161). Through their influence on muscular contraction effectiveness and the resultant force output; neuromuscular propagation,

excitation-contraction (E-C) coupling, substrate availability, and muscle blood flow have all been cited as contributing peripheral factors to muscle fatigue (56).

Excitation-contraction coupling describes the process necessary to convert an action potential (AP) to cross-bridge formation in muscle cells leading to a contraction (139). The number of sequences and complexity of the process means that identifying a fatigue induced mechanism of E-C coupling failure is difficult. Propagation of the AP along the sarcolemma and into the transverse tubules (t-tubules) initiates the E-C coupling sequence. Assessment of neuromuscular propagation can be achieved through observed changes in the compound muscle AP (i.e. M-wave) amplitude, with a reduction in M-wave amplitude indicating conversion impairment of axonal AP into a sarcolemmal AP (70). Several processes are involved in this conversion including branch-point failure (failure of the axonal AP to invade all the branches of the axon), a failure of excitation-secretion coupling in pre-synaptic terminal, a depletion of neurotransmitter, a reduction in the quantal release of neurotransmitter, and a decrease in the sensitivity of the post-synaptic receptors and membrane (56). Impairments in propagation can also be assessed via changes in high frequency stimulation force output. Referred to as high frequency fatigue, reductions in force via this type of stimulation indicates an inability to generate APs repeatedly at the high frequencies, which is vital for a muscle fiber to produce maximal or near maximal force. This form of fatigue appears to occur because of an inability to restore Na^+ and K^+ gradients across the sarcolemma before the next neural impulse (37). Changes in high frequency stimulated force output have been shown following short duration maximal stretch-shortening cycle (SSC) exercise (164,169), whereas declines in M-wave amplitude occur more frequently in low intensity contractions of long duration (14,61).

Metabolic alterations following intense activity are closely related to decreases in force capacity of the muscle. Depletion of high energy phosphate stores following short duration high intensity exercise quickly replenishes within 2-5 mins coinciding with a restoration of contractile force capacity (149). Glycogen levels remain high during these types of abrupt intense activity, whereas during prolonged submaximal exercise depletion of muscle glycogen stores has been associated with fatigue (57,76,150). Accumulation of metabolites resulting from energy conversion may also influence the muscle's ability to produce force. With intense activity, ATP production rate cannot match the demand and by-product accumulation of hydrogen ions (H^+),

ADP and inorganic phosphate serves to down-regulate ATPase activity, slowing the actin-myosin interaction and rate of cross-bridge dissociation (17,32). While the association between force depression and a lower pH has long thought to be strong, recent studies have shown complete restoration of contraction force after ~2 mins of recovery despite H⁺ levels remaining elevated (149). In further support, peak power (PP) output following maximal cycling was restored within a similar time course as phosphocreatine (131), and comparable recovery profiles of inorganic phosphates and muscle force were also reported post short duration exercise (9). Such evidence suggests that accumulation of H⁺ and lactate is probably of limited importance in causing fatigue in mammals (3,185).

The presence of central fatigue can be demonstrated by an increase in the increment of force (superimposed twitch) evoked by electrically stimulating the motor nerve of a muscle during a maximal voluntary contraction (MVC [13]. An increased superimposed twitch means that some motor units were not recruited during the MVC and that central processes proximal to the site of motor axon stimulation are contributing to loss of force. Supraspinal excitation impairments have been observed during both short high-force contractions as well as prolonged maximal and submaximal contractions (13,167). A decline in force during these prolonged contractions was accompanied by progressive increase in superimposed twitch and as such fatigue was considered central in nature (147). Reduction in central activation has also been reported during and after numerous forms of sporting exercise including squash (75), tennis match-play (74), prolonged cycling (106), downhill running (112), marathon (147) and ultramarathon running (125). While full understanding of central fatigue mechanisms remains elusive, Taylor and Gandevia (167) cited a decrease in excitatory input, an increase in inhibitory input (e.g. firing of type III or IV afferent fibers associated with metabolite build-up or muscle damage), and a decrease in the responsiveness of motoneurons through a change in their intrinsic properties (late adaptation). It was further suggested that all three actions are likely to occur during prolonged fatiguing activities (167).

2-3-2. Sub-Acute Muscle Fatigue

Recovery or time to restoration of homeostasis from centrally mediated fatigue has been reported to occur 2-3 mins post maximal contraction or high intensity exercise and greater than 10 mins following prolonged submaximal efforts (167). While equivocal reports regarding the presence of central activation exists following fatiguing dynamic contractions (104) and prolonged running

protocols (138,155), those that report impairment suggested that recovery of central mediated responses exceeds 30 mins (138). Clarity as to whether these long lasting effects are due to central sensitization or continuing afferent activity remains unclear, although continued afferent firing may play a more significant role following exercise eliciting greater muscle damage (124,167). Despite speculation from acute laboratory fatiguing tasks that central fatigue responses may disrupt performance more than a reduction in maximal muscle force (69), few studies, if any, have reported the instances of such fatigue after a typical training bout or indeed successive training bouts. It is abundantly clear that further research is required in order to provide clarity over the expected recovery-time course of centrally mediated fatigue mechanisms in order to understand the implications in a high performance training environment.

The majority of peripheral factors linked to acute muscular fatigue recover relatively quickly after exercise cessation. Given the incongruent recovery-time courses of metabolic changes and force capacity, the involvement of metabolic factors in long-lasting fatigue are considered doubtful (3,27,57). Equally as unlikely to explain long-lasting fatigue following high intensity short duration exercise is deterioration of AP propagation which has shown to recovery within 5 to 10 mins of activity termination (13,18,27,66). In contrast, M-wave amplitudes were depressed for a minimum of 15 mins following progressive cycling to fatigue (93) and supramaximal cycling (6), suggesting that longer repetitive contractions induce greater alterations in AP propagation. Furthermore, a 48 h reduction in sarcolemmal excitability following 22 days of endurance cycling has also been observed (146). High frequency fatigue may therefore persist longer than originally thought, especially following longer duration activity or repetitive exercise on consecutive days.

Following a single exercise bout, alterations in the E-C relaxation process is generally accepted as the most probable peripheral mechanism for delayed force recovery (69). A substantial number of studies assessing the force recovery profile following acute fatiguing interventions have used high- and low-frequency stimulation of the muscle. During these studies, a phenomenon known as low frequency fatigue (LFF) was observed. First described by Edwards and colleagues (54), LFF is characterized by a proportionately greater loss of force in response to low- versus high-frequency muscle stimulation. This form of fatigue is long-lasting, taking hours and even days to subside and was suggested to be caused by muscle fiber damage or impairment in the E-C

coupling mechanism (54). In support of muscle fiber damage, it has been noted that LFF is a prominent characteristic following eccentric or isometric exercises at a long muscle length and has also been observed during the muscle fiber repair process (14,53). Along with affecting performance via reduced force production capabilities, the occurrence of LFF may also affect central drive and sense of effort experienced during voluntary contractions, as well as activation patterns needed to produce targeted levels of force (99). At low exercise intensities these alterations have been perceived by athletes as heavy legs (62,172). Table 2-1 highlights studies reporting the recovery-time course of high and low-frequency stimulated force of the knee extensor muscles following numerous acute fatiguing interventions. Despite providing confirmation of a prolonged force recovery profile at low stimulation frequencies, it is interesting to note that there are also many observations of depressed high frequency stimulated force at concurrent time points. This is in contrast to literature suggesting that maximum high frequency fatigue tends to develop 1-2 h post fatiguing contraction and then dissipates well before low frequency force is restored (54).

In an attempt to bridge the gap between laboratory assessment of neuromuscular function and applied settings, investigations which track changes in neuromuscular performance via more functional performance tests have gained popularity (Table 2-2). In high performance settings the benefit of such investigation lies in establishing minimum recovery periods necessary for repeated maximal performance in competitive phases. However, no conclusions regarding the exact mechanism(s) of long-lasting performance degradation can be drawn, and a relationship between NMF at the peripheral level and functional performance tests is often assumed. Through observed congruency between patterns of recovery in LFF and jump height following a heavy resistance exercise bout, Raasstad and Hallen (141) provided support for use of functional performance tests such as a countermovement jump (CMJ) to represent NMF. Conversely, peripheral fatigue was reported not responsible for the observed decrease in CMJ performance following a marathon as the associated changes were not seen in muscle twitch characteristics (136). Skurydas and colleagues (156) concluded that the relationship between functional performance tests and LFF following 100 maximal intensity drop jumps was unclear, with decrease in low frequency twitch force larger than the observed decrease in jump height (156,158). Such findings, combined with those highlighted in Table 2-2, provide some indication of a relationship between LFF and jump

performance following acute fatiguing interventions. However, if the time course of recovery is mapped solely using functional performance tests the exact mechanisms of NMF remain unclear.

Table 2-1. Investigations showing acute fatigue-induced force responses of maximal voluntary contractions as well as high- and low- frequency stimulation of the knee extensor muscles.

Fatiguing Exercise	Subjects	Parameter	Pre-Post Change	Recovery Time
SSC Exercise Tasks				
Box-Stepping (44) – 60 mins @ 20 steps/min	Males (n=5)	Peak twitch torque Tetanic torque (20Hz)	↓ 25% ↓ 55%	>20h >20h
Drop Jumps (154) – 100 reps continuous	Untrained healthy males (n=12)	MVC Tetanic torque (20Hz) Tetanic torque (50Hz) 20-50Hz ratio CMJ Height	↓ 19% ↓ 50% ↓ 23% ↓ 37% ↓ 44%	>24h >24h >24h >24h >24h
Drop Jumps (154) – 100 reps; 1 rep every 20s	Untrained healthy males (n = 12)	MVC Tetanic torque (20Hz) Tetanic torque (50Hz) 20-50Hz ratio	↓ 23% ↓ 72% ↓ 37% ↓ 52%	>24h >24h >24h >24h
Resistance Exercise				
Back Squat – 10x10 @ 70% 1RM (75) – 20x1 @ 100% 1RM (76)	Strength athletes Males (n=10) Females (n=9) Males (n=10) Females (n=9)	MVC (males) MVC (females) MVC (males) MVC (females)	↓ 47% ↓ 29% ↓ 24% ↓ 21%	48h 24h 2-24h 2-24h
Isotonic RE protocol (138) – 3x3 Back+front squat; 3x6 KE @ 70% 1RM – 3x3 Back+front squat; 3x6 KE @ 100% 1RM	Strength athletes Males (n=8) Males (n=8)	Isokinetic KE Tetanic torque (20Hz) Tetanic torque (50Hz) SJ Height Isokinetic KE Tetanic torque (20Hz) Tetanic torque (50Hz)	↓ ~7% ↓ ~21% ↓ ~12% ↓ 12% ↓ ~13% ↓ ~40% ↓ ~12%	30-33h 30-33h 26-33h <3h 26-33h 26-33h
Prolonged Intermittent Simulated or Actual Game Play				
Squash (72) – 1h squash match	Well-trained players (n=10)	MVC	↓ 16%	<0.5h
Tennis (71) – 3h standard tennis match	Well-trained players (n=12)	MVC Tetanic torque (20Hz) Tetanic torque (80Hz) 20-80Hz ratio	↓ 10% ↓ 12% ↔ ns ↓ 12%	0.5h <0.5h <0.5h <0.5h
Soccer (141) – 90 min simulated game on natural grass	Amateur players (n=10)	MVC Peak twitch torque SJ Height	↓ ~12% ↔ ns ↓ ~8%	<0.5h <0.5h <0.5h

CMJ = Countermovement jump; MVC = Maximal Voluntary Contraction; KE = Knee Extensor; RM = Repetition Maximum; SSC = Stretch Shortening Cycle; ↑, ↔ ns, ↓ = increase, no change, decrease; ns = not statistically significant;

Table 2-2. Investigations assessing delayed recovery after acute fatigue-induced interventions or sports using functional performance tests.

Fatiguing Exercise	Subjects	Parameter	Pre-Post Change	Recovery Time
<i>SSC Exercise Tasks</i>				
Plyometrics (32)	Healthy trained males (n=24)	MVC	↓ ns	na
		CMJ Height	↓ 8%	72-96h
		SJ Height	↓ 8%	72-96h
<i>Resistance Exercise</i>				
Back Squat	Males (n=5)	MVC	↓ ~20%	4-7 days
– 10x10 @ 70% 1RM (28)	Females (n=3)	CMJ Height	↓ ~9%	3-4 days
		SJ Height	↓ ~14%	3-4 days
		DJ Height	↓ ~10%	3-4 days
High intensity strength session (70)	Club standard rowers (n=8)	CMJ Height	↓ 18% @ 2h	>48h
		SJ Height	↓ 10% @ 2h	>48h
<i>Endurance Exercise</i>				
Ironman Triathlon (130)	Experienced well-trained triathlete (n=1)	MVC	↓ 50%	<24h
		CMJ Height	↓ 50%	<8 days
		SJ Height	↓ 50%	<8 days
<i>Prolonged Intermittent High Intensity team sports</i>				
Australian Rules Football (ARF) match (35)	Professional ARF players (n=22)	CMJ flight time	↓ 4%	>24h
		CMJ mean power	↓ 9%	>24h
ARF Season (36) – 22 match season	Professional ARF players (n=15)	CMJ flight:contract	↓ 1 to 17%	na
Rugby League match (113)	Professional rugby league players (n=17)	CMJ peak force	↓ 19%	<24h
		CMJ peak power	↓ 30%	24-48h
		CMJ PRFD	↓ 36%	24-48h
Intercollegiate Soccer match (82)	Female players (n=19)	CMJ peak force	↔ ns	↓ 16% @ 24h
		CMJ peak power	↔ ns	↓ 9% @ 24h
		SJ peak force	↔ ns	↓ 12% @ 24h
		SJ peak power	↔ ns	↓ 9% @ 24h
International Soccer match (4)	Female players (n=22)	20m sprint	↓ 3%	<5h
		CMJ Height	↓ 5%	>69h

CMJ = Countermovement jump; SJ = Squat jump; DJ = Drop jump; MVC = Maximal Voluntary Contraction; PRFD = Peak Rate of Force Development; RM = Repetition Maximum; SSC = Stretch Shortening Cycle; ↑, ↔, ↓ = increase, no change, decrease; ns = not statistically significant; na = not reported.

2-3-3. Accumulated fatigue: Repetitive bouts

While understanding the factors limiting human performance during single maximal efforts or competition has received much attention by investigators, relatively little is understood about the mechanisms answerable to reduced force capacities during periods of extreme or successive physical loading. Regardless of evidence reporting 4 days of recovery to dissipate LFF and performance reductions (31,141,158), high performance dictates that athletes train or compete successively without full restoration. Despite this, a limited number of NMF investigations of highly trained competitive athletes exposed to repeated bouts of exercise exist.

A handful of studies using well-established methodology have reported changes in central fatigue or LFF following training periods consisting of multiple training sessions or competitive bouts. Stewart and colleagues (163) observed force degradation during both voluntary and induced contractions following 3 consecutive days of prolonged cycling, which persisted for at least 72 h. Likewise, measurements of maximal force, central drive and neuromuscular propagation (M-wave) were depressed after 18 h of recovery on days 9 and 17 of a 22 day simulated Tour de France cycle race (146). Due to persistent neuromuscular alterations over the simulated race, the authors concluded that the repetition of transient acute force loss after each exercise bout attributed to chronic changes in voluntary muscle force production over subsequent cycling bouts.

Despite a lack of lab-based research, numerous investigations have assessed the effect of repetitive exercise bouts on neuromuscular function via functional performance tests in a variety of settings. For example, Cormack et al. (39) used a countermovement jump (CMJ) metric to assess NMF over a 22 match (~7 month) Australian Rules football season concluding that players were in a compromised neuromuscular state at 60% of collected data points. Incomplete restoration of CMJ performance was also observed during an international handball tournament (142,145), while 24 h of recovery proved insufficient for restoration of maximal isometric strength following 3 matches on the first day of a wrestling tournament (105). The practicality of functional tests for monitoring NMF and training responses will be discussed in more detail in section 2-4.

2-3-4. Accumulated Fatigue: Overtraining Syndrome

As evidenced above, both short term and long-lasting NMF can result from a single fatiguing bout. While magnitude of fatigue and the subsequent recovery-time course varies depending on exercise type and intensity, consensus on recovery from “normal” training fatigue is suggested to be less than 24 hours (20,159) or up to 72 hours for more intensive or prolonged sessions (102). For an elite athlete to refrain from training for 24 hours, let alone more than 72 hours, is undesirable. It is often logistically difficult to ensure that athletes are exposed to the appropriate training stimuli whilst avoiding the negative consequences of prolonged or excessive fatigue. When such an imbalance exists between the overall strain of training and the individual’s tolerance of stress then long-term performance decrements can occur (121).

In general, overtraining (OT) is described as an imbalance between stress and recovery (100). However, rather than OT existing as an objective condition, it is thought to lie on a continuum, which begins with acute fatigue and can progress to overtraining syndrome (OTS) if recovery requirements of the athlete are not met. The most recent definition asserts that OT is an accumulation of training and non-training stress resulting in long-term decrement in performance capacity with or without related physiological and psychological signs and symptoms of OT (121). The critical factor in describing the OT phenomena is if training results in decreased performance capacity which may take several weeks or months to recover; not simply manifestations of reported signs and symptoms.

Despite the known existence of an OTS many athletes are required to complete large volumes of intensive physical training in order to improve performance. This is particular relevant for high performance athletes who are so well trained that they must constantly push the windows of adaptation in order to gain the edge in performance. Unfortunately for these athletes, excessive physical training, incomplete recovery and high general stress may translate into an unavoidable performance reduction and altered mood states which have been referred to as overreaching (OR). In a similar vein to OT, OR has been defined as an accumulation of stress resulting in a short-term decrement in performance capacity which may take from several days to several weeks to recover (121). The only distinction between OT and OR would therefore seem to be the time needed for restoration of performance. Accurate diagnosis of either OR or OT is problematic and can only be made when performance remains reduced through a recovery period that is longer than a few

weeks or months. In search of optimal adaptation, OR is sometimes deliberately induced in athletes prior to a period of recovery to stimulate performance supercompensation (80). This planned short-term OR has been labeled functional overreaching (FOR [122]). If inadequate recovery is allowed during periods of intensified training, then non-functional overreaching (NFOR) may occur and in extreme cases can lead to fully blown OTS. Often, OTS and NFOR are used interchangeably but for clarity it has been suggested that NFOR is the process that leads to the outcome of OTS.

2-3-5. Fatigue Summary

Following a training stimulus the nature of acute fatigue after-effects can be neural, mechanical and metabolic. While metabolic fatigue tends to be short lived, with full recovery coinciding with activity cessation (76), NMF can have much longer lasting effects due to the complexity of central and peripheral impairment (54,62). These persistent NMF after-effects can also be accompanied by dysfunction of the autonomic nervous system (ANS) when athletes are exposed to sustained periods of intensified training without adequate recovery, culminating in prolonged performance capacity deterioration.

Decades of research in the basic sciences has focused on the mechanisms of fatigue responsible for deterioration of force production during exercise. While fatigue responses to single exercise bouts and those associated with periods of intensified training are often not discussed collectively, the global mechanisms of fatigue are well documented. Whether the principal limiting factors associated with fatigue originate from changes in skeletal muscle metabolism (peripheral) or from changes in neural efferent command (central) remains contested (69,162). Fluctuation and recovery-time course of physiological capacities during and subsequent to fatiguing exercise has also been investigated, however much less data is available demonstrating the profiles associated with intensive training periods involving a succession of fatiguing bouts. To fully understand the mechanisms responsible for fatigue under these circumstances a different, less reductive methodological approach is likely required.

2-4. ATHLETE MONITORING

The principle of training can be reduced to a simple “dose-response” relationship. The “response” in this relationship can be measured as a change in performance or the adaptation of a physiological system. The “dose” of training or physiological stress is associated with the TL (107). Monitoring plays a vital role in establishing this relationship and guiding the balance between increasing physical TL, appropriate recovery and performance goals (160). The following section presents a selection of promising objective and subjective markers that are typically applied by sport scientists to monitor symptoms of fatigue in order establish a better understanding of the training dose-response relationship in world-class athletes.

2-4-1. Training Load or “Dose” Quantification

Optimizing training first involves careful monitoring of what the athlete is currently doing (i.e. dose). Training dose quantification is often focused on the tracking of external TL which is prescribed by coaches (e.g. 4 x 1000m at 240s each with 180s recovery). While recent developments using wearable sensors provide a source of high resolution external TL data, the stimulus for training-induced adaptations is actually derived from the physiological stress imposed on athletes (i.e. the internal TL). As external TL is the main determinant of the internal TL (59), theory suggests that coaches and sport practitioners must understand the interplay between both in order to track fatigue and positively impact performance (90,113). A variety of methods are available to achieve this including Global positioning systems (GPS), training diaries, rating of perceived exertion (RPE), direct observation as well as heart rate (HR) response.

2-4-1-1. External Training Load

Once Roger Bannister was capable of completing 10 x 400m starting every 3mins in 60s, his coach Frantz Stampfl believed he could run a 4 min mile. This is an example of the earliest form of athlete monitoring using external TL and was subsequently proven accurate. The simple logic revolves around the expectation of a certain competitive result once an athlete was physically adept to complete a certain training session (59). Since then, new technologies offer a more insightful analysis of exercise intensity and 3-dimensional movement which is particularly relevant in capturing the external TL of team sport athletes (113).

Global Positioning Systems. As a satellite-based navigational technology, GPS was originally designed for military purposes. Development of portable units has broadened the application of GPS to sports allowing for greater understanding of physical activity through the provision of more detailed information in a spatial context (45). Not surprisingly, the velocity of a task directly influences the validity of distance measured by GPS (8) and on balance it seems that the higher the sample rate, the more valid GPS becomes for measuring distance (113).

In team sports, where the entire spectrum of running velocities occur, the advent of higher frequency GPS technology (10-15Hz) has enabled accurate description of player speed, movement patterns (accelerations and decelerations) and distance travelled in rugby league, rugby union, American football, Australian rules football, cricket, hockey and soccer (45). By quantifying the individual demands placed on athletes in these sports, GPS data can provide real-time analysis of competition performance, assess different positional workloads and establish training intensities (91). Player movement patterns and activity profiles (external TL) can be used in addition to tactical information and physiological responses (internal TL) to characterize competitive match play (117)

The integration of accelerometry within more advanced GPS units allows body load parameters (measured in G-force) to be assessed through collation of all forces imposed on players during competition and sport-specific training (45). This is particularly relevant in collision-based team sports where categorizing the frequency and severity of player-to-player collision as well as impact with the ground enhances the ability of coaches to monitor all stressors related to the sport. The application of GPS technology has revolutionized the body of knowledge around player demand in collision-based team sport through detection of impact characteristics across a match, between matches, between levels of competition, and between types of matches. Further, GPS data not only allows intriguing inter-sport comparisons but has proven invaluable to the coaches and sports practitioners in allowing the tailoring of training to the activity profiles required by players in competition (6). GPS technology has very few disadvantages in terms of quantifying external TL. However, consideration must be given to the fact that in non-professional settings there will be a financial cost associated with the equipment as well as the expertise and time required to collect, manage, analyze and interpret the vast amount of data (117).

2-4-1-2. Internal Training Load

The emergence of technology provides a number of exciting opportunities in terms of analyzing external TL, however, since monitoring and training adaptation is highly individualized the importance of tracking internal TL should not be understated. Systematic approaches to the analysis of internal TL have been described in numerous sports mainly through observation of athlete's HR response but also through collection and manipulation of athlete reported RPE (87). These individualized indices of training stress are arguably the most useful methods in quantifying TL and consist of Training Impulse (TRIMP), Summated HR zone score, Lucia's TRIMP and Session-RPE (10,55,58,111).

Training Impulse. Training Impulse (TRIMP) is a proposed method to quantify a training session into an arbitrary unit of physical effort (11). Banister and colleagues (11) suggested that an athlete's HR response to exercise, along with exercise duration may be a plausible measure of physical effort, as it is based on the extent to which exercise raises HR between resting and maximal levels. The basic TRIMP is calculated using training duration, maximal HR, resting HR and average HR during the exercise session. To avoid the bias of long duration low intensity activity the TRIMP equation also incorporates a weighting factor which emphasizes high-intensity exercise and is based on the lactate profiles of trained men and women relative to increase in exercise intensity (11).

Banister's original TRIMP concept has since evolved and been used in research. The summated HR zone score is one such modification that facilitates the quantification of interval training by dividing the training session into duration spent in each of 5 HR zones (i.e. 50 - 60%, 60 - 70%, 70 - 80%, 80 - 90% and 90 - 100% of HR max). Duration in each zone is multiplied by a different multiplier factor, which weights the higher intensities zones more than lower intensities, and is then summated to provide an estimate of the internal TL known as Edwards' TL (55). More recently, Lucia and colleagues (111) proposed another approach to determine internal TL in endurance athletes (Lucia's TRIMP). Although similar to Edwards' TL, Lucia's TRIMP utilizes individual parameters collected during laboratory testing in order to quantify internal TL opposed to predefined HR zones. Specifically, Lucia's TRIMP summates the product of time spent in three different HR zones: Zone 1: below the ventilatory threshold; Zone 2: between the ventilator threshold and the respiratory compensation point; Zone 3: above the respiratory compensation

point; by a coefficient (k) relative to each zone ($k = 1, 2, 3$ for zone 1, 2, 3 respectively). In terms of practicality, the ability to quantify any training session into a single arbitrary TL figure is highly appealing. However, these HR-based methods have two major limitations; firstly, HR monitors are required to be worn throughout training and second, the TRIMP equations require some form of steady-state HR measurements; which influences its effectiveness for exercise consisting of alternating high-intensity exercise and recovery (107).

Session-Rating of Perceived Exertion. By substituting RPE for HR data, Foster et al. (58) introduced a simple system for coaches to monitor the load of several different modalities of training (technical, tactical, endurance, speed, and strength). Athletes are required to subjectively rate training session intensity using an RPE scale (0 to 10) based on the understanding that they can inherently monitor the physiological stress their body is experiencing (58). A single arbitrary unit for internal TL is calculated by multiplying training duration (mins) or the number of repetitions for resistance training (154) by the RPE intensity value provided retrospectively by the athlete.

An attractive feature of the Session-RPE (sRPE) is that the perception of effort is a reflection of the combination of the physiological stress at that time, whether that be consequence of resistance training, high-intensity interval training or plyometric training (58). Studies have shown that the sRPE is a valid and reliable measure of TL during constant load exercise (83). Favorable comparison of sRPE have also been reported with more complex and objective methods of quantifying internal TL in endurance (60), swimming (181), soccer (90), and resistance trained athletes (48). Despite promise shown in these sports, it was originally speculated that this method of assessing TL was not suited to collision-based team sports such as rugby as the underlying physiological stress arising from collisions was thought not well represented by the RPE score (107). This concern was proven unfounded as evidence of convergent validity between sRPE and other measures of exercise intensity (e.g., HR and blood lactate concentration) during both rugby union (45) and rugby league (42,67,103) with correlations reported similar to those of other sports. Additionally, it has also been shown that the match sRPE is moderately correlated ($r = 0.54$) to the number of tackles completed during a game in professional rugby league, suggesting that the global perceived exertion is also affected by tackling (43). Although further studies are needed, on the basis of these studies it is plausible to suggest that the sRPE method is an acceptable indicator of TL and can be applied to the rugby codes as well as other collision-based sports.

2-4-2. Performance or “Response” Quantification

All the indices of training stress are gaining popularity in determining TL. This recognition stems from the accuracy with which these methods can determine internal TL and in turn, provide crucial training guidance in order to produce more predictable performances (21). However, optimal guidance and hence, performance, is not only reliant on accurate monitoring of TL but also understanding the exercise response as well as the ability to measure and quantify training-induced adaptations.

2-4-2-1. Performance Indicators

Competition outcome is arguably the most pertinent and obvious indicator of either an optimal or suboptimal balance between training and recovery. As stated by Smith (159) competition is not only seen as the greatest form of training but also the pinnacle of testing and monitoring. However, there are a number of issues associated with relying on competitive performance as a regular monitoring tool. Firstly, repeated maximal performance efforts can negatively impact regular training regimes due to fatiguing effects, which is impractical, especially during a competitive season. Secondly, defining maximal performance in field or court based sports is challenging, if not impossible (20). Nonetheless, establishing key underlying physiological capacities can be achieved through a range of functional performance tests. Due to the close relation of these tests to actual performance the outcome measures are often referred to as performance indicators. In line with this method, neuromuscular function and levels of NMF are commonly assessed using vertical jump. Other tests such as maximal ergometer, running or cycling tests exist but due to the substantial amount of induced fatigue, these assessments are difficult to administer regularly and will not be discussed.

Vertical Jumps. In applied settings, neuromuscular status has been most conveniently assessed using various jump models (e.g. CMJ, squat jump). A plethora of research exists investigating the time course of jump performance recovery from fatiguing interventions (38,64,74,84,105,132,145,184). Jump procedures are useful as they reflect SSC capability of the lower-limb musculature and have been recommended as an appropriate tool for tracking long-lasting LFF caused by E-C coupling impairments (62). Moreover, jump protocols are easy to administer and cause minimal additional fatigue.

Video analysis is considered the criterion method for jump performance monitoring during periods of heavy loading; however, other less time consuming approaches have been used including vane jump and reach apparatus (33,41,42,63,126), contact or switch mats (82,184), and force platforms (38,105,119,132,145). Athletic performance assessment has most commonly occurred through portable force plate analysis of the CMJ (38,84,96). Ronglan et al. (145) demonstrated a significant decrement in CMJ height over 3 days of elite handball competition and Hoffman et al. (81) reported various changes in peak power (PP), peak force (PF), and peak rate of force development (PRFD) in American football players over the time-course of a game. Compared with a control group, Coutts and colleagues (41,42) observed clinically important reductions in jump height of rugby league players in response to a 6-week training block of deliberate OR. In contrast, a lack of jump height sensitivity to a fatigue-inducing Australian Rule Football match was reported by Cormack et al. (39), who also stated that only 6 of the 18 CMJ force-time variables analyzed via a force plate declined significantly following the match. In addition, the recovery time profiles of these jump parameters varied greatly (from 24 h to 120 h post-match [38]), a concept recently highlighted in rugby league players whereby PF of a CMJ recovered quicker than PP and PRFD following a competitive match (116).

While the research provides support for vertical jumping as a valuable tool in monitoring training tolerance, it also highlights considerable differences in jump performance variable response and the need for clarity as to the most appropriate parameters for assessing NMF. Specifically, the reliability of jump parameters require more thorough investigation as typical error values reported for some variables are >8-12% which are relatively high (39,44,49,88,152). As explained recently by Twist and Highton (170), the simple observation of a change in any fatigue measure should be interpreted with caution especially if reliability is poor. Based on modified standardized effects (e.g. multiplying by factors of 0.3, 0.9, and 1.6), the authors presented a method to determine meaningful magnitudes of small, moderate, and large changes relating to a number of fatigue assessments in rugby league players including neuromuscular function tests. More work is needed to firstly establish more reliable assessment protocols, and then secondly to validate the smallest important change necessary for determining the presence of NMF in athletes participating in other sports.

2-4-2-4. Heart Rate Response

The ANS functions during and after physical exercise to maintain homeostasis, and repeated exposure to an exercise stress causes physiological adaptation, reducing homeostatic perturbation in response to subsequent stressors (21). Consequently, examining ANS responsiveness to changes in TL may indicate the body's ability to tolerate or adapt to an exercise stimulus (7,21). Since the ANS controls cardiovascular function through sympathetic and parasympathetic modulation, and the balance of parasympathetic and sympathetic modulation is altered following changes in TL, research has specifically focused on conveying training status through autonomic HR regulation (16). Resting HR and heart rate recovery (HRR) are popular measurements associated with regulation of the ANS which are often used as identifying signs of training tolerance (22).

Resting Heart Rate. Proposed as a reflection of amplified sympathetic tone, one of the first signs of OTS reported in the literature was an increased resting HR (23). Despite some initial support (51), the majority of subsequent studies observed no differences in resting HR between OR and normal states (65,81,94,109,161). In a meta-analysis, Bosquet and colleagues (23) suggested resting HR is not a valid sign of FOR, NFOR or OTS as only trivial increases were reported in the overall effect size of 34 studies investigating effects of progressive TL on HR indices. Notably, after short-term training interventions (≤ 2 weeks) the authors observed greater increases in resting HR compared to no alterations when TL increases accrued over periods greater than 2 weeks (23). While this time effect suggests that resting HR may be useful as a valid sign of short-term fatigue, attempting to delineate between day-to-day variability ($\sim 3-5$ bpm) and fatigue-induced alterations is fraught with difficulty and imprecision (20). However, support for the accuracy of sleeping HR as a monitoring tool is gaining impetus since many of the extraneous factors affecting HR are reduced (94,180).

Heart Rate Recovery. Heart rate recovery is determined as the rate at which HR decreases after cessation of moderate to heavy exercise and reflects the coordinated interaction between parasympathetic re-activation and sympathetic withdrawal (98). As such, HRR has the potential to provide insight into the balance of parasympathetic and sympathetic HR modulation and has not only been shown to be a marker of positive training adaptation (\downarrow HRR) but also an indicator of training intolerance (\uparrow HRR [16]). Subsequently, HRR data was incorporated in the novel Lamberts and Lambert submaximal cycle test (LSCT), which was proposed as a practical

monitoring tool of preparedness that can be incorporated into a cyclist's warm-up (105). This test requires that an athlete cycles at a fixed predetermined HR while a combination of power output, HRR data and RPE are measured (108). Although still unsupported in others sports, the positive results in cycling underline the usefulness of HRR and emphasize the significance of interpreting multiple outcome measures (objective, subjective & measured HRR) in detecting small but meaningful changes in performance. More importantly, being submaximal and requiring only 17 minutes to complete the LCST is unique in offering a performance assessing monitoring tool that can be administered regularly without negatively impacting on desired training effects (108).

2-4-2-3. Athlete Self-Report Measures

In order to be truly effective, regular monitoring tools must aid in the identification of all factors that may contribute to both competition and training. Consequently, the purpose of monitoring is not only to track TL and the physiological responses to exercise but also examine all components that impact on an athlete's performance including stressors such as fear of failure, excessive expectations from coach or public, and demands of competition as well as the social areas of an athlete's life (159). Disturbances in self-reported wellbeing are known to be associated with OR and OT (87,121,173) and such disturbances may also reflect an increased risk of injury (95,97) and illness (5,189). Typical support for athlete self-report measures (ASRM) use published questionnaires with evidence of validity and reliability such as the Profile of Mood States (120), the Recovery-Stress Questionnaire for Athletes (100) and the Daily Analyses of Life Demands for Athletes (148).

Recovery Stress Questionnaire for Athletes. Acknowledging the importance of an interdisciplinary approach to athlete monitoring, Kellmen and Kallus (100) developed the Recovery-Stress Questionnaire for athletes (RESTQ-Sport) in order to assist with identification of athletes' sources of excessive physical and mental stress, as well as the extent of the current recovery activities. This is achieved by measuring the frequency of current stress and recovery-associated activities via a 77-item questionnaire; where high scores in the stress- associated activity scales reflect intense subjective stress, and high scores in the recovery- oriented scales indicate good recovery activities. The documented value of the RESTQ-Sport in both anaerobic and aerobic based sports suggests that changes in the questionnaires measures are not only sensitive to TL fluctuations but also likely to appear prior to symptoms of NFOR (41). Subsequent to this, Kellmann and

colleagues (100) developed a seven-item self-monitoring and evaluation instrument known as the Recovery-Cue. The Recovery-Cue was developed to quickly measure perceived exertion, perceived recovery, and recovery effort in an attempt to monitor early warning signs of possible NFOR on a more frequent basis than possible with the relatively lengthy RESTQ-Sport. Various strategies have been recommended whereby the shorter Recovery-Cue is used on a weekly basis, leaving the slightly more time consuming RESTQ-Sport until the end of a training phase or prior to competition (100). This reflects an attempt to improve implementation by reducing athlete burden and increasing relevance, however this may be at the expense of validity and typically result in reduced sensitivity (151).

2-4-3. Monitoring Summary

Recent evidence suggests that many athletes, coaches and support staff are taking an increasingly scientific approach to athlete monitoring (168). Despite increasing popularity and attempts to practically quantify training- and non-training induced stress, no single marker in any sport science discipline has been identified which allows accurate prediction of performance. As evident in the large number of studies and reviews present above, athlete monitoring should not be limited to a single subjective or objective measure, instead combining numerous measures is recommended and common in applied settings. The nature of the monitoring system employed is likely to be very different depending on the sport, not only due to the individual physiological adaptation and exercise response but also because of the specificity required to be practical and relevant to differing sports. Several methodological consideration summary tables for the monitoring tools reviewed can be found in Appendix A. These considerations are particularly poignant in *collision-based* team sports such as Canadian football.

2-5. ATHLETE MONITORING IN CANADIAN FOOTBALL

The sports of Canadian and American football were both developed in the mid-19th Century, evolving from the British game of rugby. While Canadian and American football are in essence the same game, there are some key rule differences. For example, Canadian football has larger pitch measurements and one more player per side (Table 2-3). Due to the stark similarities between the two games and confounded by scarcity of research in Canadian football; the following section operates under the premise that the physical demands of the games are similar. Therefore, while

it is acknowledged that all the research cited below was conducted on the American version of the game, for the purpose of this review the sports of Canadian and American football will be referred to collectively as football.

Table 2-3. Key rule differences between Canadian and American football.

-
- The Canadian field of play is 110 yards long by 65 yards wide (101 m by 59 m), rather than 100 yards long by 53.3 yards wide in American football
 - Canadian teams have 12 players on the field per side, while there are 11 in the US
 - In Canadian football teams have three attempts to move the ball forward by ten yards, compared with four in the American game
 - In Canadian football the gap between the main lines of the offensive and defensive teams at the start of each play has to be one yard. It is less than a third of this distance in American football
 - The end zone is larger in Canadian football (20 vs. 10 yards) and the goal posts are on the goal line instead of at the back of the end zone. This makes for more scoring in the Canadian game.
 - The Canadian game has no “fair catch” rule on punts; therefore, there is always a return that requires more tackling.
 - Time allowed between plays is different (i.e. offense has 20 seconds to snap the ball in Canadian vs. 40 seconds in American)
-

2-5-1. Demands of Football

Football is a high intensity anaerobic collision-based team sport requiring great levels of muscular strength, power, speed and agility. Intermittent in nature, football is characterized by short-duration high intensity bouts of exercise, incorporating movements such as sprinting, back pedaling, accelerating, decelerating and physical collisions, separated by transient periods of low intensity between plays allowing for recovery and strategizing (92). Taking place over four 15-minute quarters, a football game consists anywhere from 50 to 75 maximal intensity plays which on average last 5.2s at the collegiate level (140). Although a team does not have to wait for any specific length of time to begin the next play, the play clock (which tracks the time remaining until the start of the next play) does not begin until the referee has set the ball. Thus, the rest interval (i.e., recovery period) between plays generally exceeds 25 s in duration. During a college football game, the average time between plays is 32.7 s, whereas during professional games rest interval ranges from between 26.9 and 36.4 s (84). This exercise to rest ratio would pose a significant stress to the anaerobic energy system as the amount of recovery between plays does not appear to be

sufficient to allow complete restoration of intramuscular phosphocreatine (37). However, depending on position the requirements per play can vary dramatically.

A football team is comprised of numerous positions each requiring very different skill sets for success. Based on anthropometrics, strength, speed and endurance, three distinct groups of football players have been identified: 1) offensive and defensive linemen; 2) defensive backs, offensive backs and wide receivers; and 3) linebackers and tight-ends (137). Linemen commonly weigh in excess of 140 kg and are rarely required to run greater than 10m per play, whereas wide receivers and defensive backs often weigh less than 95kg and required to run anywhere from 5 to 50m per play. Dependent on position, collegiate players cover distances of 3000 to 5500 m during matches, comprising of time spent executing low-intensity running (~0.1–10 km/h), moderate-intensity running (~10.1–16.0 km/h), high-intensity running (~16.1–23.0 km/h), and very-high-intensity running/ sprinting (>23.0 km/h [182]). The diverse positional requirements are reflected in the largest disparity of high-intensity-distance covered per game between wide receivers (655.0 ± 196.3m) and offensive lineman (131.1 ± 65.7m).

In addition to the running demands, football players are also exposed to frequent violent collisions and blunt force trauma associated with repeated contact with opponents and the ground during tackling, blocking and ball-carrying activities (84). A recent study using Global Positioning Systems (GPS) to investigate impact profiles of collegiate football players over a 12 game regular season observed significant differences across positional groups (183). Wide receivers sustained more *light to moderate* (5-6.5 G force) impacts than other offensive groups during a season, while running backs were exposed to more *severe* (>10 G force) impacts, with the exception of the quarterbacks. On the defensive side, the defensive tackle group sustained more *heavy* and *very heavy* (7.1-10 G force) impacts than any other position.

Collectively, these data provide evidence that football games impose high internal metabolic loads on players, which may compromise the maintenance of peak performance during the course of game and over a season. Players also need to contend with exposure to a high number of violent collisions. Although not studied in football, reports in both rugby codes has shown game collision to cause muscle tissue damage, sensations of tiredness and neural disruption which potentially contribute to immediate and prolonged fatigue (52,115,118,119,170).

2-5-2. Monitoring Challenges in Canadian Football

Unique demands imposed on football players during a game will inevitably lead to an equally complex and individual fatigue response. Recovery is also complicated by a typical in-season training structure whereby weekly games are separated by 4 to 5 days of football practice and strength and conditioning (S&C) sessions. Therefore, it is crucial for coaches and practitioners to implement a valid and relevant monitoring system that provides a better understanding of the dose-response relationship for each player during these competitive periods. However, there are a number of additional methodological considerations when implementing an athlete monitoring system in collision-based sports (Appendix. A).

While HR metrics for quantifying TL is considered the gold standard, the use of HR monitors in football is confounded not only by cost (80-100 players per team), but the unpredictable and violent collision means that HR devices may be damaged or players reluctant to wear such devices due to risk of injury. An alternative solution is the sRPE method, which has been validated in numerous sports; including both rugby codes (46,67,105). Lambert and Borresen (104) suggested however, that despite RPE catering for how players felt, the underlying physiological stress arising from collisions might not be represented with the score. In response, Coutts et al. (43) reported match sRPE moderately correlated ($r = 0.54$) to the number of completed tackles in a professional rugby league game and cited all the positive support for the metric in the collision-based team sport literature (refer to section 2-4-1-2). While reports are promising, to the author's knowledge no data is available to support use in football and due to the greater maximal effort-to-rest ratio than rugby codes as well as the subsequent heavier reliance on the anaerobic system, a football specific validation of sRPE is warranted.

In terms of monitoring a football player's NMF response to a given TL, the literature review reveals that the most logical form of assessment in terms of practicality, reliability and validity would be functional performance tests, specifically a vertical jump model. While limited in American football and non-existent in Canadian football, investigations of competitive match play from rugby league (116,118) and Australian rules football (38) has provided excellent support for the use of the CMJ as a NMF monitoring measure in collision-based team sports (see section 2-4-2-1). Significant correlations between post-match CMJ performance reduction and the number of heavy impacts a player receives during a rugby league match have been recently

reported (116). Undoubtedly, monitoring CMJ is a valuable tool to the coach and support staff of team sport athletes exposed to frequent collisions. However, when considering the high injury rates in collision-based team sports compared with other team sports such as soccer (53.6 [football] vs 18.4 [soccer] injuries per 1000 hours of athlete exposure [2,50]), the probability of executing regular maximal CMJ protocols is not ideal. A need for an alternative and less taxing NMF monitoring tool is therefore evident. Although not commonly used as a monitoring tool in applied high performance settings, a potential solution to practical NMF monitoring in collision-based team sports may lie in the assessment of postural control.

2-5-2-1. Postural Control

Postural control refers to a complex and permanent re-establishment process of balance which aims to maintain the vertical projection of the human body's center of gravity within the base of support (134). By measuring the variation of moment around the ankle or displacement of the center of foot pressure (CoP) postural control can be quantified in terms of postural sway (34). Acute aggravation of postural sway is caused by exercise due to the amplification of liquid movements in response to the increased energy needs met by cardiac and respiratory muscular contractions (25). Furthermore, fatigue generated by exercise affects the regulatory system of posture control through alterations in the handling and quality of visual, vestibular, musculotendinous, articular and cutaneous sensorial information (134).

In this context characterization of postural control within the framework of whole body or "general muscular" exercise such as sport has provoked much interest. Exercise involving running, cycling, walking and ironman triathlon have been shown to alter the effectiveness of postural regulating mechanisms through mechanical impacts on the musculoskeletal system as well as fatigued induced physiological effects (49,72,86,110,129,130,179). Acute physiological effects on postural disturbance after general muscular exercise has shown to be most prominent at intensities greater than 60% of maximal HR (130) or 70% ventilatory threshold (123). While metabolic activation, which increases the cardiac and breathing rhythm, acutely attenuates the amplitude of body sways, metabolites released by the fatiguing muscle fibers are likely to play a more prominent role in postural control disturbance at higher intensities (71). Specifically, Windhorst (186) attributes a diminished facilitation of muscle-spindle afferents on post-exercise

metabolite accumulation manifesting in less efficient postural regulation and reduced motor output.

The influence of sensory alterations on postural degradation are more pronounced in running exercise than walking or cycling due the different exposure to impact on the musculoskeletal system (134). Studies suggest that heightened disturbances in both visual and vestibular feedback systems are due to the repetitive horizontal and vertical accelerations of the head induced by running. Particularly after prolonged running, a decrease in utricular (horizontal) and saccular (vertical) sensitivity combined with movement-generated visual and somatosensory conflicts lead to a more distinct deterioration of postural control (49,110). Running and cycling also differ in terms of muscle activation with very little eccentric action exhibited during concentrically dominated cycling exercise (130). Since more muscle damage and soreness is produced through eccentric contractions compared with concentric (178) and muscle damage deteriorates proprioception (135), eccentric contractions likely contribute more to postural control deterioration. This type of impairment has been demonstrated up to 24 hours post plyometric exercise (168). Running not only creates greater mechanical constraints at the level of active muscle, tendons and cutaneous receptors than cycling but also induces stronger concentric and eccentric contractions than walking, generating greater damage for proprioception as well as the plantar cutaneous mechanoreceptors (49).

Muscular exercise in general induces perturbations of the neuromuscular system that involves changes in muscle strength and postural control (19) and the degree of impairment depends on the intensity, duration and mode of exercise. Sports that have significant mechanical constraints such as those involving a substantial amount of running, jumping or cutting maneuvers are more likely to affect postural control more than those sports where the body is supported, particularly when the exercise is intensive and prolonged. Observation of postural control impairment following actual match or game play has been reported in soccer (26,77), volleyball (143), and handball (188). As evidenced above, in the context of implementing a non-fatiguing and uninterrupted athlete monitoring system the potential of postural sway as a submaximal measure of NMF in Canadian football warrants further investigation.

2-6. LITERATURE REVIEW SUMMARY & IMPLICATIONS

To perform at a high level athletes are required to train aggressively and fatigue is an integral part of this process. For continual performance improvement at the elite echelons of sport, training theory states that exposure to a highly disruptive stress, such as summation of small training stressors, is vital for supercompensation and adaptation to occur. In other words, top-level athletes are in a cyclical state of training-fatigue adaptation, and this cycle is often imperfect (i.e. athletes often train fatigued). Effective monitoring of fatigue is consequently crucial in understanding and managing the training process as it allows identification of an athlete's recovery ability and helps determine appropriate TLs to maximize performance.

While numerous modalities are available for monitoring the training dose-response relationship in athletes, limited scientific research exists confirming the validity of each tool particularly in applied settings, where long term exposure to high frequencies of TL is inevitable (e.g. competitive seasons). Consideration of these limitations is a key determinant for and against including certain measures into an effective monitoring system. This, along with identifying the specific type of monitoring necessary for the sport and individual, make implementing an effective athlete monitoring system highly situational and sport specific.

Determining the most effective monitoring system for the sport of football is particularly difficult, not only because of its unique and violent nature, but also because of a distinct lack of sport specific research. This shortage of knowledge means that selection and validation of appropriate monitoring tools is often extrapolated from other collision-based team sports such as rugby or Australian Rules football. However, due to the obvious difference in physiological game demands alone, this approach has limitations. Furthermore, despite being a professional sport little is known about the acute or long-term training dose-response relationship of Canadian or American football players which is vital for interpreting monitoring data and guiding training effectively. Similar to many collision-based team sports, the shortfall of published knowledge may be hampered by the secrecy of professional settings, but is also limited by a number of practical and methodological challenges unique to the sport. These challenges include but are not limited to; erratic and frequent blunt force trauma, highly individual or position specific physiological game demands and a substantial probability of injury.

2-7. REFERENCES

1. Abiss, C, and Laursen, P. Is part of the mystery surrounding fatigue complicated by context? *J Sci Med Sport* 10: 277-279, 2007.
2. Agel, J, Evans, T, Dick, R, Putukian, M, and Marshall, SW. Descriptive epidemiology of collegiate men's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train* 42(2): 278-285, 2007.
3. Allen, D, Lamb, G, and Westerblad, H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev* 88: 287-332, 2008
4. Andersson, H, Raastad, T, Nilsson, J, et al. Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. *Med Sci Sports Exerc* 40(2): 372-380, 2008.
5. Anglem, N, Lucas, SJE, Rose, EA, and Cotter, JD. Mood, illness and injury responses and recovery with adventure racing. *Wilderness Environ Med* 19, 30-38. 2008.
6. Arnaud, S, Zattara-Hartmann, C, Tomei, C, et al. Correlation between muscle metabolism and changes in M-wave and surface electromyogram: dynamic constant load leg exercise in untrained subjects. *Muscle and Nerve* 20: 1197-1199, 1997.
7. Aubert, AE, Seps, B, and Beckers, F. Heart rate variability in athletes. *Sports Med* 33:889-919, 2003.
8. Aughey, RJ. Applications of GPS technologies to field sports. *Int J Sports Physiol Perf* 6: 295-310, 2011.
9. Baker, A, Kostov, K, Miller, R, et al. Slow force recovery after long-duration exercise: metabolic and activation factors in muscle fatigue. *J Appl Physiol* 74(5): 2294-2300, 1993.
10. Banister, E, Calvert TW. A systems model of training for athletic performance. *Aust J Sport Med* 7: 57-61, 1975
11. Banister, E. *Modeling elite athletic performance*. In: Physiological Testing of the High-Performance Athlete. JW. MacDougall, Champaign, IL: Human Kinetics, 1991. pp. 403-424.
12. Behm, D. Force maintenance with submaximal fatiguing contractions. *Can J App Physiol* 29(3): 274-293, 2004.
13. Behm, D, St-Pierre, M, and Perez, D. Muscle inactivation: assessment of interpolated twitch technique. *J Appl Physiol* 81(5): 2267-2273, 1996.
14. Behm, D, and St-Pierre, M. Effects of fatigue duration and muscle type on voluntary and evoked contractile properties. *J Appl Physiol* 82(5): 1654-1661, 1997.
15. Behm, D, and St-Pierre, M. The effect of strength training and disuse on the mechanisms of fatigue. *Sports Med* 25(3): 173-189, 1998.
16. Bellenger, CR, Fuller, JT, Thomson, RL, Davison K, Robinson, EY, and Buckley, JD. Monitoring athletic training status through autonomic heart rate regulation: A systematic review and meta-analysis. *Sports Med* 46:1461-1486. 2016.

17. Bergstrom, M, and Hultman, E. Relaxation and force during fatigue and recovery of the human quadriceps muscle: relations to metabolic changes. *Eur J Physiol* 418: 153-160, 1991.
18. Bigland-Ritchie, B, Kukulka, C, Lippold, O, et al. The absence of neuromuscular transmission failure in sustained submaximal contractions. *J Physiol* 330: 265-278, 1982.
19. Bizid, R, Jully, JL, Gonzalez, G, Francois, Y, Dupui, P, and Paillard, T. Effects of fatigue induced by neuromuscular electrical stimulation on postural control. *J Sci Med Sport* 12: 60–66, 2009.
20. Bompa, TO, and Haff, G. *Periodization: Theory and Methodology of Training* - 5th Ed. Champaign, IL: Human Kinetics, 2009.
21. Borresen, J, and Lambert, M. Autonomic control of heart rate during and after exercise. *Sports Med* 38(8): 633-646, 2008.
22. Borresen, J, and Lambert, M. Changes in heart rate recovery in response to acute changes in training load. *Eur J Appl Physiol* 101: 503- 511, 2007.
23. Bosquet, L, Merkari S, Arvisais D, et al. Is heart rate monitoring a convenient tool to monitor over-reaching? A systematic review of the literature. *Brit J Sports Med* 42: 709-714, 2008.
24. Botterill, C, and Wilson, C. *Overtraining: Emotional and interdisciplinary dimensions*. In: Enhancing recovery: Preventing underperformance in athletes. Kellman, M. Champaign, IL: Human Kinetics. 2002. pp. 143-159.
25. Bove, M, Faelli, E, Tacchino, A, Lofrano, F, Cogo, CE, and Ruggeri, P. Postural control after a strenuous treadmill exercise. *Neurosci Lett* 418: 276–281, 2007.
26. Brito, J, Fontes, I, Ribeiro, F, Raposo, A, Krstrup, P, and Rebelo, A. Postural stability decreases in elite young soccer players after a competitive soccer match. *Phys Ther Sport* 13(3): 175–179, 2012.
27. Bruton, J, Lannergren, J, and Westerblad, H. Mechanisms underlying the slow recovery of force after fatigue: importance of intracellular calcium. *Acta Physiol Scand* 162: 285-293, 1998.
28. Busso, T, Carasso, C, and Lacour, JR. Adequacy of a systems structure in the modeling of training effects on performance. *J Appl Physio* 71(5): 2044-2049, 1991.
29. Busso, T, Hakkinen, K, Pakarinen, A et al. A systems model of training responses and its relationship to hormonal responses in elite weight-lifters. *Eur J Appl Physio* 61(1-2): 48-54, 1990.
30. Busso, T, Candau, R, and Lacour, JR. Fatigue and fitness modelled from the effects of training on performance. *Eur J Appl Physio* 69(1): 2044-2049, 1994.
31. Byrne, C, and Eston, R. The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *J Sports Sci* 20: 417-425, 2002.

32. Cady, E, Elshove, H, Jones, D, et al. The metabolic cause of slow relaxation in fatigued human muscle. *J Physiol* 418: 327-337, 1989.
33. Callister, R, Callister, RJ, Fleck, SJ, et al. Physiological and performance responses to overtraining in elite judo athletes. *Med Sci Sports Exer* 22(6): 816-824, 1990.
34. Caron, O, Gelat, T, Rougier, P, and Blanchi, JP. A comparative analysis of the center of gravity and center of pressure trajectory path lengths in standing posture: an estimation of active stiffness. *J Appl Biomech* 16: 234–247, 2000.
35. Chatzinikolaou, A, Fatouros, I, Gourgoulis, V, et al. Time course of changes in performance and inflammatory response after acute plyometric exercise. *J Strength Cond Res* 24(5): 1389-1398, 2010.
36. Chiu, LZ, and Barnes, JL. The fitness-fatigue model revisited: Implications for planning short- and long term training. *Strength Cond J* 25(6): 42-51.2003
37. Clausen, T. Na⁺-K⁺ Pump regulation and skeletal muscle contractility. *Physiol Reviews* 83: 1269-1324, 2003.
38. Cormack, SJ, Newton, RU, and McGuigan, M. Neuromuscular and endocrine responses of elite players to an Australian Rules football match. *Int J Sports Physiol Perf* 3(3): 359-374, 2008.
39. Cormack, SJ, Newton, RU, McGuigan, MR, et al. Neuromuscular and endocrine responses of elite players during an Australian Rules football season. *Int J Sports Physiol Perf* 3: 439-453, 2008.
40. Coutts A, Reaburn P, Piva T, et al. Monitoring overreaching in rugby league players. *Eur J Appl Physiol* 99: 313-324, 2007.
41. Coutts AJ, Reaburn P, Piva T, et al. Changes in selected biochemical, muscular strength, power, and endurance measures during deliberate overreaching and tapering in rugby league players. *Int J Sport Med* 28: 116-124, 2007a
42. Coutts, AJ, Murphy, A, Pine, M, Reaburn, P, and Impellizzeri, F. Validity of the session-RPE method for determining training load in team sport athletes. *J Sci Med Sport* 6: 525-535, 2003.
43. Coutts, AJ, Sirotic, AC, Knowles, H, and Catterick, C. *Monitoring training loads in professional rugby league*. In: Reilly, T, and Korkusuz, F, eds. *Science and Football VI*. London, UK: Routledge, 2008. pp. 272-277.
44. Cronin, J, Hing, R, and McNair, P. Reliability and validity of a linear position transducer for measuring jump performance. *J Strength Cond Res* 18(3): 590-593, 2004.
45. Cummins, C, Orr, R, O'Connor, H, and West, C. Global positioning systems and micro technology sensors in team sports: A systematic review. *Sport Med* 43: 1025-1042, 2013.
46. Cunniffe, B, Griffiths, H, Proctor, W, Davies, B, Baker, JS, and Jones, KP. Mucosal Immunity and Illness Incidence in Elite Rugby Union Players across a Season. *Med Sci Sports Exer* 2: 388-397, 2010.

47. Davies, C, and White, M. Muscle weakness following eccentric work in man. *Eur J Appl Physiol* 392: 168-171, 1981.
48. Day, ML, McGuigan, MR, Brice, G, and Foster, C. Monitoring exercise intensity during resistance training using the session-RPE scale. *J Strength Cond Res* 18: 353-358, 2004.
49. Derave, W, Tombeux, N, Cottyn, J, Pannier, JL, and De Clercq, D. Treadmill exercise negatively affects visual contribution to static postural stability. *Int J Sports Med* 23: 44-49, 2002.
50. Dick, R, Ferrara, MS, Agel, J, Courson, R, Marshall, SW, Hanley, MJ, and Reifstack, F. Descriptive epidemiology of collegiate men's football injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train* 42(2): 221-233, 2007.
51. Dressendorfer, R, Wade, C, and Schaff, J. Increased heart rate in runners: a valid sign of overtraining? *Physician Sports Med* 27(7): 77-86, 1985.
52. Duffield, R, Murphy, A, Snape, A, Minett, GM, and Skein, M. Post-match changes in neuromuscular function and the relationship to match demands in amateur rugby league matches. *J Sci Med Sport* 15: 238-243, 2012.
53. Ebbeling, C, and Clarkson, P. Muscle adaptation prior to recovery following eccentric exercise. *Eur J Appl Physiol* 60: 26-31, 1990.
54. Edwards, R, Hill, D, Jones, D, et al. Fatigue of long duration in human skeletal muscle after exercise. *J Physiol* 272: 769-778, 1977.
55. Edwards, S. *High performance training and racing*. In: The Heart Rate Monitor Book. Edwards, S. Sacramento, CA: Feet Fleet Press, 1993. pp. 113-123.
56. Enoka, R. *Neuromechanics of Human Movement*. 2nd ed. Champaign, IL: Human Kinetics. 2002.
57. Fitts, R. Cellular mechanisms of muscle fatigue. *Physiol Reviews* 74(1): 49-94, 1994.
58. Foster, C, Florhaug, JA, Franklin, J, Gottschall, L, Hrovatin, LA, Parker, S, Doleshal, P, and Dodge, C. A New Approach to Monitoring Exercise Training. *J Strength Cond Res* 15(1): 109-115, 2001.
59. Foster, C, Rodriguez-Marroyo, JA, and de Koning, JJ. Monitoring training loads: The past, the present and the future. *Int J Sport Physiol Perf* 12(S2) S22-28, 2017.
60. Foster, C. Monitoring training in athletes with reference to overtraining syndrome. *Med Sci Sports Exerc* 30: 1164-1168, 1998.
61. Fowles, J, Green, H, Tupling, R, et al. Human neuromuscular fatigue is associated with altered Na⁺ -K⁺ -ATPase activity following isometric exercise. *J Appl Physiol* 92: 1585-1593, 2002.
62. Fowles, JR. Technical issues in quantifying low-frequency fatigue in athletes. *Int J Sports Physiol Perf* 1: 169-171, 2006.
63. Fry, A, Kraemer, W, Lynch, J, et al. Does short-term near-maximal intensity machine resistance training induce overtraining? *J Strength Cond Res* 8(3): 188-191, 1994a

64. Fry, A, Kraemer, W, Stone, M, et al. Endocrine and performance responses to high volume training and amino acid supplementation in elite junior weightlifters. *Int J Sport Nutri* 3: 306-322, 1993.
65. Fry, A, Kraemer, W, Van Borselen, F, et al. Performance decrements with high-intensity resistance exercise overtraining. *Med Sci Sports Exer* 26(9): 1165-1173, 1994.
66. Fuglevand, A, Zackowski, K, Huey, K, et al. Impairment of neuromuscular propagation during human fatiguing contractions at submaximal forces. *J Physiol* 460(1): 549-572, 1993.
67. Gabbett, T, and Domrow, N. Relationships between training load, injury, and fitness in sub-elite collision sport athletes. *J Sports Sci* 25(13): 1507-1519, 2007.
68. Gabbett, T. *Athletic development*. Champaign, IL: Human Kinetics. 2007.
69. Gandevia, S. Neural control in human muscle fatigue: changes in muscle afferents, motoneurons and motor cortical drive. *Acta Physiol Scand* 162: 275-283, 1998.
70. Gandevia, S. Spinal and supraspinal factors in human muscle fatigue. *Physiol Reviews* 81(4): 1725-1789, 2001.
71. Garland, SJ, and Kaufman, MP. *Role of muscle afferents in the inhibition of motoneurons during fatigue*. In: Gandevia, S, Enoka, R, McComas, AJ, Stuart, DG, Thomas, CK, eds. *Fatigue: Neural and Muscular Mechanisms*. Plenum, New York, 1995. pp. 271–278.
72. Gauchard, GC, Gangloff, P, Vouriot, A, Mallié, JP, and Perrin, PP. Effects of exercise-induced fatigue with and without hydration on static postural control in adult human subjects. *Int. J. Neurosci* 112, 1191–1206, 2002.
73. Gee, T, French, D, Howatson, G, et al. Does a bout of strength training affect 2,000 m rowing ergometer performance and rowing-specific maximal power 24 h later? *Eur J Appl Physiol* 111: 2653-2662, 2011.
74. Girard, O, Lattier, G, Micaleff, J-P, et al. Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. *Brit J Sports Med* 40: 521-526, 2006.
75. Girard, O, Micaleff, J-P, Noual, J, et al. Alteration of neuromuscular function in squash. *J Sci Med Sport* 13: 172-177, 2010.
76. Green, HJ. Mechanisms of muscle fatigue in intense exercise. *J Sports Sci* 15(3): 247-256, 1997.
77. Greig, M and Walker-Johnson, C. The influence of soccer-specific fatigue on functional stability. *Physical Ther Sport* 8: 185-190, 2007
78. Hakkinen, K. Neuromuscular fatigue and recovery in male and female athletes during heavy resistance training. *Int J Sport Med* 14: 53-59, 1993.
79. Hakkinen, K. Neuromuscular fatigue in males and females during strenuous heavy resistance loading. *Electro Clin Neurophysiol* 34: 205- 214, 1994.
80. Halson, S, and Jeukendrup, A. Does overtraining exist? An analysis of overreaching and overtraining research. *Sports Med* 34(14): 967-981, 2004.

81. Halson, S, Bridge, M, Meeusen, R, et al. Time course of performance changes and fatigue markers during intensified training in trained cyclists. *J Appl Physiol* 93: 947-956, 2002.
82. Hamilton, D. Drop jumps as an indicator of neuromuscular fatigue and recovery in elite youth soccer athletes following tournament match play. *J Aus Strength Cond* 17(4): 3-8, 2009.
83. Herman, L, Foster, C, Maher, MA, Mikat, RP, Porcari, JP. Validity and reliability of the session RPE method for monitoring exercise training intensity. *J Sports Med* 18:14-17, 2006.
84. Hoffman, J, Maresh, CM, Newton, RU, Rubin, MR, French, DN, et al. Performance, biochemical, and endocrine changes during a competitive football game. *Med Sci Sports Exerc* 1845-1853, 2002.
85. Hoffman, J, Nussle, V, and Kang, J. The effect of an intercollegiate soccer game on maximal power performance. *Can J Appl Physiol* 28(6): 807-817, 2003.
86. Hoffman, MD, Gilson, PM, Westenburg, TM, and Spencer, WA. Biathlon shooting performance after exercise of different intensities. *Int J Sports Med* 13: 270-273, 1992.
87. Hooper, SL, Mackinnon, LT, and Hanrahan, S. Mood states as an indication of staleness and recovery. *Int J Sport Psych* 28, 1-12, 1997.
88. Hori, N, Newton, R, Andrews, W, et al. Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *J Strength Cond Res* 21(2): 314-320, 2007.
89. Hunter, S, Butler J, Todd G, et al. Supraspinal fatigue does not explain the sex differences in muscle fatigue of maximal contractions. *J Appl Physiol* 101: 1036-1044, 2006.
90. Impellizzeri, FM, Rampinini, E, Coutts, AJ, Sassi, A, and Marcora, SM. The use of RPE-based training load in soccer. *Med Sci Sports Exerc* 36: 1042-1047, 2004.
91. Impellizzeri, FM, Rampini, E and Marcora, SM. Physiological assessment of aerobic training in soccer. *J Sport Sci* 23(6): 583-592, 2005.
92. Iosia, MF, and Bishop, PA. Analysis of exercise-to-rest ratios during division IA televised football competition. *J Strength Cond Res* 22:332-340, 2008.
93. Jammes Y, Zattara-Hartmann, C, Caquelard, F, et al. Electromyographic changes in vastus lateralis during dynamic exercise. *Muscle and Nerve* 20: 247-249, 1997.
94. Jeukendrup, A, Hesselink, M, Kuipers, H, et al. Physiological changes in male competitive cyclists after two weeks of intensified training. *Int J Sport Med* 13(7): 534-541, 1992.
95. Johnson, U. and Ivarsson, A. Psychological predictors of sport injuries among junior soccer players. *Scand J Med Sci Sports* 21, 129-136, 2011.
96. Johnston, RD, Gibson, NV, Twist, C, Gabbett, TJ, MacNay, SA, and MacFarlane, NG. Physiological responses to an intensified period of rugby league competition. *J Strength Cond Res* 27(3): 643-654. 2013.
97. Junge, A. The Influence of Psychological Factors on Sports Injuries: Review of the Literature. *Am J Sports Med* 28, S-10-S-15, 2000.

98. Kannankeril, PJ, Le, FK, Kadish, AH, et al. Parasympathetic effects on heart rate recovery after exercise. *J Invest Med.* 52:394–401, 2004.
99. Keeton, R and Binder-Macleod, S. Low-frequency fatigue. *Physical Therapy* 86: 1146-1150, 2006.
100. Kellman, M, and Kallus, W. *Recovery-Stress Questionnaire for Athletes.* Champaign, IL: Human Kinetics, 2001.
101. Kellman, M. *Enhancing Recovery: Preventing Underperformance in Athletes.* Champaign, IL: Human Kinetics, 2002.
102. Kentta, G and Hassmen, P. Overtraining and recovery: A conceptual model. *Sports Med* 26(1): 1-16, 1998.
103. Killen, NM, Gabbett, TJ, and Jenkins, DG. Training loads and incidence of injury during the preseason in professional rugby league players. *J Strength Cond Res* 24(8): 2079-2084, 2010.
104. Klass, M, Guissard, N, and Duchateau, J. Limiting mechanisms of force production after repetitive dynamic contractions in human triceps surae. *J Appl Physiol* 96(4): 1516-1521, 2004.
105. Kraemer, W, Fry, A, Rubin, M, et al. Physiological and performance responses to tournament wrestling. *Med Sci Sports Exerc* 33(8): 1367- 1378, 2001.
106. Kremenec I, Glace B, Ben-Avi S, et al. Central fatigue after cycling evaluated using peripheral magnetic stimulation. *Med Sci Sports Exerc* 41(7): 1461-1466, 2009.
107. Lambert, MI, and Borresen, J. Measuring training load in sports. *Int J Sports Physiol Perform* 5:406–411, 2010.
108. Lamberts, R, and Lambert, M. Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. *J Strength Cond Res* 23(3): 1005-1010, 2009.
109. Lehmann, M, Baumgartl, P, and Wiesenack, C. Training-Overtraining: influence of a defined increase in training volumes vs training intensity on performance, catecholamines and some metabolic factors in experienced middle- and long-distance runners. *Eur J Appl Physiol* 64(2): 169-177, 1992.
110. Lepers, R, Bigard, AX, Diard, JP, Gouteyron, JF, and Guezennec, CY. Posture control after prolonged exercise. *Eur J Appl Physiol Oc Physiol* 76 (1) 55-61, 1997.
111. Lucia, A, Hoyos, A, Santalla, C, Earnest, C, and Chicharro, M. Tour de France versus Vuelta a Espana: Which is harder? *Med Sci Sports Exerc* 35: 872-878, 2003.
112. Martin, V, Millet, G, Lattier, G, et al. Why does knee extensor muscles torque decrease after eccentric-type exercise? *J Sports Med Phys Fitness* 45: 143-151, 2005.
113. Macfarlane, TU, Scott, TJ, and Kelly, VG. The validity and reliability of Global Positioning Systems in team sport: A brief review. *J Strength Cond Res* 30(5): 1470-1490, 2015.
114. McGregor, SJ, Weese, RK, and Ratz, IK. Performance modelling in Olympic 1500m finalist: A practical approach. *J Strength Con Res* 23(9): 2515-2523, 2009.

115. McLean, BD, Coutts, AJ, Kelly, V, McGuigan, MR, and Cormack, SJ. Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *Int J Sports Physiol Perform* 5(3): 367-83, 2010.
116. McLellan, CP, and Lovell, DI. Neuromuscular responses to impact and collision during elite rugby league match play. *J Strength Cond Res* 26(5): 1431–1440, 2011.
117. McLellan CP, Lovell DI, Cass GC. Performance analysis of elite Rugby League match play using global positioning systems. *J Strength Cond Res* 25(6): 1703–10, 2011c
118. McLellan, CP, Lovell, DI, and Gass, GC. Biochemical and endocrine responses to impact and collision during elite rugby league match play *J Strength Cond Res* 25(6): 1553-1562, 2011b.
119. McLellan, CP, Lovell, DI, and Gass, GC. Markers of postmatch fatigue in professional rugby league players. *J Strength Cond Res* 25(4): 1030-1039, 2011.
120. McNair, D, Lorr, M, and Dopplemann, L. Profile of mood states manual. San Diego: Educational and Industrial Testing Service. 1992.
121. Meeusen, R, Dulcos, M, Foster, C, et al. Prevention, diagnosis and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). *Eur J Sport Sci* 13(1): 1-24, 2013.
122. Meeusen, R, Piacentini, M, Busschaert, B, et al. Hormonal responses in athletes: the use of a two bout exercise protocol to detect subtle differences in (over)training status. *J Appl Physiol* 91: 140-146, 2004.
123. Mello, RG, de Oliveira, LF, and Nadal, J. Effects of maximal oxygen uptake test and prolonged cycle ergometer exercise on the quiet standing control. *Gait Posture* 32, 220–225. 2010.
124. Millet, G, and Lepers, R. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Med* 34(2): 106-116, 2004.
125. Millet, G, Lepers, R, Maffiuletti N, et al. Alterations in neuromuscular function after an ultramarathon. *J Appl Physiol* 92: 486-492, 2002.
126. Montgomery, P, Pyne, D, Cox, A, et al. Muscle damage, inflammation, and recovery interventions during a 3-day basketball tournament. *Eur J Sport Sci* 8(5): 241-250, 2008.
127. Morton, RH. Modelling training and overtraining. *J Sport Sci* 15(3); 335-340. 1997.
128. Mujika, I, Busso T, Lacostes, L, et al. Modeled response to training and taper in competitive swimmers. *Med Sci Sports Exerc* 28(2): 251-258. 1996.
129. Nagy, E, Toth, K, Janositz, G, Kovacs, G, Feher-Kiss, A, Angyan, L, and Horvath, G. Postural control in athletes participating in an ironman triathlon. *Eur J Appl Physiol* 92, 407–413, 2004.
130. Nardone, A, Tarantola, J, Giordano, A, and Schieppati, M. Fatigue effects on body balance. *Electro Clin Neurophysiol* 105, 309–320. 1997.

131. Neville, M, Bogdanis, G, Boobis, L, et al. *Muscle metabolism and performance during sprinting*. In: Biochemistry of Exercise IX. Maughan, R and Shireffs, S, eds. Champaign IL: Human Kinetics. 1996. p. 243-260.
132. Nindl. B, Leone. C, Tharion. W, et al. Physical performance responses to 72 h of military operational stress. *Med Sci Sports Exerc* 34(11): 1814-1822, 2002.
133. Nosaka, K, Abbiss, C, Watson, G, et al. Recovery following an Ironman triathlon: A case study. *Eur J Sport Sci* 10(3): 169-165, 2010.
134. Paillard, T. Effects of general and local fatigue on postural control: A review. *Neuroscience Biobehavioral Reviews* 36: 162-176, 2012.
135. Paschalis, V, Nikolaidis, MG, Giakas, G, Jamurtas, AZ, Pappas, A, and Koutedakis, Y. The effect of eccentric exercise on position sense and joint reaction angle of the lower limbs. *Muscle Nerve* 35: 496–503, 2007.
136. Petersen, K, Hansen, C, Aagaard P, et al. Muscle mechanical characteristics in fatigue and recovery from a marathon race in highly trained runners. *Eur J Appl Physiol* 101: 385-396, 2007.
137. Pincivero, DM, and Bompa, TO. A physiological review of American football. *Sports Med* 23(4), 247-260, 1997.
138. Place, N, Lepers, R, Deley ,G, et al. Time course of neuromuscular alterations during a prolonged running exercise. *Med Sci Sports Exerc* 36(8): 1347-1356, 2004.
139. Place, N, Yamada, T, Bruton, and J, et al. Muscle fatigue: from observations in humans to underlying mechanisms studied in intact single muscle fibers. *Eur J Appl Physiol* 110: 1-15, 2010.
140. Plisk, S, and Gambetta, V. Tactical metabolic training, part I. *Strength Cond* 19:44–53, 1997.
141. Raastad, T, and Hallen, J. Recovery of skeletal muscle contractility after high- and moderate-intensity strength exercise. *Eur J Appl Physiol* 82: 206-214, 2000.
142. Rhea, M. Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res* 18(4): 918-920, 2004.
143. Ribeiro, F, Santos, F, Gonçalves, P, and Oliveira, J. Effects of volleyball match-induced fatigue on knee joint position sense. *Eur J Sport Sci* 8(6): 397–402, 2008.
144. Robineau, J, Jouaux, T, Lacroix, M, and Babault, N. Neuromuscular fatigue induced by a 90 minute soccer game modeling. *J Strength Cond Res* 26(2): 555-562, 2012.
145. Ronglan, L, Raastad, T, and Borgeson, A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scand J Med Sci Sports* 16(4): 267-273, 2006.
146. Ross, E, Gregson, W, Williams, K, et al. Muscle contractile function and neural control after repetitive endurance cycling. *Med Sci Sports Exerc* 42(1): 206-212, 2010.
147. Ross, E, Middleton, N, Shave, R, et al. Corticomotor excitability contributes to neuromuscular fatigue following marathon running in man. *Exp Physiol* 92(2): 417-426, 2007.
148. Rushall, B. A tool for measuring stress tolerance in elite athletes. *J Appl Sport Psych* 2: 51-66, 1990.

149. Sahlin, K and Ren, J. Relationship of contraction capacity to metabolic changes during recovery from a fatiguing contraction. *J Appl Physiol* 67(2): 648-654, 1989.
150. Sahlin, K. Metabolic factors in fatigue. *Sports Med* 13(2): 99-107, 1992.
151. Saw, AE, Main, LC, and Gatin, PB. Monitoring athletes through self-report: Factors influencing implementation. *J Sports Sci Med* 14, 137-146 2015.
152. Sheppard J, Cormack S, Taylor K, et al. Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *J Strength Cond Res* 22(4): 1320-1326, 2008.
153. Siff, MC. *Supertraining* -6th Ed. Denver, CO: Supertraining Institute, 2003.
154. Singh, F, Foster, C, Tod, D, McGuigan, MR, Monitoring different types of resistance training using session rating of perceived exertion. *Int J Sports Physiol Perform* 2(1):34-45, 2007.
155. Škof, B, and Strojnik, V. Neuromuscular fatigue and recovery dynamics following prolonged continuous run at anaerobic threshold. *Brit J Sports Med* 40: 219-222, 2006.
156. Skurvydas, A, Dudoniene, V, Kalvenas, A, et al. Skeletal muscle fatigue in long-distance runners, sprinters and untrained men after repeated drop jumps performed at maximal intensity. *Scand J Med Sci Sports* 12: 34-39, 2002.
157. Skurvydas, A, Jacscaninas, J, and Zachovajevs, P. Changes in height of jump, maximal voluntary contraction force and low-frequency fatigue after 100 intermittent or continuous jumps with maximal intensity. *Acta Physiol Scand* 169: 55-62, 2000.
158. Skurvydas, A, Mamkus, G, Dudoniene, V, et al. The time-course of voluntary and electrically evoked muscle performance during and after stretch-shortening exercise is different. *J Med Sci Sports* 6: 408-416, 2007.
159. Smith, D, and Norris S, *Training load and monitoring an athlete's tolerance for endurance training*. In: Enhancing recovery: Preventing underperformance in athletes. Kellman, M, ed. Champaign, IL: Human Kinetics. 2002. pp. 81-101.
160. Smith, D. A framework for understanding the training process leading to elite performance. *Sports Med* 33: 1103-1126, 2003.
161. Sjøgaard, K, Gandevia, S, Todd, G, et al. The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. *J Physiol* 573(2): 511-523, 2006.
162. St Clair Gibson, A, Lambert, M, and Noakes, T. Neural control of force output during maximal and submaximal exercise. *Sports Med* 31(9): 637-650, 2001.
163. Stewart, R, Duhamel, T, Rich, S, et al. Effects of consecutive days of exercise and recovery on muscle mechanical function. *Med Sci Sports Exerc* 40(2): 316-325, 2008.
164. Strojnik, V, and Komi, P. Neuromuscular fatigue after maximal stretch- shortening cycle exercise. *J Appl Physiol* 84(1): 244-350, 1998.
165. Suzuki, S, Sato, T, Maeda, A, and Takahashi, Y. Program design based on a mathematical model using rating of perceived exertion for an elite Japanese sprinter: A case study. *J Strength Cond Res* 20(1): 36-42, 2006.

166. Taha, T and Thomas, SG. Systems modelling of the relationship between training and performance. *Sports Med* 33(14): 1061-1073. 2003.
167. Taylor, J and Gandevia, S. A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *J Appl Physiol* 104(2): 542-550. 2008.
168. Taylor, KL, Chapman, DW, Cronin, JB, Newton, MJ, and Gill ND. Fatigue monitoring in high performance sport: A survey of current trends. *J Aus Strength Cond* 20(1): 12-23, 2012
169. Tomazin, K, Dolenc, A, and Strojnik, V. High-frequency fatigue after alpine skiing. *Eur J Appl Physiol* 103: 189-194, 2008.
170. Twist, C, and Highton, J. Monitoring fatigue and recovery in rugby league players. *Int J Sports Physiol Perf* 8: 467-474, 2013.
171. Twist, C, Gleeson, N, and Eston, R. The effects of plyometric exercise on unilateral balance performance. *J Sports Sci* 26, 1073–1080, 2008.
172. Urhausen, A, and Kindermann, W. Diagnosis of overtraining. What tools do we have? *Sports Med* 32(2): 95-102, 2002.
173. Urhausen, A., Gabriel, H. H., Weiler, B. and Kindermann, W. Ergometric and psychological findings during overtraining: a long-term follow-up study in endurance athletes. *Int J Sport Med* 19: 114-120, 1998.
174. Verkhoshansky Y. Principles of planning speed/strength training program in track athletes. *Legaya Athleticka* 8: 8–10, 1979.
175. Verkhoshansky Y. *Fundamentals of Special Strength Training in Sport*. Livonia, MI: Sportivny Press, 1986.
176. Verkhoshansky Y. How to set up a training program in speed strength events. *Soviet Sports Rev* 16: 123–126, 1981.
177. Verkhoshansky Y. *Programming and Organization of Training*. Livonia, MI: Sportivny Press, 1988
178. Vissing, K, Overgaard, K, Nedergaard, A, Fredsted, A, and Schjerling, P. Effects of concentric and repeated eccentric exercise on muscle damage and calpain/calpastatin gene expression in human skeletal muscle. *Eur J Appl Physiol* 103: 323–332, 2008.
179. Vuillerme, N, and Hintzy, F. Effects of a 200 W–15 min cycling exercise on postural control during quiet standing in healthy young adults. *Eur J Appl Physiol* 100: 169–175, 2007.
180. Waldeck, M, and Lambert, M. Heart rate monitoring during sleep: implications for monitoring training status. *J Sci Med Sport* 2: 133-138, 2003.
181. Wallace, LK, Slattery, KN, and Coutts, AJ. The Ecological Validity and Application of the Session-RPE Method for Quantifying Training Loads in Swimming. *J Strength Cond Res* 23(1): 33-38, 2009.
182. Wellman, AD, Coad, SC, Goulet, GC, and McLellan, CP. Quantification of competitive game demands of NCAA division I college football players using global positioning systems. *J Strength Cond Res* 30(1), 11-19 2015.

183. Wellman, AD, Coad, SC, Goulet, GC, Vernon, GC, and McLellan, CP. Quantification of accelerometer derived impacts associated with competitive games in NCAA division I college football players. *J Strength Cond Res* Ahead of Print 2016
184. Welsh, TT, Alemany, JA, Montain, SJ, et al. Effects of intensified military field training in jumping performance. *Int J Sport Med* 29: 45-52, 2008.
185. Westerblad, H, Allen, D, Bruton, J, et al. Mechanisms underlying the reduction of isometric force in skeletal muscle. *Acta Physiol Scand* 162: 253-260, 1998.
186. Windhorst, U. Muscle proprioceptive feedback and spinal networks. *Brain Res Bull* 73: 155–202, 2007.
187. Zatsiorsky, and Kraemer, W. *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics, 2006.
188. Zech, A, Steib, S, Hentschke, C, Eckhardt, H, and Pfeifer, K. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. *J Strength Cond Res* 26(4): 1162–1168, 2012.
189. Zorrilla, EP, Luborsky, L, Mckay, JR, Rosenthal, R, Houldin, A, Tax, A, Mccorkle, R, Seligman, DA, and Schmidt, K. The relationship of depression and stressors to immunological assays: A meta-analytic review. *Brain Behavior Immunity* 15: 199-226, 2001.

THESIS TRANSITION

Chapter III describes a season long comparison of heart rate (HR) and RPE based TL indices aimed at validating the sRPE method for quantifying internal TL of Canadian football players during practice. Due to the limitations associated with players wearing HR monitors when exposed to collision, validation of sRPE in the first study affords us the ability to easily and effectively collect accurate TL with an entire football team through the remainder of the thesis (e.g. increase sample size).

Chapter III - Clarke, N, Farthing, JP, Norris, SR, Arnold, BE, and Lanovaz, JL. Quantification of training load in Canadian football: application of Session-RPE in collision-based team sports. *J Strength Cond Res* 27(8); 2198-2205, 2013.

Author's roles: *Study Design:* JF, NC, SN and BA. *Study conduct:* NC and JF. *Data collection:* NC. *Data Analysis:* JL, NC and JF. *Drafting manuscript:* NC. *Revising manuscript content:* SN, BA, and JF. *Approving final version of manuscript:* All authors.

CHAPTER III

QUANTIFICATION OF TRAINING LOAD IN CANADIAN FOOTBALL: APPLICATION OF SESSION-RPE IN COLLISION-BASED TEAM SPORTS

3-1. ABSTRACT

The session-rating of perceived exertion (sRPE) method for quantifying internal training load (TL) has proven to be a highly valuable and accurate monitoring tool in numerous team sports. However, the influence of frequent impact during Canadian football on the validity of this subjective rating tool remains unclear. The aim of this study was to validate Session-RPE application to a prolonged intermittent high intensity collision-based team sport through correlation of internal TL data collected using two criterion heart rate-based measures known as Polar Training-Impulse (TRIMP) and Edwards' TL. Twenty male participants (age = 22.0±1.4 years) from the competitive roster of the University of Saskatchewan Canadian football team were recruited. Session-RPE, Polar TRIMP and Edward's TL data were collected daily over the 2011 Canadian Interuniversity Sport pre- and competitive season (11 weeks; 713 total practice sessions). On average each player contributed 36 sessions of data to the analysis. Statistically significant correlations ($p < 0.01$) between sRPE with Polar TRIMP (r range: 0.65 to 0.91) and with Edwards' TL (r range: 0.69 to 0.91) were found for all individual players. This study provides confirmation that sRPE is an inexpensive and simple tool which is highly practical and accurately measures an individual's response (internal TL) to Canadian football practice. Furthermore, when considering the number of individuals involved world-wide in collision-based team sports, this tool has the potential to impact a large proportion of the global sporting community.

3-2. INTRODUCTION

The importance of accurately assessing and balancing increasing training loads with recovery is critical to understanding and optimizing performance in any sport (3,25). While a multitude of factors contribute to the body's adaptive response and subsequent performance, collision-based

team sports present a unique challenge with respect to assessing the influence of violent impact forces on training load (TL) monitoring.

Training programs are typically prescribed in terms of an external TL. Defined as the work completed by an athlete (e.g. distance ran), external TL is measured independent of internal characteristics (i.e. an athlete's physiology). For example, in track and field, coaches often prescribe training based on distance and/or time (i.e. 10 x 100m at 18 s each with 90s recovery). While external TL is important in terms of planning and training outcomes, the stimulus for adaptation is determined by the relative physiological stress imposed on the athlete or internal TL (27). Therefore, in order to evaluate training status and accumulative fatigue, monitoring internal TL is considered more relevant and is highly valuable in avoiding injury and symptoms of overtraining (21).

Whereas a number of methods are available for coaches to quantify internal TLs, the practicalities of such techniques do not easily lend themselves to collision-based team sports, such as Canadian football. One heart rate (HR)-based method which has proven useful in quantifying team sport internal TL is the concept of Training Impulse (TRIMP). Originally developed by Banister (3) as a strategy for integrating the components of training into a single term, this systems analysis approach is ideal for evaluating the majority of physical components within team sport training and competition. In Canadian football, however, there are a number of challenges to the TRIMP concept that complicate the accurate measurement of training-imposed stress on a player. Firstly, as with many team sports, the intermittent nature of football, with random, discrete bouts of activity varying in both intensity and duration poses particular difficulties (1). Secondly, the HR equipment necessary to monitor an entire team is relatively expensive and requires a certain level of expertise to collect and interpret. This is particularly restrictive to a football team which can consist of rosters of over 80 players, compared to soccer squads of approximately 22 players. Finally, and most importantly, the frequent collisions and invasive nature of wearing HR monitors in addition to football equipment mean that players may be reluctant to wear the devices and adjustments to equipment is rarely possible. In light of these challenges, there is a need for an alternative method for quantifying internal TLs in Canadian football that is both practical and reliable.

The session-rating of perceived exertion (sRPE) method was first introduced by Foster et al. (13) as a simple system for strength and conditioning coaches to monitor the internal TL of several different training modalities. Based on the understanding that an athlete can inherently monitor their own stress levels, sRPE allows a subjective intensity rating of the entire training session (13). Unlike conventional RPE methods, which rely on RPE values being reported throughout the session, sRPE encourages athletes to simplify the countless intensities experienced and view a session with a single global rating. To ensure a rating representative of the entire training session, athletes are asked to indicate intensity by referring to a numerical value on the Foster's Modified Borg (FMB) scale 30 minutes after completing the session (5,13). A single arbitrary unit for global internal TL is then calculated by multiplying the training duration (mins) by the RPE intensity value provided retrospectively by the athlete. Coaches are then able to evaluate trends in training, injury, and illness in relation to sRPE and the global intensity of the training session (13).

Undoubtedly, the simplicity of sRPE and ease of interpretation is the major advantage within team sports compared with other reported methods. Successful early comparisons of sRPE with more complex methods of internal TL quantification were reported in endurance sports (12,28), non collision-based team sports (7,16) and resistance trained athletes (8). Based on this evidence research focusing on training modalities (17) and neuromuscular fatigue (20) in collision-based sport has utilized sRPE in order to quantify TL despite no pre-existing collision specific validation of the method. More recently, sRPE has been validated within the collision-based team sport of rugby league (18). However, due to its continuous nature, rugby league has a greater reliance on aerobic energy provision than Canadian football (14,24). Similar to the American version, Canadian football is distinguished by discrete, intense anaerobic bursts of work coupled with short rest periods between plays. Violent blocking and tackling are inherent within these high intensity plays and can produce considerable physical and physiological strain (24). Consequently, Canadian football imposes a unique stress on individual players that needs to be recognized and factored into a periodized plan through accurate monitoring of internal TL. Despite extensive research, the influence of frequent impact during Canadian (or American) football on the validity of sRPE remains unclear. Therefore, the aim of the current project was to validate sRPE as a measure of internal TL within Canadian football practice sessions using HR-based methods as the

criterion measure. It was hypothesized that sRPE would present significant individual correlations between HR-based internal TL methods collected during Canadian football practice sessions.

3-3. METHODS

3-3-1. Experimental Approach to the Problem

Pilot study. To negate any possible learning effects associated with the reliability of sRPE (13) a pilot study was implemented during the entire 2010 Canadian Interuniversity (CIS) football season. Session-RPE internal TL data of all players on the University of Saskatchewan (U of S) competitive roster ($N=78$) was collected for all practice sessions and competitive games.

Current study. Of the 62 returning players who completed the 2010 pilot study, 20 were recruited for the current investigation and were also re-familiarized with this FMB scale prior to study commencement. The limited number of players recruited compared with the pilot study was solely due to availability of HR equipment. Practice session internal TL data using both sRPE and HR response methods were collected and used for comparison during the entire 2011 pre- and competitive CIS football season (11 weeks, 713 practice sessions in total). Session-RPE data was also collected for competitive games solely to provide an indication of TL. CIS football presents a unique model from which to evaluate the influence of heavy collisions on sRPE as the program not only comprises of a high performance cohort but also involves more collision compared with practice sessions of professional American and Canadian football teams who are contractually obliged to minimize the amount of contact per training week.

3-3-2. Subjects

Twenty male participants were recruited from the competitive roster of the 2011 U of S Canadian football team (Table 3-1). Players were all regular starters from the 2010 CIS season and were recruited to participate due to the greater potential TLs associated with full practice session and regular competitive game involvement. The top three players on positional depth charts created by the U of S coaching staff were approached and asked to volunteer. Players were representative of all positions excluding kickers. It is mandatory for all athletes to be screened and receive medical clearance by a clinical physician prior to participation in CIS sport and therefore, all

subjects were considered healthy. Inclusion criteria for the competitive roster were based on subjective observations of an experienced coaching staff during numerous sport specific performance and selection camps. This rigorous selection process allows a confident definition of this population as high performance. All players gave written consent according the American College of Sports Medicine guidelines, which conform to the Declaration of Helsinki. Ethical approval was obtained from the U of S Biomedical Research Ethics Board (Appendix E-1/2).

3-3-3. CIS Football Season structure and training

For both 2010 and 2011 the pre-season consisted of a 10 day training camp with two football specific practice sessions per day culminating with one exhibition game. Immediately following the pre-season, a 9 week competitive season began with 8 competitive games and 1 bye week. During both seasons, the post-season consisted of one week of practice before the team was eliminated in the first round of playoffs. Practice sessions were planned solely by the coaching staff which included tactical, technical and conditioning components (2010 = 48 sessions; 2011 = 51). In a typical week all players participated in 4 practice sessions (Monday, Tuesday, Wednesday & Thursday) and a competitive CIS game (Friday). Full contact was incorporated into practice sessions during the first 3 days of a training week, where helmets and full pads were worn. During the practice prior to game day (typically Thursday), contact was minimal for all starters with players wearing just helmet and shoulder pads. Active recovery sessions were held on the day following the game (Saturday) and one day was dedicated to complete rest (Sunday). During the competitive season the weekly training plan varied slightly depending on game day scheduling. All practice sessions were completed on modern artificial turf at the U of S football stadium.

3-3-4. Procedures - Measures of Internal Load

Practice Session-RPE. Using the FMB scale (Table 3-2) each player's RPE intensity was collected verbally approximately 30 minutes after completion of every practise session (after a 15 min cool down and ~10-15 min debriefing by the head coach). This timing ensured that the perceived effort be reflective of the entire session rather than the most recent exercise intensity. The FMB scale has proven frequently successful with athletes in previous sRPE studies (7,8,12,16,28) and players were asked to report intensity relative to other football practises which included all aerobic, anaerobic and contact components. In accordance with Foster et al. (13), an arbitrary unit that

represents each individual player internal TL was then calculated by multiplying the training duration (minutes) by training intensity (RPE value retrospectively indicated). Training or practice duration was defined as the time elapsed from the beginning of team warm-up until the completion of the last training component prescribed by the head coach.

Table 3-1. Player details, number of practice session for which both Session-RPE and HR-Based TL data was collected and games played during 2011 CIS Season.

Player	Position	Age	Height (m)	Weight (kg)	Practice Sessions	Games Played			
						Ex	Reg	Poff	Total
P1	QB	22	183	77.1	45	1	8	1	10
P2	WR	22	185	88.4	30	1	7	0	8
P3	WR	23	185	93	45	1	4	1	6
P4	WR	22	185	83.1	28	0	8	1	9
P5	RB	24	177	90.7	37	1	6	1	8
P6	RB	21	165	84	28	1	6	0	7
P7	OL	21	193	140.6	37	1	8	1	10
P8	OL	20	188	127	43	1	8	1	10
P9	OL	24	183	127.2	43	1	8	1	10
P10	DB	20	177	91.6	31	1	6	1	8
P11	DB	23	183	86.2	48	1	8	1	10
P12	DB	21	183	90.7	36	1	8	1	10
P13	DB	23	172	88.5	39	1	8	1	10
P14	LB	22	185	102.1	42	1	7	1	9
P15	LB	24	183	95.3	32	1	8	1	10
P16	DE	20	185	104.3	26	0	6	1	7
P17	DE	20	188	106.6	37	1	6	1	8
P18	DL	23	190	131.5	23	1	7	1	9
P19	DL	23	185	115.6	39	1	8	1	10
P20	DL	22	185	115.2	29	1	8	1	10
<i>Mean</i>		22	183	101.9	35.9				8.9
<i>SD</i>		1.38	6.26	18.4	7.2				1.2

QB = Quarterback; WR = Wide Receiver; RB = Running Back; OL = Offensive Lineman; DB = Defensive Back; DE = Defensive End; DL = Defensive Lineman; Ex = Exhibition; Reg = Regular Season; Poff = Playoff.

Competitive Session-RPE. RPE intensity was also collected verbally approximately 30 minutes after competitive games from players who competed in a minimum of three quarters. Internal TL was calculated by replacing training duration with the time elapsed from kickoff to the final whistle. Competitive sRPE was collected for the purpose of tracking TL (Fig. 3-2A & 3-2B) and was not used for comparison against HR data as competitive games were not conducive to wearing HR monitors.

Table 3-2. Foster’s modified Borg scale (13).

Rating	Descriptor
0	Rest
1	Very, very easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	
7	Very Hard
8	
9	
10	Maximal

Heart rate. Thirty to 60 minutes prior to a practice session each player was fitted with a HR monitor on the chest in accordance with the manufacturer’s guidelines (Polar Team2 Pro, VantageNV, Polar® Electro, Kempele, Finland). Bespoke padding that protected the player, opponents and HR monitor from collisions were created using football hip pads and Velcro© strips (Fig. 3-1). Each HR monitor consisted of an individually coded transmitter to avoid interference and HR was recorded every 3s during each practice session. To reduce HR recording error, the online feature of the Polar Team2 system was used to provide live monitoring of HR responses from all 20 players throughout practice sessions. Although rare, any irregularities were identified and fixed at the next convenient stoppage to avoid any interference with regular practice. Players were also briefed as to the correct fitting procedure, location of the HR monitor and how to ensure that the monitors were functioning properly once in place. Upon practice session completion HR data were saved on a portable PC using the specific Polar Team2 software and subsequently exported and analyzed further using Excel (Microsoft Corporation, Redmond, WA, USA) and custom written MATLAB routines (Mathworks, Natick, MA, USA).

The second HR-based method was proposed by Edwards (10). Known as Edwards’ TL, this HR-based measure determines internal TL by measuring the product of the accumulated training duration (minutes) of 5 HR zones by a coefficient relative to each zone (50–60% of HRmax = 1, 60–70% of HRmax = 2, 70–80% of HRmax = 3, 80–90% of HRmax = 4, 90-100%

of HRmax = 5) and then summing the results (10). Heart rate maximums were predicted by age (HRmax = 220-age) and only complete HR data was used for comparison. Incomplete data was typically due to players not being able to complete or participate in full practice due to injury.

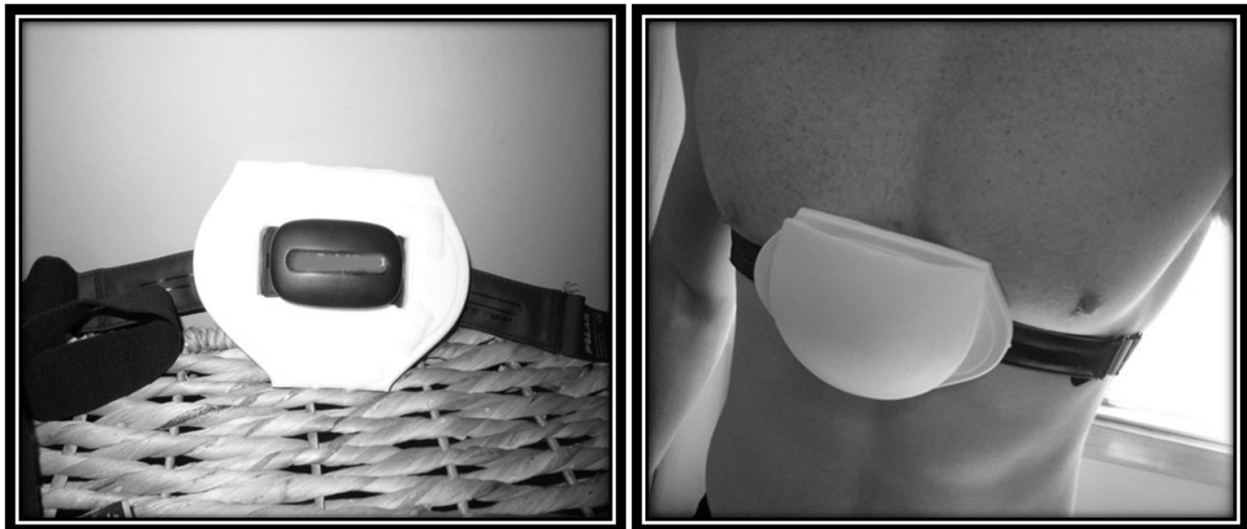


Figure 3-1. Bespoke HR monitor protector. Protector was trimmed to fit each player's normal clothing and equipment.

3-3-5. Statistical Analyses

Individual Pearson's product moment correlations between sRPE TL and HR-based TL were computed using the number of practice sessions as cases for each player according to the methods of Wallace et al. (28) and Impellizzeri et al. (16).

Based on these data an estimate of the population correlation between sRPE TL and HR-based TL was 0.75. Using this estimate of effect size (ES), a power calculation was computed for the correlation using Delta = 2.80 and ES = 0.75, and it was determined that a minimum of 15 participants was required to achieve 80% power at alpha = 0.05. Alpha level was set as 0.05.

3-4. RESULTS

Weekly training cycles (periodization) of mean internal TL described using sRPE is shown for both the 2010 and 2011 CIS Seasons (Fig. 3A, B). Competitive sRPE was also included although no HR data was collected during competition. Maximum TL loads were reported after competitive

games and during the pre-season that included two practice sessions per day (Days 0 to Pre. 1, Fig. 3B). Weekly practice session TL typically peaked during the second or third session post game and progressively decreased as the next game approached.

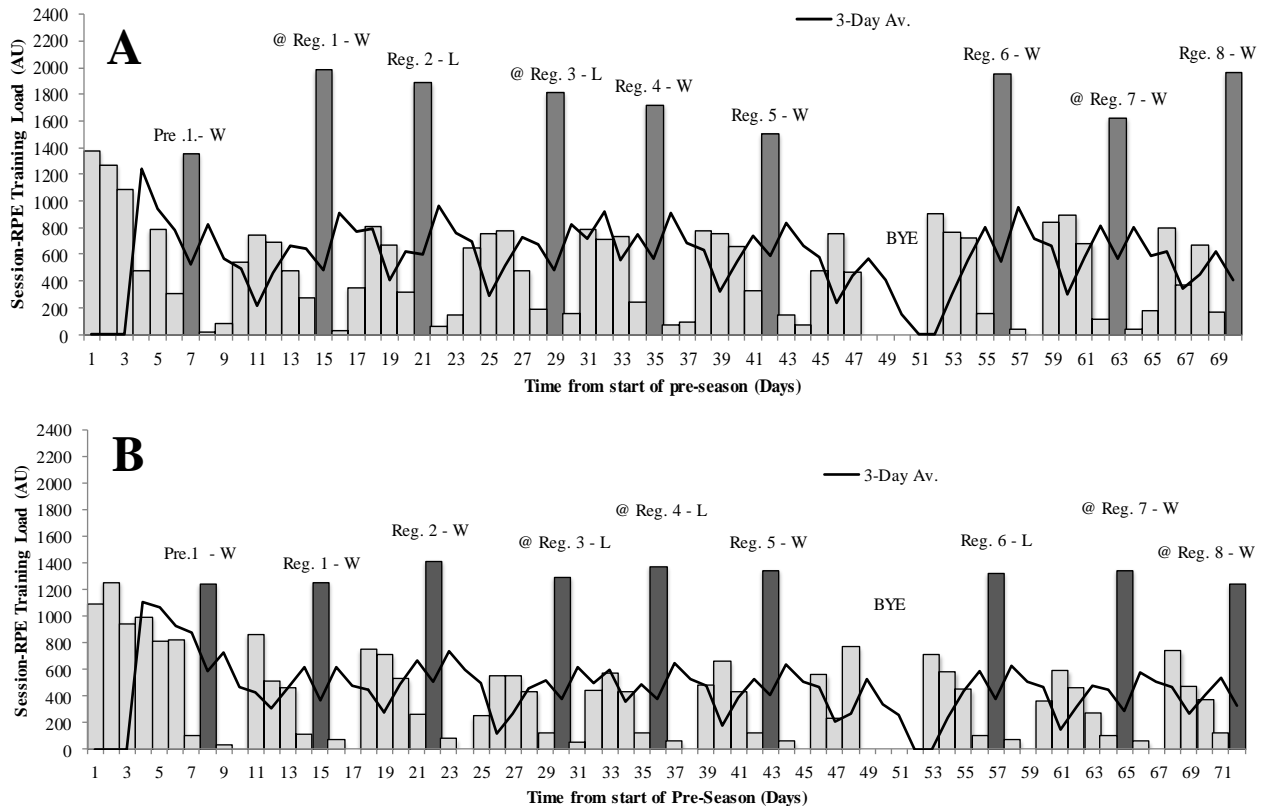


Figure 3-2. Daily team internal training load (TL) for **A**) 2010 and **B**) 2011 CIS preseason (Days 0 to 7) and competitive football season. 3-Day average represents the average TL of the previous 3 practise days and can be indicative of rested state. Light columns represent practise sessions. Dark columns represent competitive games with result (W = Win; L = Loss). AU = Arbitrary unit; Pre. = Pre-season Exhibition game; Reg. = Regular season conference game; @ = Away game.

During football practice sessions, significant ($p < 0.01$) correlations were observed between sRPE with Polar TRIMP ($r = 0.65-0.91$) and with Edwards' TL ($r = 0.69-0.91$) respectively. Individual correlations are presented in Table 3-3. Figure 3-3 is a representative example of how sRPE describes similarly both Edwards' TL and Polar TRIMP during football practice sessions.

Table 3-3. Individual correlation coefficients (r) between Session-RPE and two HR-based training load methods. Each player contributed an average 36 practise sessions of data to the analysis. All individual correlations were statistically significant ($p < 0.01$).

Player	Correlation with Session-RPE	
	Polar TRIMP	Edwards' TL
P1	0.74	0.77
P2	0.86	0.87
P3	0.84	0.79
P4	0.66	0.69
P5	0.80	0.82
P6	0.80	0.80
P7	0.77	0.81
P8	0.82	0.84
P9	0.67	0.83
P10	0.81	0.88
P11	0.77	0.79
P12	0.65	0.75
P13	0.75	0.85
P14	0.75	0.79
P15	0.76	0.76
P16	0.80	0.85
P17	0.79	0.82
P18	0.91	0.91
P19	0.89	0.88
P20	0.76	0.77
Min	0.65	0.69
Max	0.91	0.91
Mean	0.78	0.80
SD	0.07	0.05

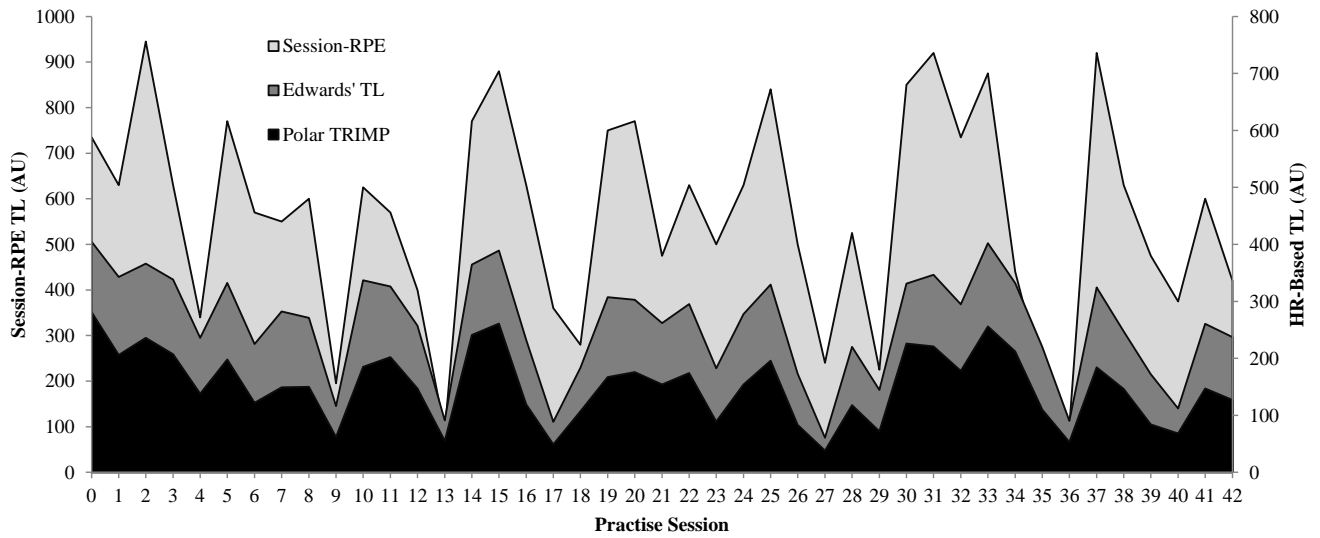


Figure 3-3. Representative comparison of one player's (Player 8) practice training load patterns calculated using the Session-RPE, Edwards' TL and Polar TRIMP methods; AU = Arbitrary unit.

3-5. DISCUSSION

The present study is the first to apply sRPE to Canadian football in order to monitor internal TL of practice sessions. Significant correlations were demonstrated between two criterion HR-based internal TL measures (Edwards' TL & Polar TRIMP) and sRPE. As expected and in agreement with previous literature (7,8,12,16,28) our results support the notion that sRPE is a valid tool for monitoring internal TL in numerous sports. Importantly, however, this non-invasive measurement has now been shown to accurately represent internal TL in a team sport that involves frequent impact force through violent collisions.

Significant correlations (ranging from 0.65 to 0.91) reported in the current investigation are similar to other reported sRPE and HR-based TL comparisons in soccer (16) ($r = 0.50-0.85$) and slightly lower than those found in endurance athletes (12) ($r = 0.75-0.90$). In explanation, Impellizzeri et al. (16) suggested that the reduced correlation strength in soccer compared with endurance events is due to an increased provision of energy via anaerobic pathways leading to an overestimation of internal TL through higher RPE values. Support for this notion is evident in previous research that reported higher RPE values during intermittent compared with work-matched steady-state protocols (9). Although the metabolic requirements of soccer and football are much different, the superior anaerobic reliance of these sports is a common characteristic, whereas the frequency and intensity of physical contact in football is much greater. Increased neural disruption, muscle tissue damage and stress due to the violent collisions associated with a football game have been reported (15), which potentially could lead to greater pain perception and increased reported RPE values. Therefore, the higher anaerobic energy provision as well the combative nature of football may go some way to explain the slightly reduced correlations in football compared to endurance sports. Furthermore, the unpredictable frequency and nature with which both high intensity bursts and physical contact occurs during football may account for the wide range of individual correlations seen within the present study (Table 3-3). Despite the wide range of correlation values, all were statistically significant at the 99% confidence level.

The most appealing element of sRPE to Canadian football and other collision-based team sports is the psychobiological nature of the single RPE value. The original sRPE concept was based on the inherent ability of an athlete to subjectively monitor both physiological and psychological stress placed on their body during training (12). When both anaerobic and aerobic

energy systems are concurrently activated, such as seen in intermittent team sports, research has shown RPE to be a more than reliable measure of exercise intensity (2). Furthermore, RPE is predicted more accurately with the combination of HR and blood lactate concentration as opposed to either variable alone (5). As mentioned previously, it is plausible to suggest therefore, that sRPE may be sensitive to both the physical damage and mental pain experienced with multiple violent football collisions.

The line separating optimal training and overtraining remains undefined; however, research has shown RPE values to be sensitive to changes in an athlete's physiological and psychological tolerance to training (22). Additional support has been seen in overtraining studies reporting greater RPE values for a given HR during overreaching (19), as well as increased RPE values to a standardized exercise stimulus from athletes in a heightened state of fatigue (26). As suggested by Impellizzeri et al. (16), RPE may be more sensitive than HR to an athlete's fatigue state and this may partially explain the moderate correlations seen between sRPE and HR-based TL observed in some individuals during the length of the current study. Consequently, sRPE can be considered a valuable monitoring tool that drives evidence-based guidance of an athlete's training in collision-based sports, in order to maintain the intricate training-recovery balance and avoid overtraining.

Developing and maintaining fitness over the course of an entire Canadian football season, as well as preventing and recovering from injuries, requires careful planning and implementation of a relatively complex periodized training program (4). Logical weekly fluctuation of internal TL calculated via RPE would imply that the application of sRPE during a football season is representative of undulating stress placed on individual players and useful in training periodization (Figure 3-3). Within the present study, further anecdotal support was provided by the experienced coaching staff that recognized an intentional 4 day bell-shaped format in training intensity which is common in team sports with weekly competition (4). Visual validation of the preparation process convinced the coaches of sRPE's applicability and as the season progressed, TL data as well as knowledge of results was used to plan adequate recovery for the team prior to the next match.

Standardizing the timing of rating collection as well as FMB scale familiarization are two areas that can affect the reliability of sRPE (13). A definite learning effect was seen within our pilot study that implemented sRPE during the entire 2010 CIS football season (Fig. 3-2A). Despite all players being familiarized with the FMB-scale prior to this pilot study, the results suggested a learning effect may have occurred characterized by an intensity over-estimation compared with the current data. For example, on reflection of certain sessions, players would often comment on how they would have ranked a previous session lower if they had already experienced the current session. This type of learning effect was only seen during the 2010 season and may have affected the outcome of the current project if a pilot study had not been implemented. As only returning players were used in the current investigation and were all re-familiarized with the FMB scale, the pilot study was a pre-existing solution to any learning effect. In addition, the inclusion of the maximal tests during the mandatory pre-season testing ensured all players experienced intensities that theoretically equate to 10 or “Maximal effort” on the FMB scale. This provided the players with an exertion reference from which all other sessions could be gauged.

Based on the body of literature and our previous pilot study data, it was hypothesized that sRPE would accurately represent internal TL during training sessions within Canadian football. The data presented here confirm this hypothesis. However, a refinement of this method may be required in order for sRPE to truly reflect the physical stress placed on players during a competitive game. Anecdotal evidence from two seasons’ worth of sRPE monitoring (Fig. 3-2A & 3-2B) suggests that the stress imposed on each individual by a competitive game may not be truly reflected by the sRPE method. Players may over, or in some cases, under-estimate intensity depending on position played, tactical involvement, time of possession, number of plays, tackles made or received during a game. On several occasions post-game players stated that the FMB scale should be extended beyond 10 (Maximal) or another scale used to represent the pain and discomfort experienced at “game intensity”. Indeed, a recent review on the use of RPE within sport outlines that Borg’s Category-Ratio (CR-10) scale, which is often erroneously referenced in sRPE studies, permits numerical values beyond 10 while the FMB scale does not (11). By acknowledging the possibility of beyond maximal efforts and accepting RPE values of 11, 12 or even 13, the CR-10 scale (5) may therefore be more representative of the magnitude of exertion experienced during competitive football games. Due to the constraints of acquiring HR data

during competitive games, the current investigation did not include competitive game HR-based TL but acknowledges the importance of further research in this area.

3-5-1. Practical Application

Optimizing performance begins with knowing what an athlete is currently doing. As such, sRPE represents an inexpensive, non-invasive and highly practical internal TL monitoring tool that can be utilized by all Canadian football players who, due to the combative nature of the sport, may be reluctant to wear HR monitors. The practical implications of such a tool are extensive with an almost limitless number of questions relating to individual responses to collision-based training or competitive stress. In North America the number of participants in football at both ends of the health to high performance spectrum is considerable. Moreover, when extrapolating the potential findings to all collision-based sports (e.g. Rugby, Lacrosse or Ice Hockey), the application of this monitoring tool can impact and benefit a large proportion of the international health and sporting community. For example, using sRPE to quantify internal TL can help in educating parents and grass-root coaches in the intricacies of training plans and recovery strategies. Additionally, by providing evidence and increasing awareness of individual responses to collision-based physical stimulus, sRPE data can help maximize physical development in the youth and elite while minimizing overtraining, illness and injury across the board. Concussion injuries are particularly poignant currently within football along with concerns surrounding the long term health effects that repeat incidence may have on an individual. In this case, application of the sRPE method can not only aid the careful management of players back to full training but also provide a valuable tool to begin investigating the relationship between fatigue and concussion incidents.

Even at the higher echelons of professional collision sports, any form of training, performance, recovery modalities or rehabilitation interventions can be investigated with accurate determination of internal TL. Again it is the simplicity of sRPE that lends itself well to all high performance environments. By forwarding sRPE research this project will also have a far reaching impact on all areas of sport sciences targeting elite athletic preparation.

3-6. REFERENCES

1. Achten, J and Jeukendrup, AE. Heart rate monitoring: applications and limitations. *Sports Med* 33: 517-538, 2003.
2. Bangsbo, J. The physiology of soccer: with special reference to intense intermittent exercise. *Acta Physiol. Scand. Suppl* 619: 1-155, 1994.
3. Banister, E. *Modeling elite athletic performance*. In: Physiological Testing of the High-Performance Athlete. MacDougall, JW. Champaign, IL: Human Kinetics, 1991. pp. 403-424.
4. Bompa, TO. *Periodization: Theory and Methodology of Training*. Windsor. ON. Human Kinetics, 1999.
5. Borg, GAV, Hassmen P, and Langerstrom, M. Perceived exertion in relation to heart rate and blood lactate during arm and leg exercise. *Eur J Appl Physiol* 65: 679-685, 1985.
6. Busso, T, Denis, C, Bonnefoy, R, Geysant, A, and Lacour, JR. Modelling of adaptations to physical training by using a recursive least squares algorithm. *J Appl Physiol* 82: 1685-1693, 1997.
7. Coutts, AJ, Murphy, A, Pine, M, Reaburn, P, and Impellizzeri, F. Validity of the session-RPE method for determining training load in team sport athletes. *J Sci Med Sport* 6: 525-535, 2003.
8. Day, ML, McGuigan, MR, Brice, G, and Foster C. Monitoring exercise intensity during resistance training using the session-RPE scale. *J Strength Cond Res* 18: 353-358, 2004.
9. Drust, B, Reilly, T, and Cable, NT. Physiological responses to laboratory-based soccer-specific intermittent and continuous exercise. *J Sports Sci* 18: 885-892, 2000.
10. Edwards, S. *High performance training and racing*. In: The Heart Rate Monitor Book. Edwards, S. Sacramento, CA: Feet Fleet Press, 1993. pp. 113-123.
11. Eston, R. Use of Ratings of Perceived Exertion in Sports. *Int J Sports Physiol Perform* 7: 175-182, 2012.
12. Foster, C. Monitoring training in athletes with reference to overtraining syndrome. *Med Sci Sports Exerc* 30: 1164-1168, 1998.
13. Foster, C, Florhaug, JA, Franklin, J, Gottschall, L, Hrovatin, LA, Parker, S, Doleshal, P, and Dodge, C. A New Approach to Monitoring Exercise Training. *J Strength Cond Res* 15(1): 109-115, 2001.
14. Gabbett, T, King, T, and Jenkins, D. Applied physiology of rugby league. *Sports Med* 38(2): 119-138, 2008.
15. Hoffman, JR, Maresh, CM, Newton, RU, Rubin, MR, French, DN, Volek, JS, Sutherland, J, Robertson, M, Gomez, AL, Ratamess, NA, Kang, J, and Kraemer, WJ. Performance, biochemical, and endocrine changes during a competitive football game. *Med Sci Sports Exerc* 1845-1853, 2002.
16. Impellizzeri, FM, Rampinini, E, Coutts, AJ, Sassi, A, and Marcora, SM. The use of RPE-based training load in soccer. *Med Sci Sports Exerc* 36: 1042-1047, 2004.

17. Lockie, RG, Murphy, AJ, Scott, BR, and Janse de Jonge, XA. Quantifying Session Ratings of Perceived Exertion for Field-Based Speed Training Methods in Team Sport Athletes. *J Strength Cond Res* 26(10): 2721-2728, 2012.
18. Lovell, T, Sirotic, AC, Impellizzeri, FM, and Coutts, AJ. Affecting Perception of Effort (session-RPE) During Rugby League Training. *Int J Sports Physiol Perform* [Epub ahead of print], 2012.
19. Martin, DT, and Anderson, MB. Heart rate-perceived exertion relationship during training and taper. *J Sports Med Phys Fitness* 40: 201–208, 2000.
20. McLean, BD, Coutts, AJ, Kelly, V, McGuigan, MR, and Cormack, SJ. Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *Int J Sports Physiol Perform* 5(3): 367-83, 2010.
21. Meeusen, R, Duclos, M, Gleeson, M, Rietjens, G, Steinacker J, and Urhausen, A. Prevention, diagnosis and treatment of the Overtraining Syndrome. *Eur J Sport Sci* 6(1): 1-14, 2006.
22. Morgan, WP. Psychological components of effort sense. *Med Sci Sports Exerc* 26: 1071–1077, 1994.
23. Nissila, J, and Kinnunen, H. Heart Rate based Training Load and Recovery Time estimation. Polar Electro Oy. 2008.
24. Rhea, MR, Hunter, RL, and Hunter, TJ. Competition modeling of American football: observational data and implications for high school, collegiate, and professional player conditioning. *J Strength Cond Res* 20(1): 58-61, 2006.
25. Smith, D. A framework for understanding the training process leading to elite performance. *Sports Med* 33: 1103-1126, 2003.
26. Synder, AC, Jeukendrup, AE, Heeslink, MK, Kuipers, H, and Foster, C. A physiological/psychological indicator of overreaching during intensive training. *Int J Sports Med* 14: 29–32, 1993.
27. Viru, A, and Viru, M. *Nature of training effects*. In: Exercise and Sport Science. Kirkendall, WG. Philadelphia: Lippincott Williams and Wilkins, 2000. pp. 67-95.
28. Wallace, LK, Slattery, KN, and Coutts, AJ. The Ecological Validity and Application of the Session-RPE Method for Quantifying Training Loads in Swimming. *J Strength Cond Res* 23(1): 33-38, 2009.

THESIS TRANSITION

While the sRPE study in Chapter III was underway, a season long countermovement (CMJ) pilot study ran in parallel as to gain more interpretive jump data and to familiarize the players with regular functional performance testing. During this pilot it became very apparent that in order to regularly monitor football players a submaximal NMF test was needed as a large number of missing data points occurred due to minor injuries (sprains, strains and bruising). Based on this need, Chapter IV introduces a novel approach to monitoring NMF in collision-based sports with the examination of fatigued induced changes in postural sway following a Canadian football game simulation.

Chapter IV - Clarke, N, Farthing, JP, Lanovaz, JL, and Krentz, JR. Direct and indirect measurement of neuromuscular fatigue in Canadian football players. *Appl Physiol Nutr Metabol* 40(5); 464-473, 2015.

Author's roles: *Study Design:* NC, and JF. *Study conduct:* NC and JF. *Data collection:* NC and JK. *Data Analysis:* JL, NC and JF. *Drafting manuscript:* NC. *Revising manuscript content:* NC and JF. *Approving final version of manuscript:* All authors.

CHAPTER IV

DIRECT & INDIRECT MEASUREMENT OF NEUROMUSCULAR FATIGUE IN CANADIAN FOOTBALL PLAYERS

4-1. ABSTRACT

By assessing the effects of a fatiguing game simulation (G-Sim) on the balance of collegiate Canadian football players the purpose of this study was to evaluate postural control as a potential tool for monitoring neuromuscular fatigue (NMF) in collision-based team sports. Fifteen male Canadian Football players were recruited (mean \pm SD: age 21.8 ± 1.6 years, weight 97.6 ± 14.7 kg). Indirect NMF measures (postural sway and countermovement jump [CMJ]) were performed 24 hours before (T_{Base}), immediately before (T_{Pre}), as well as immediately (T_{Post}), 24 hours (T_{24}) and 48 hours after (T_{48}) a Canadian football G-Sim. Peak isometric knee extensor torque of a maximal voluntary contraction (MVC) and electrically evoked tetani at 20Hz (P20) and 80Hz (P80) were also collected as direct NMF measures at T_{Base} , T_{Pre} , T_{Post} , and T_{48} . Significant declines in MVC, P20 and MVC/P80 ratio were observed at T_{Post} (-15.3%, -15.7% and -12.1%; $n = 12$), along with reductions in CMJ takeoff velocity and peak power (-6.9% and -6.5%; $n = 12$) and larger area of the center of pressure trajectory (95.2%; $n = 10$) during a 60s postural sway task. All variables were no longer different than baseline by T_{48} . Acute neuromuscular impairment in this cohort is likely attributed to alterations in excitation-contraction coupling due to structural damage and central activation failure. Congruency between the direct and indirect measures of NMF suggests monitoring postural sway has the potential to identify both the neuromuscular and somatosensory alterations induced by acute game-induced fatigue in collision-based team sport players.

4-2. INTRODUCTION

Neuromuscular fatigue is defined as a transient failure to maintain or develop an expected force or power resulting in diminished performance (14). The magnitude of this performance impairment

differs according to the muscular group utilized; muscle action involved as well as exercise intensity and duration (27). Therefore, the contributions from both central and peripheral factors to patterns of fatigue are highly complex and sport specific, where interactions between central (e.g., impaired descending neural drive) and peripheral (e.g., impaired excitation-contraction coupling) fatigue mechanisms are difficult to distinguish (15). As high intensity collision-based team sports are characterized by violent and erratic repeated impact, understanding the factors contributing to practice and match-induced fatigue are fraught with difficulty. While the importance of monitoring and maintaining the balance between adaptation and recovery in these sports is vital, the combative nature and unpredictable stress imposed on each individual presents a unique challenge not only to monitoring but also interpreting neuromuscular fatigue (NMF) measures.

While limited in both American and Canadian football, investigations of competitive match play from rugby league (22,23) and Australian rules football (10) has provided excellent support for the use of the CMJ as a NMF monitoring measure in collision-based team sports. Significant correlations between post-match CMJ performance reduction and the number of heavy impacts a player receives during a rugby league match have been recently reported (22). Undoubtedly therefore, monitoring CMJ is a valuable tool to the sport scientist and coach of team sports athletes who are exposed to frequent collisions. However, when considering the high injury rates within collision-based team sports (36.8 to 53.6 injuries per 1000 hours of athlete exposure (A-E) to rugby and American football games respectively [11,17]) compared with other team sports such as soccer (18.4 injuries per 1000 hours of A-E to matches [1]), the likelihood and practicality of being able to regularly use maximal CMJ protocols to assess neuromuscular function is far from ideal, particularly in professional settings. A need for an alternative and less taxing NMF monitoring tool is therefore evident.

A potential solution to practical NMF monitoring in collision-based team sports may be the assessment of postural sway. While postural stability is not directly related to the stretch-shortening cycle (SSC) or performance, any decrease in the ability to control posture may be representative of impairment of neuromuscular control as it is known that fatigue modifies the peripheral proprioceptive system (35). This hypothesis is partly supported by a number of studies that have examined changes in static postural control after different fatigue protocols in non-

athletic but healthy populations. Most of the studies reported a significant increase in postural sway after localized (38) and whole-body fatigue (22,42). While inconsistent results in athletic populations have been reported (5,30,35,43) all those studies using either actual match or simulating game exercise report a fatigue related reduction in postural stability. Furthermore, numerous reports have attributed fatigue-related changes in neuromuscular control and dynamic stability to injuries sustained by soccer and ice hockey players during the last third of practice or matches (18,31). Most importantly, static balance tasks are neither taxing nor likely to be hampered by minor injuries and therefore can be administered more regularly than maximal tests including immediately post game.

Based on this body of evidence we hypothesize that postural sway will be sensitive to acute simulated football game induced fatigue and that monitoring this variable may help decrease the high injury rates in collision-based team sports by presenting early warning signs of impaired neuromuscular control. By assessing the effect of simulated game-induced fatigue on the balance of collegiate Canadian football players the primary purpose of this study was to evaluate postural sway as a potential alternative or supplementary tool for monitoring NMF in collision-based team sports.

4-3. METHODS

4-3-1. Experimental Approach to the Problem

Pilot Study. Countermovement jump and postural sway data were collected weekly on the University of Saskatchewan's football team travelling roster ($n = 44$) during the entire 2011 (Aug-Dec) Canadian Interuniversity (CIS) competitive football season. Due to the inclusion of vertical jump in the team's pre-season (May-Jul 2011) test battery participants were highly familiar with CMJ trials; however, a learning effect was seen with postural sway within the first month of testing. Therefore, this pilot study was seen as a pre-existing solution to any learning effects associated with postural sway during the current study which was completed during the 2012 pre-season (May-Jul) to minimise deterioration of task familiarity.

Current study. Fifteen participants who completed the 2011 season long pilot study were recruited for the current study. All participants performed a set of direct and indirect measures of NMF before and after a single bout of high intensity Game Simulation (G-Sim) exercise designed to replicate the physiological demands of a Canadian football game. By comparing these measures this study aimed not only to validate and introduce a less taxing and more practical neural fatigue test for collision-based team sports but also to elucidate potential contributing central and peripheral mechanisms to simulated game-induced fatigue in high performance Canadian football players.

4-3-2. Participants

Fifteen well-trained male Canadian football players (mean \pm SD: age 21.8 ± 1.6 years, weight 97.6 ± 14.7 kg, height 187.2 ± 5.2 cm) volunteered to participate in this study. All participants were recruited from the competitive roster of the 2011 University of Saskatchewan (U of S) Canadian football team. This cohort was confidently defined as a ‘high performance’ due to the rigorous competitive roster inclusion criteria that was based on subjective observations of an experienced coaching staff during numerous sport specific performance and selection camps. Participants represented all positions within football excluding kickers and had at least 4 years of football training history and 2 years of competitive experience at the CIS level. Prior to the commencement of the study, all participants were made aware of the risks and benefits associated with participation before providing written consent according to the American College of Sports Medicine guidelines, which conform to the Declaration of Helsinki. Ethical approval was obtained from the U of S Biomedical Research Ethics Board.

4-3-3. Experimental Design

Data collection occurred during the team’s 2012 pre-season (May-Jul) training. In order to avoid disrupting preparation for the new season testing was scheduled in accordance with a planned transition week in training. Weekly training load (TL) was controlled as best as possible by providing all participants with identical 7-day training program and schedule. As participants were all well educated in recovery strategies, no specific instructions in this regard were given. Participants were asked to maintain the team’s current off-season strategies that included an active recovery, stretching, hydration and good nutritional choices. No cold tub immersion techniques

were used. Average weekly physical training during the 4 month pre-season period prior to study participation was 12.5 ± 3.2 hours per week which included football specific practices, resistance training, speed and agility training as well as similar G-Sim bouts for conditioning.

During the scheduled testing week participants were asked to attend 4 lab sessions which involved a total of 5 test time points (T_{Base} , T_{Pre} , T_{Post} , T_{24} and T_{48}). The first visit to the lab (T_{Base}) was designated for familiarizing the participants with the maximal effort strength and all neural fatigue tasks in order to alleviate any learning effects of the testing procedures. During the second visit participants completed the G-Sim preceded (T_{Pre}) and followed (T_{Post}) by all direct and indirect neuromuscular tests (Fig. 4-1). In order to aid recovery it was decided that only indirect measures would be collected during the third lab visit which occurred 24 hours after the G-Sim (T_{24}). On the final visit, 48 hours post G-Sim (T_{48}), participants completed all direct and indirect neuromuscular tests once again. On arrival for all lab visits and prior to any testing, participants performed a standardized 20 minute warm-up which included 12 minutes jogging followed by 8 minutes of dynamic movements. All testing sessions began at the same time of day.

4-3-4. High Intensity Game Simulation

The high intensity G-Sim bout was designed based on football game analysis (34) as well as heart rate (HR) responses collected during Canadian football training and game play in the 2011 CIS Season (9-*Ch.III*). The session utilized 4 quarters of 12 to 18 high intensity exercise stations (plays). Each station combined a 5 yard shuttle sprint with an explosive upper body, agility or whole body movement designed to mimic those found within football. Stations were initiated by a whistle and a varying rolling clock was used to imitate work to rest intervals composite with a game (34). For example, each station was designed to be completed within 5 to 15s with a maximal effort. This being the case, if a 60s rolling clock was used and a participant completed the station in 10s, then they received 50s rest prior to the start of the next station. During this recovery period they were required to walk to the start of the next station (maximum distance 5 to 10 metres). Rolling clocks, and hence recovery, varied along with the number of stations (plays) per quarter to imitate the variability of high intensity activity executed during actual game and training scenarios. In each quarter, the last station was always a shuttle sprint consisting of 8 changes of direction and 300 yards in total distance. Three minutes rest was given between the first and

second quarter, 6 minutes between halves, and a further 3 minutes between the third and fourth quarter.

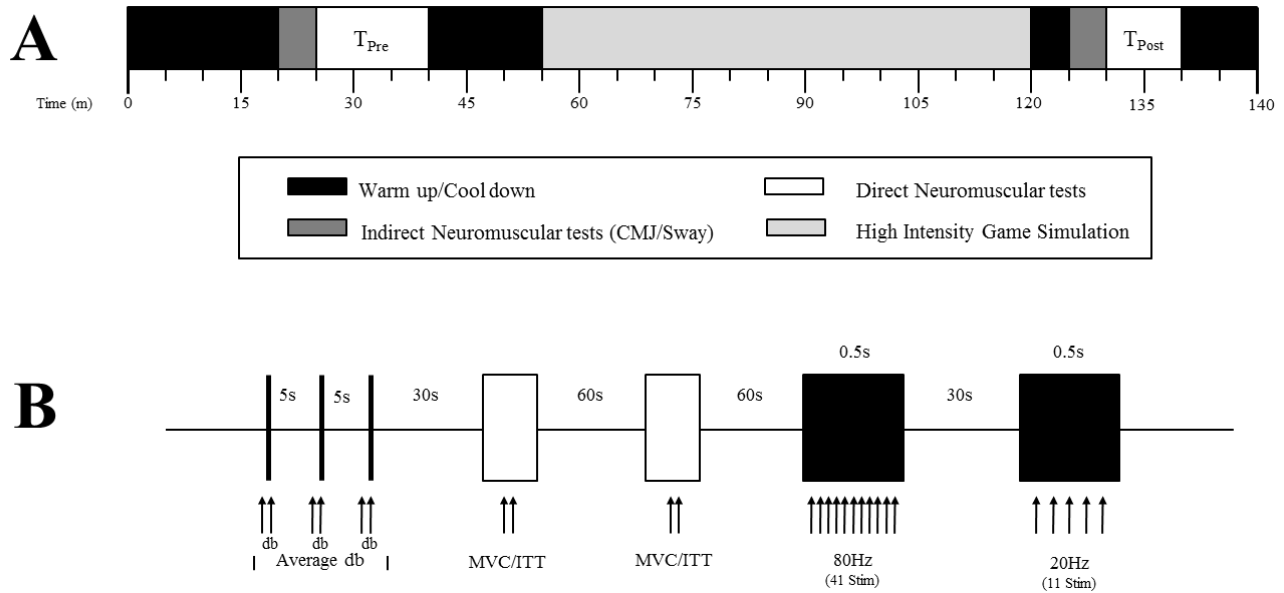


Figure 4-1. **A)** Experimental set-up for day of Game simulation. Set-up for all other testing sessions was identical but ended after the first direct neuromuscular tests (e.g. 40 mins in length). **B)** Direct neuromuscular test set-up. MVC = Maximal Voluntary Contraction; ITT = Interpolated Twitch Technique; db = Doublet; CMJ = Countermovement Jump; T_{Pre}/T_{Post} = test immediately before/after game simulation.

4-3-5. Exercise Characteristics

Session-Ratings of Perceived Exertion. Using Foster’s Modified Borg Scale (9-Ch.III,12) each participant’s rating of perceived exertion (RPE) was collected verbally approximately 30 minutes after completion of G-Sim. This timing ensured that the perceived effort be reflective of the entire session rather than the most recent exercise intensity. In accordance with Foster et al. (12), an arbitrary unit that represents each individual participant’s internal TL was then calculated by multiplying the G-Sim duration (minutes) by training intensity (RPE value retrospectively indicated).

Training Impulse. On arrival for the second lab visit (45 minutes prior to G-Sim) each participant was fitted with a HR monitor on the chest in accordance with the manufacturer's guidelines (Polar® Team2 Pro, VantageNV, Polar® Electro, Kempele, Finland). To avoid interference each monitor consisted of an individually coded transmitter and HR was recorded every 3s during the G-Sim. Once testing was complete HR data was saved on a portable PC and using the specific Polar® Team2 software TL was automatically calculated in the form of Polar Training Impulse (TRIMP). This calculation incorporated Banister's original TRIMP formula in a tailored recovery estimation model (29). Data was subsequently exported and analyzed further using Excel (Microsoft Corporation, U.S.).

Heart Rate Maximum. Similar G-Sim bouts were a regular occurrence within the U of S Football 2012 off-season training program. As part of the team's on-going TL monitoring all participants wore HR monitors during these sessions. This data was used to obtain a G-Sim relative heart rate maximum (HRmax). To clarify, an average of the highest HR measured during all G-Sim bouts completed during the 3 weeks prior to study commencement was used as maximum reference value. Those participants not achieving a HR within 5% of HRmax were not included in the results.

4-3-6. Direct Neuromuscular Fatigue Measures

Right knee extensor (KE) function was measured by four dependent variables to directly assess NMF. Due to the supramaximal and somewhat invasive nature, and to minimize participant burden and avoid adverse effects on recovery, direct measures were only measured at 4 time points (T_{Base} , T_{Pre} , T_{Post} , and T_{48}).

Maximal Isometric Torque. The primary outcome measure was maximal voluntary contraction (MVC). An isometric MVC of the KE muscles was completed on a Humac NORM isokinetic dynamometer to assess changes in strength after the G-Sim. Participants were placed in a seated position and trunk–thigh angle was set at 90°. Upper body movements were limited by two crossover shoulder harnesses and a belt across the waist. Once the knee flexion–extension axis was aligned with dynamometer axis, the lever arm attachment was secured to the shank with a strap. Knee angle was fixed at 80 ° of flexion (0 ° corresponding to full knee extension). At each time point participants performed two 4s MVC of the KE muscles with a 1 min rest period between

the two trials (Fig. 4-1.). Verbal encouragement was given during every trial and the contraction with highest peak torque was used for further analysis.

Electrically evoked contractions. A Digitimer Constant Current High Voltage Stimulator (Model DS7AH, Hertfordshire, England) was used to supramaximally activate the KE muscles. Activation of the KE muscles was achieved through stimulation of the femoral nerve using two circular electrodes (Medicompex, Ecublens, Switzerland), 50 cm² (10 cm x 5 cm). The cathode electrode was manually pressed into the femoral triangle by the experimenter while the anode was located opposite in the gluteal crease. Electrode positioning was marked on the skin in order to ensure repeatability of stimulations across all time points. Prior to the MVCs, a series of resting control twitches (0.5ms rectangular pulses) were used to determine the current (milliamps - mA) required to reach maximum resting twitch torque. Starting with a very low level of current, barely detectable by the participant, the intensity was raised progressively (10 mA increment) until a plateau in twitch force occurred as detected by the dynamometer. The current used to deliver the maximum twitch torque, plus an additional 20% was maintained for the rest of the testing session to ensure supramaximal stimulation of the nerve.

Individual optimal maximum twitch torque intensity (supramaximal current) was re-assessed on every new visit to the lab. The current needed to recruit all quadriceps motor units maximally and synchronously ranged from 80–200 mA. Three paired stimuli (12.5 ms apart; 0.5ms pulse duration); each separated by a 5 s interval, were delivered to the resting KE muscles prior to the MVCs and then averaged to calculate peak twitch torque (PT).

Voluntary muscle activation. Maximal voluntary activation (VA) was estimated using the interpolated-twitch technique (ITT [3,14]) during the KE MVCs described above. Using the same supramaximal current identified during PT assessment, an electrically evoked paired stimulus was manually triggered both at the peak of an MVC (superimposed twitch) and again at 5 seconds after MVC (control twitch). The ratio of the amplitude of the superimposed twitch over the size of the evoked control twitch in the relaxed muscle was then used to calculate the estimated level of VA (Eq. 4-1).

$$\% \text{ Voluntary Activation} = \left(1 - \frac{\text{superimposed twitch}}{\text{control twitch}} \right) \times 100$$

[Equation 4-1]

High and Low Frequency Fatigue. As a single twitch may not be considered a good indicator of peripheral fatigue (27), two sustained stimuli of 0.5s were delivered in order to quantify high and low frequency fatigue measures. These tetanic stimulations were evoked on relaxed muscle after the MVCs at frequencies of 80 and 20Hz (e.g., 40 and 10 stimuli delivered in a train, respectively; 0.5ms pulse duration). These measures allowed for a more accurate assessment of muscle contractile function (16,27). Peak torque for the two frequencies (P80 and P20, respectively) was measured and the P20/P80 ratio calculated. Another estimate of voluntary activation was provided by considering the MVC/P80 ratio (16). Custom software in LabVIEW (Version 8.6) was used to obtain stimulator pulses and torque. A desktop computer equipped with an analog-to-digital converter was used to convert the analog signals from each device to digital signals, which were displayed in LabVIEW and recorded to disk for later analysis using Excel (Microsoft Corporation, U.S.). Torque and stimulator pulse data from the Excel files was used to compute voluntary activation percent, low frequency fatigue (P20/P80 ratio), and MVC/P80 ratio using custom scripts written in MATLAB (MathWorks, Natick, MA USA).

4-3-7. Indirect Neuromuscular Fatigue Measures

During each time point (T_{Base} , T_{Pre} , T_{Post} , T_{24} and T_{48}) and prior to any direct NMF measures, three maximal CMJs were performed followed by a 60s postural sway task. Athletic footwear was required for the CMJ but participants stood barefoot for postural tests. Both tasks were performed on a Bertec Na4060-10 force platform using the specific experimental protocol shown below. The force platform utilized a Bertec Amplifier Model Am6800 set at a gain of 2 and frequency of 1000Hz for CMJ and a gain of 5 and frequency of 2000Hz for postural sway. Calculations for take-off velocity (TOV), peak power (PP), and peak vertical force (PF), and postural sway parameters were completed using custom scripts in MATLAB (MathWorks, Natick, MA USA).

Countermovement Jump. Participants were instructed to fix hands on their hips and jump as high as possible with no directions regarding speed or depth. The trial with the greatest TOV was used in the data analysis as this was considered the performance measure. Peak vertical force was obtained from the ground reaction force (GRF) data. Integration of the GRF data, combined with body mass, allowed calculation of the vertical velocity profile which was used to obtain TOV. The

velocity data were combined with the GRF data to obtain PP. Jump initiation was defined as the point where the force-curve dropped below a threshold of 2.5% bodyweight at the start of the counter-movement and take-off was calculated when the force dropped to zero (25).

Postural Sway Assessment. The Romberg-sharpened task was adopted in order to assess postural sway (37). Participants were instructed to position the heel of the non-dominant foot in front of the toe of the dominant foot leaving no space between the feet. The arms were stabilized by placing the hands on the hips with the elbows flexed at approximately 100°. Each participant was provided a short time period (between 2-5 minutes) for re-familiarization with the required posture as all participants had taken part in our pilot study. Data recording started once the participant was stable in the requested position and lasted 65s. Participants were instructed to look straight ahead, stand on the force platform as still as possible and close their eyes after 5s had elapsed, cued visually by the experimenter. Data from the first 5s of the task were discarded and only the last 60s analyzed. Environmental auditory distractions were nullified throughout the task by providing the participants with noise cancelling headphones which also streamed white noise.

The Anterior/Posterior (A/P) and Medio/Lateral (M/L) displacement (mm) of the Center of Pressure (CoP) was determined from the GRF. Oscillations of CoP along the A/P (x) and M/L (y) axis were used to quantify postural sway through examination of peak-to-peak amplitude (CoP_{x/y}) and standard deviation (CoP_{SDx/y} [37]). As these parameters are considered representative of the total trajectory around the median position (36), the CoP_{x/y} values were also converted into an area (CoP_A) using equation 4-2. In order to reduce the high variability due to initial balance adjustments and any short duration extreme excursions of the CoP, the CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Therefore the adjusted CoP data included 95% of the original data points.

$$CoP_A = \pi \left(\frac{CoP_y}{2} \right) \left(\frac{CoP_x}{2} \right)$$

[Equation 4-2]

4-3-8. Reliability

Test-retest reliability of direct and indirect variables was assessed between T_{Base} and T_{Pre} for all 15 participants using the intra-class correlation coefficient (ICC) and technical error of the

measurement (TEM). In addition, percent change from T_{Base} was calculated and a one sample t-test ran against zero to provided additional assurance of baseline data accuracy (Table 4-1). In line with previous literature (8), all direct measures showed moderate to good reproducibility with ICCs ranging from 0.67 to 0.99 and TEM from 6.3% to 13.2%. Good reliability was also shown with the three CMJ variables (ICC $r = 0.77$ to $.98$; TEM = 5.1 to 5.7%). Analyzing reliability of the sway parameters with the filtered amplitudes contenting 95% of the original data points provided moderate to good reproducibility (ICC = 0.73 to $.99$; TEM =12.1 to 20.5%). Although TEM ranges of sway variables are still relatively large compared with other measures, they reflect the reported minimum difference of 10-30% necessary to depict a measurable change in a postural sway (4). One sample t-tests revealed that all direct and indirect variables were not significantly different from zero ($P < 0.05$) when converted into percent change with T_{Base} set as baseline.

4-3-9. Statistical Analyses

All data are expressed as means \pm SD (text and tables) and means \pm SE (figures). Percent change from T_{Base} was calculated and one-way repeated measures analysis of variance (ANOVA) was utilized to analyze data for all dependent variables. For the direct measures of NMF, the one-way ANOVA was conducted using 3 time points (T_{Pre} , T_{Post} and T_{48}) whereas for indirect measures 4 time points were used in the ANOVA (T_{Pre} , T_{Post} , T_{24} and T_{48}). The assumption of sphericity was explored and controlled for all variables using the Greenhouse-Geisser adjustment where appropriate. Alpha for omnibus ANOVA tests was set at $P < 0.05$ and effect size was calculated using partial eta squared (η_p^2). When significant main effects were found, alpha adjusted post hoc testing followed. Post hoc multiple comparisons tests were based on the trends in the data. A maximum of three comparisons were conducted for each variable, therefore an adjusted alpha level of $P < 0.016$ was used for these comparisons to minimize inflation of Type I error. For direct measures, multiple comparisons were: T_{Pre} vs. T_{Post} ; T_{Post} vs. T_{48} and T_{Pre} vs. T_{48} . For indirect measures, the comparisons were: T_{Pre} vs. T_{Post} ; T_{Pre} vs. T_{24} and T_{Pre} vs. T_{48} . All analyses were conducted using IBM SPSS version 20.

Sample size estimates indicated a range of 3-15 participants was needed to detect a minimum expected change of 10%, at 80% power and alpha = 0.05 for all direct measures and CMJ variables. For postural sway, higher variability meant that a minimum expected change of

40% was used to account for the higher TEM. In this case, the required n was estimated at 13 for 80% power and $\alpha = 0.05$.

Table 4-1. Test-retest reliability of direct and indirect variables assessed using time points 24 hours before (T_{Base}) and immediately before (T_{Pre}) game simulation. All 15 participants data was analyzed using the intra-class correlation coefficient (ICC), technical error of the measurement (TEM), and a one sample t-test of percent change from T_{Base} ran against zero.

Postural Sway	CoP_x (mm)	CoP_y (mm)	CoP_{SDx} (mm)	CoP_{SDy} (mm)	CoP_A (mm²)	
T_{Base}	38.1±11.1	26.9±9.5	9.7±3.0	6.9±2.7	884.7±593.1	
T_{Pre}	38.9±13.9	25.7±7.5	9.9±3.6	6.6±1.9	851.9±516.6	
Change (%)	0.8±8.3	-2.8±12.9	2.1±8.3	-2.5±13.2	-2.7±8.8	
t -test (p)	0.758	0.511	0.442	0.569	0.347	
ICC range	0.91 - 0.99	0.73 - 0.99	0.91 - 0.99	0.73 - 0.98	0.94 - 0.99	
TEM (%)	12.1	20.5	12.3	21.7	15.1	
CMJ	TOV (m/s)	PP (W)	PF (Nm)			
T_{Base}	2.98±0.19	5638.1±1011.1	2472.2±291.9			
T_{Pre}	2.99±0.22	5718.2±982.9	2515.5±312.4			
Change (%)	0.6±1.9	1.9±2.8	0.9±5.5			
t -test (p)	0.284	0.089	0.603			
ICC	0.95-0.99	0.94-0.99	0.77-0.94			
TEM (%)	4.5	5.7	9.7			
Direct Measures	MVC (Nm)	P20 (Nm)	P80 (Nm)	MVC/P80	VA (%)	PT (Nm)
T_{Base}	361.9±78.8	246.1±78.4	408.1±100.1	0.94±0.31	89.1±8.1	103.4±18.6
T_{Pre}	373.9±82.9	243.1±78.9	416.6±97.3	0.95±0.32	88.9±8.4	111.1±21.9
Change (%)	3.7±7.2	-0.31±10.2	2.5±4.7	1.4±9.4	-0.08±6.2	8.2±13.5
t -test (p)	0.121	0.919	0.106	0.662	0.964	0.067
ICC	0.91-0.99	0.80-0.98	0.96-0.99	0.94-0.99	0.67-0.97	0.63-0.95
TEM (%)	9.7	13.3	6.3	10.6	8.8	18.7

MVC = Maximal voluntary contraction; VA = Voluntary Activation; PT = Peak Twitch Torque; P20 = Peak Torque with 20Hz stimulation; P80 = Peak Torque with 80Hz stimulation; CMJ = Countermovement jump; TOV = Take-Velocity; PP = Peak Power; PF = Peak Force; CoPSD_{x/y} = Center of Pressure standard deviation along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoP_{x/y} = Center of Pressure displacement along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoPA = Area covered by CoP trajectory. CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Values are means ± SD.

4-4. RESULTS

4-4-1. Exercise Characteristics

All 15 participants completed the G-Sim achieving an average maximum HR 187.5 ± 9.3 bpm. Mean TL based on Polar TRIMP was 182.9 ± 34.9 AU and 638.2 ± 54.4 AU utilizing sRPE. Three participants failed to reach the minimum criteria for the G-Sim HR ($>95\%HR_{max}$) and were therefore excluded from further data analysis. Table 4-2 summarizes all direct and indirect measurements collected.

Table 4-2. Direct and indirect neuromuscular fatigue (NMF) measures 24 hours before (T_{Base}), immediately before (T_{Pre}), immediately (T_{Post}), 24 hours (T_{24}) and 48 hours after (T_{48}) a high intensity Canadian football game simulation.

	T_{Base}	T_{Pre}	T_{Post}	T_{24}	T_{48}
Direct NMF Measures ($n=12$)					
MVC (Nm)	361.9 ± 78.8	373.9 ± 82.9	$303.9 \pm 67.1^*$	-	374.3 ± 82.7
VA (%)	89.1 ± 8.1	88.9 ± 8.4	78.1 ± 15.3	-	90.3 ± 7.8
PT (Nm)	103.4 ± 18.6	111.1 ± 21.9	91.9 ± 21.8	-	107.5 ± 20.8
P20 (Nm)	246.1 ± 78.4	243.1 ± 78.9	$188.5 \pm 54.4^*$	-	247.5 ± 73.7
P80 (Nm)	408.1 ± 100.1	416.6 ± 97.3	381.6 ± 79.6	-	410.2 ± 96.3
P20/P80	0.60 ± 0.12	0.58 ± 0.11	0.49 ± 0.09	-	0.61 ± 0.11
MVC/P80	0.94 ± 0.31	0.95 ± 0.32	$0.84 \pm 0.31^*$	-	0.95 ± 0.27
Indirect NMF Measures					
<i>CMJ ($n=12$)</i>					
TOV (m/s)	2.98 ± 0.19	2.99 ± 0.22	$2.79 \pm 0.31^*$	2.94 ± 0.17	2.97 ± 0.19
PP (W)	5638 ± 1011	5718 ± 982.9	$5375 \pm 1221^*$	5574 ± 948.6	5648 ± 948.6
PF (N)	2472 ± 291.9	2516 ± 312.4	2439.4 ± 400.4	2441.6 ± 405.9	2413.7 ± 294.6
<i>Postural Sway ($n=10$)</i>					
CoP _{SDx}	9.7 ± 3.0	9.9 ± 3.6	$11.6 \pm 3.2^*$	10.5 ± 2.9	10.9 ± 3.8
CoP _{SDy}	6.9 ± 2.7	6.6 ± 1.9	$11.8 \pm 5.7^*$	9.1 ± 3.8	9.3 ± 4.8
CoP _x	38.1 ± 11.1	38.9 ± 13.9	$45.1 \pm 11.9^*$	41.5 ± 11.5	41.4 ± 11.4
CoP _y	26.9 ± 9.5	25.7 ± 7.5	$43.2 \pm 18.1^*$	35.2 ± 14.2	36.9 ± 19.9
CoP _A	885 ± 593	852 ± 517	$1645 \pm 1026^*$	1256 ± 838	1345 ± 1075

MVC = Maximal voluntary contraction; VA = Voluntary Activation; PT = Peak Twitch Torque; P20 = Peak Torque with 20Hz stimulation; P80 = Peak Torque with 80Hz stimulation; CMJ = Countermovement jump; TOV = Take-Velocity; PP = Peak Power; PF = Peak Force; CoPSD_{x/y} = Center of Pressure standard deviation along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoP_{x/y} = Center of Pressure displacement along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoP_A = Area covered by CoP trajectory. CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Values are means \pm SD. *significantly different from T_{Base} $p < 0.016$. Statistical analysis was based on percent change from T_{Base}

4-4-2. Direct Neuromuscular Fatigue Measures

Torque and Voluntary Activation. The one-way ANOVA for KE MVC torque ($F_{(2,22)} = 43.4$; $P < 0.05$; $\eta_p^2 = 0.84$) and the MVC/P80 ratio ($F_{(2,22)} = 8.5$; $P < 0.05$; $\eta_p^2 = 0.54$) revealed a significant effect of time. Mean KE MVC torque decreased significantly from T_{Pre} to T_{Post} ($-15.3 \pm 9.5\%$ from 373.4 ± 82.9 to 303.9 ± 67.0 Nm; $P < 0.016$) and returned to baseline within 48 hours ($n = 12$; Fig. 3-2). A similar significant decrease between T_{Pre} and T_{Post} was also demonstrated within the MVC/P80 ratio ($-12.1 \pm 11.9\%$ from 0.95 ± 0.33 to 0.85 ± 0.31 ; $P < 0.016$) before returning to baseline after 48 hours.

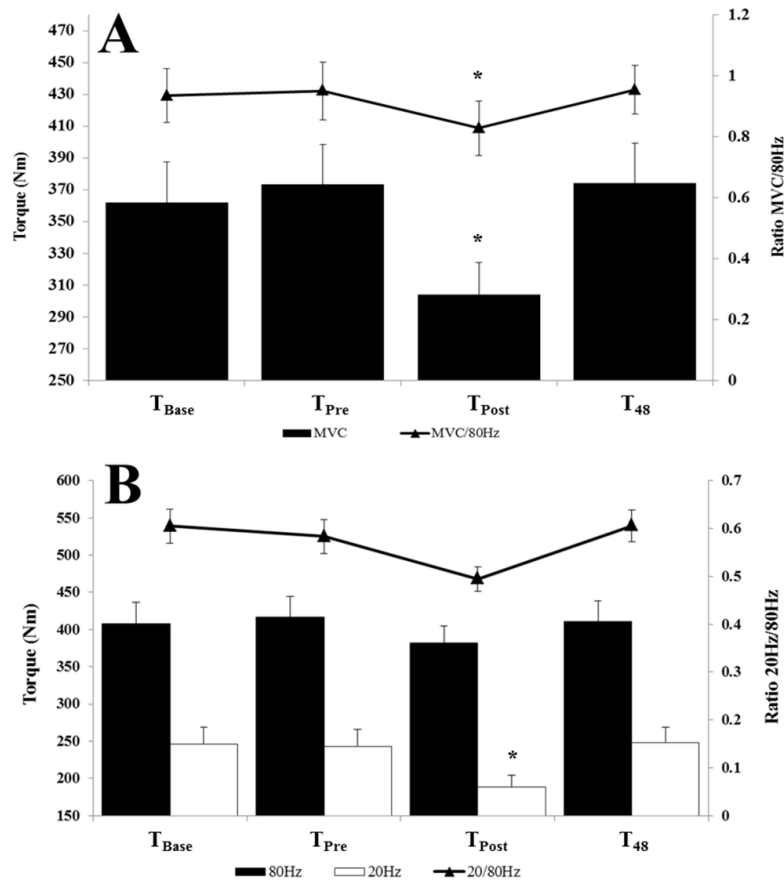


Figure 4-2. Mechanical response of A) Maximal isometric voluntary contraction (MVC) and MVC/80-Hz tetanus contraction (80Hz) ratio as well as B) 80-Hz tetanus (80Hz), 20-Hz tetanus (20Hz) and 20Hz/80Hz ratio contraction of the right knee extensor muscles 24 hours before (T_{Base}), immediately before (T_{Pre}), immediately (T_{Post}) and 48 hours after (T_{48}) a high intensity Canadian football game simulation. Values are means \pm SE. *significantly different from T_{Base} $P < 0.016$.

A significant effect of time was also seen with VA percent ($F_{(2,22)} = 7.3$; $P < 0.05$; $\eta_p^2 = 0.49$) and PT ($F_{(2,22)} = 24.2$; $P < 0.05$; $\eta_p^2 = 0.69$). Post hoc analysis revealed significant pairwise differences at $P < 0.05$; however, after alpha adjustments significance was not reached despite VA declining from $88.5 \pm 1.9\%$ at T_{Pre} to $78.1 \pm 1.9\%$ at T_{Post} ($p = 0.016$). A similar non-significant pattern was seen with PT which also diminished at T_{Post} before returning to baseline 48 hours later.

High and Low Frequency Fatigue. One-way ANOVA revealed a significant effect of time for P20 ($F_{(2, 22)} = 10.8$; $P < 0.05$; $\eta_p^2 = 0.68$) and no significant time effect for P80 ($F_{(2, 22)} = 2.6$; $p = 0.114$; $\eta_p^2 = 0.19$). Figure 2 shows that P80 remains unchanged across all time points whereas P20 decreased significantly by 15.7% post G-Sim ($-15.7 \pm 11.4\%$ from 243.1 ± 78.9 to 188.5 ± 54.4 Nm; $P < 0.016$). Accordingly, the P20/P80 ratio declined from T_{Pre} to T_{Post} but did not reach significance.

4-4-3. Indirect Neuromuscular Fatigue Measures

Countermovement Jump. A significant effect of time was shown for both TOV ($F_{(2.1, 24)} = 8.7$; $P < 0.05$; $\eta_p^2 = 0.61$) and PP ($F_{(3, 33)} = 11.2$; $P < 0.05$; $\eta_p^2 = 0.73$). No significant changes over time were seen for PF ($F_{(3,33)} = 2.1$; $P = 0.117$ $\eta_p^2 = 0.16$). Compared with baseline TOV and PP significantly declined ($6.9 \pm 6.4\%$ and $6.5 \pm 6.0\%$ respectively; $P < 0.016$) at T_{Post} . Takeoff velocity and PP gradually returned to baseline over the next 48 hours ($n = 12$; Fig. 3-3).

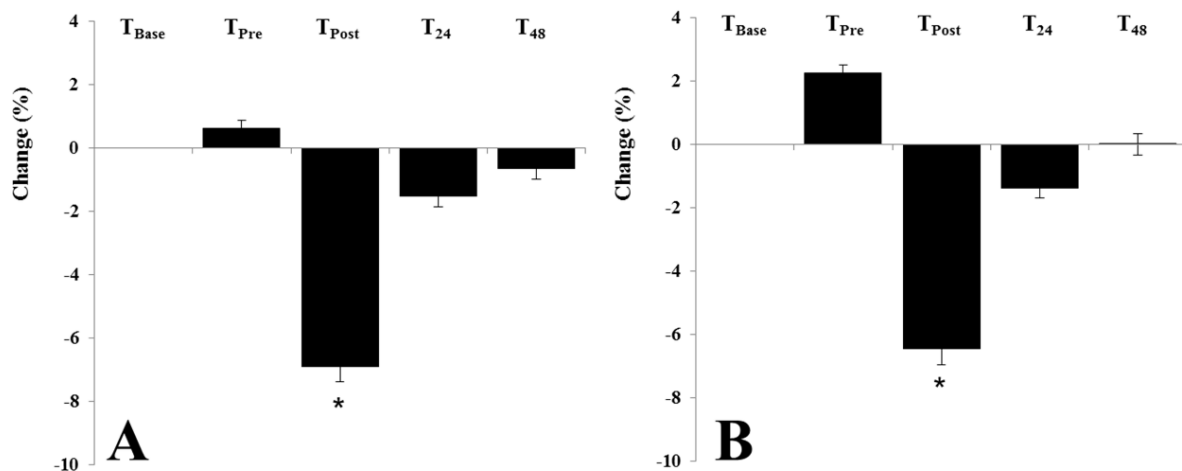


Figure 4-3. Percent change of **A**) Take-off velocity and **B**) Peak Power during execution of a maximal CMJ from 24 hours before (T_{Base}) to immediately before (T_{Pre}), immediately (T_{Post}), 24 hours (T_{24}) and 48 hours after (T_{48}) a high intensity Canadian football game simulation. Values are means \pm SE. $n = 12$. *Percent change was significantly different from T_{Base} $P < 0.016$

Postural Sway. Significant changes over time were seen in CoP_x ($F_{(3,27)} = 4.7$; $P < 0.05$; $\eta_p^2 = 0.54$), CoP_y ($F_{(1.9,17.3)} = 6.7$; $P < 0.05$; $\eta_p^2 = 0.70$), CoP_{SDx} ($F_{(3,27)} = 5.8$; $P < 0.05$; $\eta_p^2 = 0.71$), CoP_{SDy} ($F_{(1.7,15.5)} = 5.9$; $P < 0.05$; $\eta_p^2 = 0.66$), and CoP_A ($F_{(1.7,14.8)} = 7.1$; $P < 0.05$; $\eta_p^2 = 0.75$). Post Hoc analysis revealed that CoP_x and CoP_y were significantly larger at T_{Post} as well as CoP_{SDx} and CoP_{SDy} ($n = 10$). Consequently, Figure 4B shows a significant $95.1 \pm 26.4\%$ increase ($P < 0.016$) in CoP_A at T_{Post} . A significant decrease in CoP_A ($P < 0.016$) was then seen at T_{24} but values did not return to baseline within 48 hours. A representative trace of CoP changes and calculated CoP_A over all 5 time points is shown in Figure 3-4A.

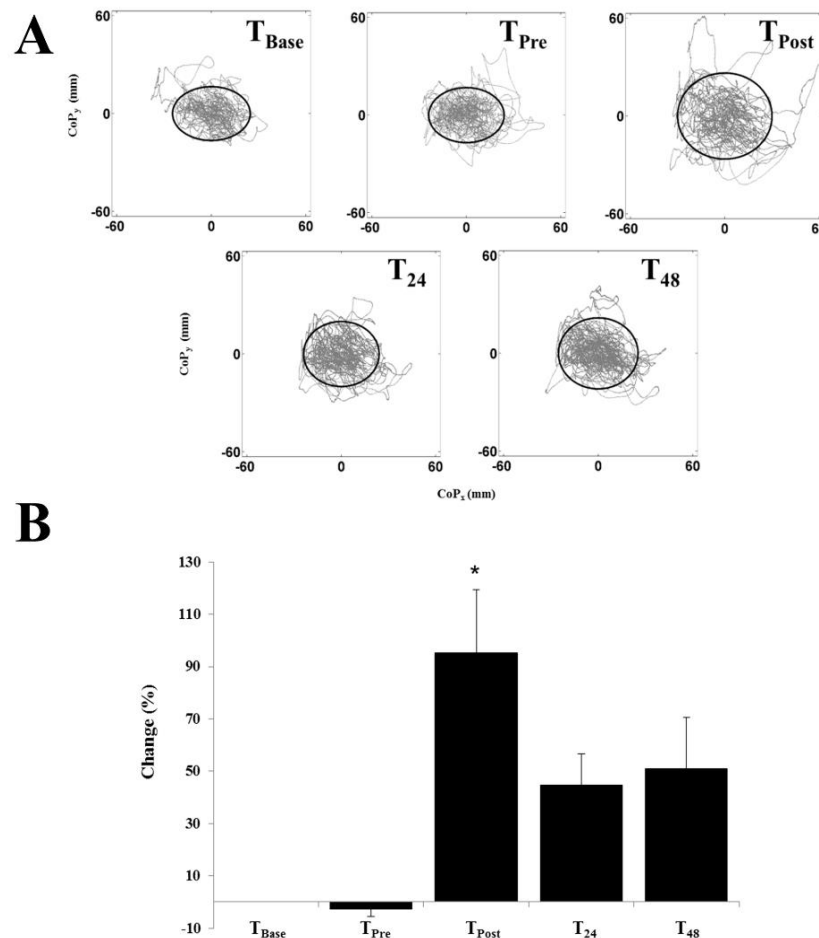


Figure 4-4. A) Representative trace of centre of pressure displacement (mm) in Anterior / Posterior (CoP_y) and Medio / Lateral (CoP_x) direction during 60 secs of the Sharpened Tandem static balance task and B) postural sway assessed by total area covered by center of pressure (CoP_A) 24 hours before (T_{Base}), immediately before (T_{Pre}), immediately (T_{Post}), 24 hours (T_{24}) and 48 hours (T_{48}) after a high intensity Canadian football game simulation. CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Therefore the adjusted CoP data included 95% of the original data points. Values are means \pm SE. $n = 10$ *Percent change was significantly different from T_{Base} $P < 0.016$.

4-5. DISCUSSION

By assessing the effects of a fatiguing G-Sim exercise bout on direct and indirect measures of NMF on collegiate Canadian football players, the primary purpose of this study was to evaluate postural control as a potential alternative or supplementary tool for monitoring NMF in collision-based team sports. The main findings revealed that G-Sim induced fatigue resulted in significant MVC and P20 torque loss in the quadriceps muscles (-15.3 and -15.7% respectively). This torque impairment was accompanied by significant reductions in TOV (-6.9%) and PP (-6.5%) of a maximal CMJ as well as significantly larger CoP_A (95.1%) during a 60s postural sway task.

4-5-1. Direct Measures: Torque reduction

To our knowledge no direct measurement of isometric MVC torque of the KE muscles has been reported after collision-based team sport match play; however, similar reductions observed in the current study have been reported following both a simulated and actual soccer match (-7 to -18.5% [2,36]), an elite handball game (-10% [40]), as well as during the time course of a tennis game (-10 to -13% [15]). The variability in torque reduction seen across these sports has been largely attributed to the role of recovery periods in limiting fatigue during high-intensity intermittent exercise (33). Despite this disparity there is a consensus that contribution from both peripheral and central neuromuscular mechanisms trigger the reduction in muscular capabilities after high-intensity intermittent sports (2,15,36,40).

Notwithstanding a significant time effect and reduction in percent VA using ITT, Bonferroni adjusted post hoc analysis revealed no significant reduction after the G-Sim. Admittedly, since we did not assess the direct measures of fatigue at 24 h we could have missed the point of greatest change in VA. However, enhanced central activation failure detection during isometric knee extension has been reported using the ratio between torques achieved with MVC and electrically-evoked contractions (MVC/P80 ratio [27]). Therefore, evidence for a central origin of fatigue-induced strength loss was apparent in our findings through the significant reduction of the MVC/P80 ratio (-12.1%) following the G-Sim. In support, central fatigue has been reported during tennis match-play which was paralleled with a progressive impairment in muscle activation and normalized electromyography (EMG) activity (15). Girard et al. (15) also reported a reduction in percent VA after the tennis match but significance was not met due to great

inter-subject variability. While the present reduction in MVC/P80 ratio emphasizes the potential role of central mechanisms in the fatigue observed within Canadian football players following a G-Sim, it remains unclear whether or not these neuromuscular alterations are caused by impairments in the higher cortical structures (supraspinal site) and/or in response to afferent inputs from metabolic changes in the muscle (spinal site) due to the limitations of these activation assessing techniques (14).

An estimate of peripheral fatigue was observed following G-Sim through detection of Low frequency fatigue (LFF). Characterized as long-lasting, LFF can be defined as a preferential decrease in the force elicited with electrical stimulations at a low frequency (P20), as compared to a high frequency (P80) [41]). Preservation of P80 throughout all time points indicated that no significant membrane excitability failure or alteration of maximum Ca^{2+} activated force occurred following the fatiguing G-Sim (15). However, the presence of LFF post G-Sim, evidenced through a significant decrease in P20, suggests a fatigue-induced reduction in Ca^{2+} release from the sarcoplasmic reticulum (SR) per action potential (6) resulting in less active cross-bridges. Attributed to structural damage to the triads (t-tubules cisternae of SR [6]) this form of compromised excitation-contraction (E-C) coupling has also been demonstrated following fatiguing plyometric (20) and eccentric (21) exercise as well as a 3h tennis match (22). Although the specific nature and purpose of movement between tennis and Canadian football differs, commonality exists in the physical demands placed on the muscles through frequent, intense and unpredictable eccentric contractions and SSC movements. Therefore, structural impairment is the most plausible explanation for the reduction in P20 (LFF) seen in Canadian footballers following the G-Sim.

4-5-2. Indirect measures

The novel aspect of the current study is that the diminished torque capabilities were allied with specific performance alterations in both a CMJ and postural sway task. Previous work examining alterations in force-power variables of maximal CMJ following collision-based team sport participation have provided conflicting results. Studies of Australian rules (10) and collegiate American football (19) suggest that players can maintain PF and PP after match play, whereas studies examining neuromuscular response to a rugby league match show significant declines in all force-power measures (22). Our study revealed a unique pattern characterized by a significant

decline in both CMJ TOV and PP immediately following the G-Sim with a preservation of PF throughout. However, in terms of force-power variable sensitivity to fatigue, our results are similar to that observed in rugby league players. McLellan et al. (24) reported that both rate of force development (RFD) and PP, after a significant decline post-match, recovered within 48 hours compared with a match-reduced PF which returned to baseline within 24 hours. The authors suggested that the velocity component of CMJ power was more sensitive to match-induced fatigue than the force component. Although the time course of PP recovery differed in our study, the preservation of PF following a fatiguing G-Sim suggests the force component of CMJ power in Canadian footballers may also be less sensitive to G-Sim fatigue than the velocity component. Different temporal recovery patterns of CMJ force-power variables between these two studies are most likely attributed to the use of a simulated game protocol versus actual competitive games.

The lack of sensitivity to fatigue of CMJ PF has been reported in previous studies investigating non-sport specific exercise (7). With this in mind, our study provides further support not only for the notion that PP of a CMJ is more sensitive to structural damage associated with high intensity exercise, but also as a consequence PP monitoring maybe more useful than PF in determining delayed recovery of the neuromuscular system in collision-based team sport athletes (22). To our knowledge the current study is the first to combine direct and indirect NMF measures in an applied setting with game-stimulated induced fatigue. Therefore, our results provide evidence that acute fatigue-induced decreases in CMJ TOV and PP can be attributed to both a less than optimal neural drive (central fatigue) and impairment of the E-C coupling mechanism (peripheral fatigue) evidenced through a reduction in MVC/P80 ratio and P20 (LFF) in Canadian football players.

One of the most promising outcomes of the current study was the significant increase in postural sway, represented by the CoP_A , after the G-Sim (~95%) indicating that neuromuscular control pathways were altered by fatigue. The negative effects of exercise-induced fatigue on the somatosensory system are well documented (35,42) and have been reported following a soccer match (5) and an elite handball game (43). A combination of match-induced decreases in strength, neuromuscular activation as well as an altered somatosensory input were proposed to contribute to the lack of postural control (5,43). With the addition of direct measures, our findings provide empirical support for these previous studies but also offer more clarity in regards to the possible

peripheral and central mechanisms responsible for the neuromuscular and somatosensory alterations seen after game-induced fatigue.

Peripheral modification of the proprioceptive system due to fatigue has been related to dysfunction of mechanoreceptors, specifically through increasing the threshold for muscle spindle discharge and consequently changing alpha/gamma co-activation (14). As muscle spindle activity is the primary contributor to joint position sense (32) any fatigue induced distribution of these receptors can negatively affect the peripheral proprioceptive system and hence postural control. The presence of LFF in our results is indicative of structural damage which, as accompanied by an inflammatory response, can disrupt the function of mechanoreceptors (35). The rapid recovery of P20 within 24 hours suggests that the microstructural damage was only minor; however, while CMJ variables return to baseline, postural instability remained elevated at 24 (44%) and 48hrs (50%) post G-Sim. While no measure of muscle soreness was collected in the present study, fatigue-induced alterations in the somatosensory system could be more sensitive to the inflammation associated with muscle damage and delayed onset of muscle soreness than those pathways involved in dynamic movements such as the CMJ.

Deleterious joint sense acuity has also been associated with diminished central processing of proprioceptive signals (35). Induced by central nervous system failure, reduced accuracy of motor control and interrupted voluntary muscle stabilizing activity has been reported after fatiguing exercise (28). While presence of central fatigue is evident in the current findings no conclusion can be made as to whether the mechanism affecting postural sway originates at the spinal or supraspinal level. However as proposed recently, evoked reflex responses (H-reflex) diminish over the time course of a 3h tennis match (16). More specifically, the fatigue-induced decreases in H-reflex amplitudes were attributed to reduced motor neuron excitability and/or increased presynaptic inhibition and thus it was concluded that the most obvious alteration in central nervous function due to a competitive tennis match originates from mechanisms at the spinal level (16). Although speculative, due the similarity in exercise characteristics, it may be plausible to suggest that mechanisms at the spinal level were major contributing factors to the detection of central fatigue in football players ultimately resulting in alterations in postural sway. While it remains impossible to determine the relative contributions of peripheral and central mechanisms, the current study suggests that alterations in both the peripheral proprioceptive

system and central processing lead to the decrease in postural stability of Canadian football players.

In line with previous studies, our results confirm that monitoring PP of a CMJ is a useful tool in identifying NMF in collision-based team sport players. In addition however, when the collection of a maximal CMJ is hampered by injury, postural sway may be an alternative, less taxing monitoring tool which is also sensitive to NMF. Indeed, combining both CMJ and postural sway monitoring may present a more comprehensive assessment of both the neuromuscular and somatosensory alterations induced by acute game simulated or match-induced fatigue. Such tools can therefore help guide the difficult balancing act between increased training load and recovery for collision-based team sport players in order to prevent overtraining or injury. For postural sway monitoring to be truly effective in professional settings further investigation into the sensitivity of CoP_A to typical TL fluctuations and accumulative fatigue associated with season-long competitive weekly cycles is warranted.

4-6. REFERENCES

1. Agel, J, Evans, T, Dick, R, Putukian, M, and Marshall, SW. Descriptive epidemiology of collegiate men's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train* 42(2): 278–285. 2007.
2. Andersson, H, Raastad, T, Nilsson, J, Paulsen, G, Garthe, I, and Kadi, F. Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. *Med Sci Sports Exerc* 40(2): 372–380, 2008.
3. Behm, D, St-Pierre, M, and Perez, D. Muscle inactivation: assessment of interpolated twitch technique. *J Appl Physiol* 81(5): 2267-2273, 1996.
4. Birmingham, TB. Test-retest reliability of lower extremity functional instability measures. *Clin J Sport Med* 10(4): 264–268, 2000.
5. Brito, J, Fontes, I, Ribeiro, F, Raposo, A, Krstrup, P, and Rebelo, A. Postural stability decreases in elite young soccer players after a competitive soccer match. *Phys Ther Sport* 13(3): 175–179, 2012.
6. Bruton, JD, Lännergren, J, and Westerblad, H. 1998. Mechanisms underlying the slow recovery of force after fatigue: importance of intracellular calcium. *Acta Physiol Scand* 162(3) 285–293, 1998.
7. Byrne, C, and Eston, R. Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions. *J Sports Sci* 20(12):951–9, 2002.
8. Cannon, J, Kay, D, Tarpenning, KM, and Marino, FE. Reproducibility and changes in twitch properties associated with age and resistance training in young and elderly women. *Scand. J Med Sci Sports* 18(5): 627–635, 2008.
9. Clarke, N, Farthing, JP, Norris, SR, Arnold, BE, and Lanovaz, JL. Quantification of training load in Canadian football: Application of Session-RPE in collision based team sports. *J Strength Cond Res* 27(8): 2198-2205, 2013.
10. Cormack, SJ, Newton, RU, McGuigan, MR, and Cormie, P. Neuromuscular and endocrine responses of elite players during an Australian rules football season. *Int J Sports Physiol Perform* 3(4): 439–453, 2008.
11. Dick, R, Ferrara, MS, Agel, J, Courson, R, Marshall, SW, Hanley, MJ, and Reifstack, F. Descriptive epidemiology of collegiate men's football injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train* 42(2): 221–233, 2007.
12. Foster, C, Florhaug, JA, Franklin, J, Gottschall, L, Hrovatin, LA, Doleshal, P, and Dodge, C. A New Approach to Monitoring Exercise Training. *J Strength Cond Res* 15(1): 109–115, 2001.
13. Fox, ZG, Mihalik, JP, Blackburn, JT, Battaglini, CL, and Guskiewicz, KM. Return of postural control to baseline after anaerobic and aerobic exercise protocols. *J Athl Train* 43(5):456-463, 2008.

14. Gandevia, SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev* 81(4): 1725–1789, 2001.
15. Girard, O, Lattier, G, Maffiuletti, NA, Micallef, J-P, and Millet, GP. Neuromuscular fatigue during a prolonged intermittent exercise: Application to tennis. *J Electromyogr Kinesiol* 18(6): 1038–1046, 2008.
16. Girard, O, Racinais, S, Micallef, J-P, and Millet, GP. Spinal modulations accompany peripheral fatigue during prolonged tennis playing. *Scand J Med Sci Sports* 21(3): 455–464, 2011.
17. Gissane, C, Jennings, D, Kerr, K, and White, J. Injury Rates in Rugby League Football : Impact of Change in Playing Season. *Am J Sports Med* 31(6): 954–958, 2003.
18. Hawkins, RD, and Fuller, CW. A prospective epidemiological study of injuries in four English professional football clubs. *Br J Sports Med* 33(3): 196–203, 1999.
19. Hoffman, JR, Maresh, CM, Newton, RU, Rubin, MR, French, DN, Volek, JS, Sutherland, J, et al. Performance, biochemical, and endocrine changes during a competitive football game. *Med Sci Sports Exerc* 34(11): 1845–1853, 2002.
20. Komi, PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech* 33(10): 1197–1206, 2000.
21. Martin, V, Millet, GY, Lattier, G, and Perrod, L. Why does knee extensor muscles torque decrease after eccentric-type exercise? *J Sports Med Phys Fitness* 45(2):143–51, 2005.
22. McLellan, CP, and Lovell, DI. Neuromuscular responses to impact and collision during elite rugby league match play. *J Strength Cond Res* 26(5): 1431–1440, 2012.
23. McLellan, CP, and Lovell, DI, and Gass, GC. Biochemical and endocrine responses to impact and collision during elite rugby league match play. *J Strength Cond Res* 25(6): 1553–1562, 2011.
24. McLellan, CP, and Lovell, DI, and Gass, GC. Markers of postmatch fatigue in Professional rugby league players. *J Strength Cond Res* 25(4):1030–1039, 2011.
25. Meylan, C, Nosaka, K, Green, J, and Cronin, J. The effect of three different start thresholds on the kinematics and kinetics of a countermovement jump. *J Strength Cond Res* 25(4): 1164–1167, 2011.
26. Miller, M, Downham, D, and Lexell, J. Superimposed single impulse and pulse train electrical stimulation: A quantitative assessment during submaximal isometric knee extension in young, healthy men. *Muscle Nerve* 22(8): 1038–1046, 1999.
27. Millet, GY, Martin, V, Lattier, G, and Ballay, Y. Mechanisms contributing to knee extensor strength loss after prolonged running exercise. *J Appl Physiol* 94(1):193–198, 2003.
28. Miura, K, Ishibashi, Y, Tsuda, E, Okamura, Y, Otsuka, H, and Toh, S. The effect of local and general fatigue on knee proprioception. *Arthroscopy* 20(4): 414–418, 2004.
29. Nissilä, J, and Kinnunen, H. Heart Rate based Training Load and Recovery Time estimation. *Polar Electro: Oy.* 1: 1-4. 2008.
30. Pau, M, Ibba, G, and Attene, G. Fatigue-induced balance impairment in young soccer players. *J Athl Train* 49(4): 454-456, 2014.

31. Pinto, M, Kuhn, JE, Greenfield, MLVH, and Hawkins, RJ. Prospective analysis of ice hockey at the Junior A level over the course of one season. *Clin J Sport Med* 9(2): 70–74, 1999.
32. Proske, U. What is the role of muscle receptors in proprioception? *Muscle Nerve* 31(6): 780–787, 2005.
33. Ratel, S, Lazaar, N, Williams, CA, Bedu, M, and Duche, P. Age differences in human skeletal muscle fatigue during high-intensity intermittent exercise. *Acta Paediatrica* 92(13): 1248–1254, 2003.
34. Rhea, MR, Hunter, RL, and Hunter, TJ. Competition modelling of American football: Observational data and implications for high school, collegiate, and professional player conditioning. *J Strength Cond Res* 20(1): 58–61, 2006.
35. Ribeiro, F, Santos, F, Gonçalves, P, and Oliveira, J. Effects of volleyball match-induced fatigue on knee joint position sense. *Eur J Sport Sci* 8(6): 397–402, 2008.
36. Robineau, J, Jouaux, T, Lacroix, M, and Babault, N. Neuromuscular fatigue induced by a 90-minute soccer game modelling. *J Strength Cond Res* 26(2): 555–562, 2012.
37. Spiliopoulou, SI, Amiridis, IG, Tsigganos, G, Economides, D, and Kellis, E. Vibration Effects on Static Balance and Strength. *Int J Sports Med* 31: 610–616, 2010.
38. Springer, BK, and Pincivero, DM. The effects of localized muscle and whole-body fatigue on single-leg balance between healthy men and women. *Gait Posture* 30(1):50–54, 2009.
39. Thompson, D, Nicholas, CW, and Williams, C. Muscular soreness following prolonged intermittent high-intensity shuttle running. *J Sports Sci* 17(5): 387–395, 1999.
40. Thorlund, JB, Michalsik, LB, Madsen, K, and Aagaard, P. Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scand J Med Sci Sports* 18(4): 462–472, 2008.
41. Vøllestad, NK. Measurement of human muscle fatigue. *J Neurosci Methods* 74(2): 219–227, 1997.
42. Vuillerme, N, and Hintzy, F. Effects of a 200 W-15 min cycling exercise on postural control during quiet standing in healthy young adults. *Eur J Appl Physiol* 100 (2): 169–175, 2007.
43. Zech, A, Steib, S, Hentschke, C, Eckhardt, H, and Pfeifer, K. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. *J Strength Cond Res* 26(4): 1162–1168, 2012.

THESIS TRANSITION

Recognizing that acute-fatiguing effects may misrepresent fatigue across extended training periods, Chapter V involves the amalgamation of the previous two studies (Chapters III & IV) over an entire Canadian football season. The primary goal was to assess postural sway as an alternative or supplementary tool for tracking NMF over extensive training and competitive periods. By concurrently collecting CMJ and TL data, the secondary aim was to examine the usefulness of CMJ in this sport specific context but also to provide further insight into the fatigue time-course response of players over a Canadian football season.

SUBMITTED FOR PUBLICATION

Chapter V - Clarke, N, Farthing, JP, Norris, SR, Arnold, BE, Chilibeck, PD, Rodgers, C, Lanovaz, JL, and Brodie, R. Novel approach to neuromuscular fatigue monitoring of a competitive collegiate season in Canadian football players.

Author's roles: *Study Design:* NC, JF, SN, PC, CR, and BA. *Study conduct:* NC, JF and BA. *Data collection:* NC. *Data Analysis:* JL, RB, NC and JF. *Drafting manuscript:* NC. *Revising manuscript content:* NC and JF. *Approving final version of manuscript:* All authors.

CHAPTER V

NOVEL APPROACH TO NEUROMUSCULAR FATIGUE MONITORING OF A COMPETITIVE COLLEGIATE SEASON IN CANADIAN FOOTBALL PLAYERS

5-1. ABSTRACT

Previous studies have demonstrated an important association between postural control and acute neuromuscular fatigue (NMF) after a simulated Canadian football game (8-*Ch.IV*). The aim of this study was to evaluate postural control as a potential alternative or supplementary tool for monitoring NMF in collision-based team sports over a competitive Canadian football season. Forty male participants (mean \pm SD: age 21.8 \pm 1.6 years, weight 97.6 \pm 14.7 kg, height 187.2 \pm 5.2cm) were recruited from the competitive roster of the University of Saskatchewan Canadian football team. Over the 2012 Canadian Interuniversity Sport pre- and competitive season (11 weeks; 9 competitive games), postural sway and countermovement jumps (CMJ) were performed weekly at 48 hrs post competitive games as indirect NMF measures. Daily global training load (GTL) was calculated using Session-RPE. Statistically significant correlations ($p < 0.01$) between GTL with CMJ takeoff velocity ($r = -0.66$, r range: -0.21 to -0.98) and peak power ($r = -0.69$, r range: -0.41 to -0.90) as well as the area covered by the center of pressure trajectory during 60s balance test ($r = 0.69$, r range: 0.45 to 0.89) were found for all individual players. Additionally, significant changes in GTL over the season (e.g. including bye week and pre- season training camp; $p < 0.01$) were reflected by significant directional changes in CMJ peak power and postural sway ($p < 0.01$). There was no evidence of differences across football positions or between starters and non-starters of the weekly game. Neuromuscular function in Canadian football players fluctuates in line with GTL over an 11-week competitive football season. Postural sway monitoring, in combination with CMJ, may present a more comprehensive assessment of both the neuromuscular and somatosensory alterations induced by these weekly fluctuations of GTL over a season. Such information may help provide guidance for the coach or sport practitioner in maintaining the balance between recovery and the demands of collision-based team sports.

5-2. INTRODUCTION

Canadian football is a thrilling, fast-paced collision-based team sport. Similar to its American counterpart, players are required to couple intense anaerobic bursts that are multi-directional and erratic in nature with low-intensity periods between plays allowing for recovery and tactical strategizing (38). In the American version, wide receivers and defensive backs can reach top end speeds of 31.5 km/h and quarterbacks can throw balls in excess of 80 km/h. Further, all players are exposed to the force trauma associated with ball-carrying, blocking and violent tackling. During a 12 game NCAA Division 1 season, football players were exposed to anywhere from 692 to 1390 impacts greater than 6 G depending on position (40). While the majority of impacts were moderate (6.1-6.5 G force), on average 12.1 ± 3.1 impacts per season were categorized as severe (>10 G Force) with running backs exposed most frequently to these severe impacts (16.6 ± 7.9 impacts per season). It is evident therefore, that not only is football one of the most violent team sports in the world but also that player injury is an inherent and stark reality of the game (11).

While the severity and frequency of injuries caused by collision are difficult to foresee in Canadian football, it is well established that by managing player training load with adequate recovery both underperformance and fatigue-induced injury (e.g. strains, sprains etc.) can be minimized (35). There are a number of tools available to both the coach and sport practitioner in establishing optimal balance between the demands placed on any given player with their individual recovery needs. Session-Rating of Perceived Exertion (sRPE) has proven to be an invaluable method for quantifying the internal global training load (GTL) of football players having recently been validated across an entire pre- and regular season in Canadian football (7-*Ch.III*,12). Despite its importance, GTL or training dose quantification is limited in usefulness unless accompanied by some form of individual response metric. The ultimate response indicator will always be performance; however, the technical intricacies and strategic nuance involved in football means that simply tracking wins and losses, or any other statistically based performance indicator (e.g. missed tackles, number of plays etc.), may not be truly reflective of an individual's fatigue state. From this standpoint however, monitoring of neuromuscular fatigue (NMF) via changes in maximal countermovement jump (CMJ) performance has proven beneficial in a number of sports. In particular, there is gathering evidence for the tracking of CMJ peak power (PP) as an effective response indicator which can be used to estimate the physical recovery time required to perform

optimally in a number of collision-based team sports including rugby (9,23,24) and Canadian football (8-*Ch.IV*).

Despite advancements in monitoring methods and technology, the reality remains that a high proportion of Canadian football players will be injured over the course of a season due to its inherent combative nature (11). Depending on the severity of the injury, it is also highly likely that scenarios will arise whereby a player who wishes to remain a starter will push through minor injuries for games and even important practices, but not exhibit the same commitment when asked to perform a NMF monitoring test such as a maximal CMJ. Under these circumstances a need to continually manage recovery remains, and so tracking NMF through changes in postural control could serve as a viable and less taxing alternative to a CMJ.

Previous studies have demonstrated an important association between postural control and acute NMF in athletic populations (4,28,30,42). Clarke and colleagues (8-*Ch.IV*) reported a 95.2% increase in the area covered by center of pressure (CoP_A) during a 60s postural sway task immediately following a simulated game in Canadian football players as well as a significant reduction in PP of CMJ (-6.5%). More importantly, the deterioration of these indirect NMF measures were acutely congruent with direct NMF measures (e.g. maximal voluntary contraction torque). These findings support the notion that postural sway monitoring may be a suitable supplementary response indicator in collision-based team sports (8-*Ch.IV*). While promising in acute-fatigue detection, to the author's knowledge there is currently no literature pertaining to postural sway fluctuation over an entire collision-based team sport season. Hrysomallis (17) revealed no significant changes in postural sway in Australian Rules football players from the start (Wk 1) to midseason (Wk 11). Unfortunately, however, with comparison of only two time points, 11 weeks apart, these findings are not comprehensive considering NMF can vary on a daily basis and early detection is important in order to avoid detrimental effects of accumulative fatigue over a season. On this basis a season-long investigation into the potential of postural sway as a NMF monitoring tool is warranted.

The primary purpose of this study was to therefore investigate the relationship between postural sway and the typical weekly fluctuations of GTL seen in a competitive Canadian Interuniversity (CIS) football pre- and regular season. For comparison, CMJ data was also collected as an empirically supported indicator of NMF in collision-based team sports (8-

Ch.IV,9,23,24,38). Furthermore, by classifying and matching GTLs of starters and non-starters weekly, our secondary aim was to reveal any potential differences in NMF accumulation that may be attributed to the stress inherent in competitive game play (40). The primary hypothesis was that postural sway would be sensitive to GTL changes over a season and that the players exposed to competitive intensity collision (game play) would exhibit greater magnitudes of weekly NMF than GTL-matched non-starters.

5-3. METHODS

5-3-1. Experimental Approach to the problem

Minimising Learning effect. Two CIS seasons (2010, 2011) worth of GTL and NMF monitoring prior to the current study (2012) served to minimize any learning effect associated with both sRPE and indirect NMF measures (7-Ch.III). Returning players on the 2012 University of Saskatchewan (U of S) competitive roster (n = 63 out of 88) were therefore well versed in the protocols and rationale of all tools utilised during the analysed season. Players were also re-familiarized with Foster's modified Borg's (FMB) scale (12) and NMF measures during the 2012 off- and pre-season. Most first year players with lack of familiarity and limited training experience were excluded unless they were exceptional and were part of the starting roster for the competitive season (n = 4).

Primary Aim – Postural sway assessment. Daily GTL data using sRPE were collected for the entire 2012 pre- and regular CIS football season (11 weeks; 9 competitive games; 52 practice sessions). Weekly CMJ and postural sway force plate data were collected 48 h post competitive games as indicators of NMF.

Secondary Aim – Starters vs. Non-Starters. In order to achieve our secondary aim a distinction between starters and non-starters was defined. As part of pre-season screening and historical team monitoring all players on the 2012 U of S football roster (N=88) were inherently required to participate in NMF monitoring (CMJ and postural sway) and track GTL. In an attempt to manage and balance experimental group size, a prediction of players likely to remain starters for the entire 2012 CIS season was made within 24 h of pre-season completion through consultation with

coaching staff. Out of the initial 88 players, 20 were identified as being predicted starters for upcoming season and another 20 players identified as non-starters with a minimum of 1 year on the team. Selection was representative of all positions within football excluding kickers and players were never made aware of this original group distinction.

All identified players (n = 40) became the experimental group for this study and were then prioritized to complete NMF measures within a consistent 3-hour window 48 h post-game in an attempt to negate any diurnal effects. This challenging schedule, combined with limited resources (1 force plate, 1 experimenter) was the sole reason for capping the group at 40. Player status (i.e. starter or non-starter) within the experimental group changed week by week and was retrospectively assigned. Starters for any given week were defined as players who competed in more than 2 quarters of the game. Non-starters were defined as players not on the active roster for that week's game. Players who dressed but were not utilized for more than 2 quarters were designated as neutral (e.g. unused substitutes). Unless injured and physical unable, all participants regardless of status completed daily GTL and weekly NMF monitoring.

Matching Training Load- High-intensity game simulation. Each week on the same day as the competitive game, all non-starters completed a high-intensity football game simulation (G-Sim). Designed by the Strength and Conditioning (S&C) coach to mimic the physical demands of a Canadian football game minus the contact, the G-Sim was implemented to allow matching of weekly GTLs with starters as best as possible. The primary reason for this was to enhance performance through individual fitness maintenance but also to allow a better NMF comparison in the current study. As previously described in more detail by Clarke et al. (8-Ch.IV), G-Sim duration was 75-90 minutes comprising a comprehensive dynamic warm-up and 4 quarters of 12 to 18 high-intensity exercise stations or "plays". Each play combined a 5 yrd sprint or agility drill with an explosive lower body, upper body or whole body movement designed to be football specific and completed maximally within 5 to 15s. Work-to-rest ratios between plays varied to reflect actual game play (29), three minutes of rest was provided between quarters 1 and 2, 3 and 4. Six minutes of rest was given between quarters 2 and 3 to mimic halftime.

5-3-2. Participants

Forty male participants (mean \pm SD: age 21.8 \pm 1.6 years, weight 97.6 \pm 14.7 kg, height 187.2 \pm 5.2cm) were recruited from the competitive roster of the 2012 U of S Canadian football team. Competitive roster inclusion was based upon a demanding selection process that comprised scouting reports, competitive performance, selection camps and a mandatory medical screening. The rigorous selection criteria allows this cohort to be confidently defined as both healthy and high performance. All players gave written consent according the American College of Sports Medicine guidelines, which conform to the Declaration of Helsinki. Ethical approval was obtained from the U of S Biomedical Research Ethics Board.

5-3-3. CIS Football Season structure and training

The 2012 pre-season consisted of an 8-day training camp with two football specific practice sessions per day culminating with one exhibition game. Immediately following pre-season, a 9-week competitive regular season commenced (8 games; 1 Bye). Figure 5-1 depicts a typical week in terms of GTL and structure during the regular season.

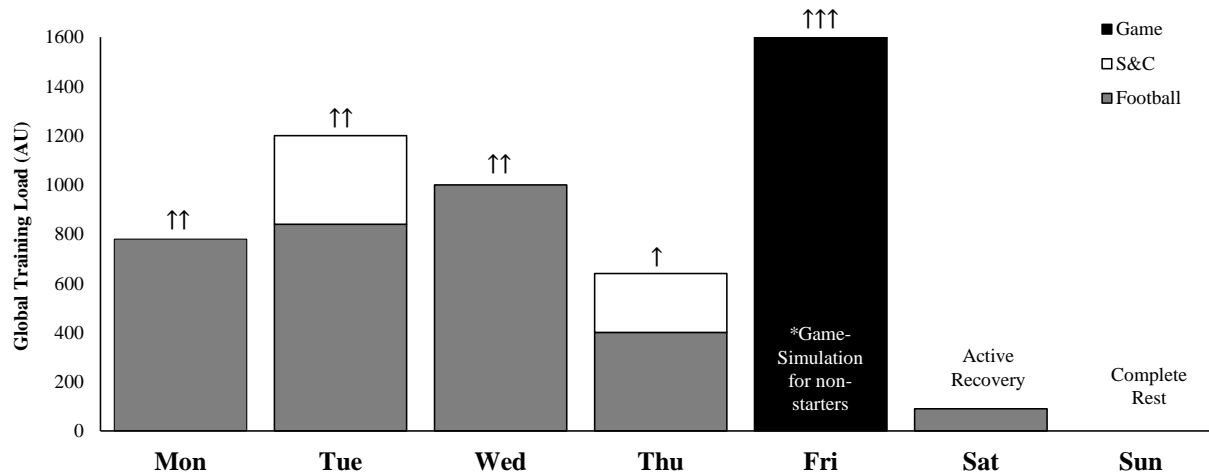


Figure 5-1. A typical regular season football week in terms of global training load (GTL) and structure. One week consists of four football practice sessions (Mon, Tue, Wed & Thu), a competitive CIS game (Fri) and two recovery days (Sat, Sun). (↑) are representations of collision intensity/frequency. ↑ = Minimal contact for all starters during practice prior to game day. ↑↑ = Full contact incorporated into football practices. ↑↑↑ = Highest impact - Game day (typically Fri). Active recovery held on the day following the game (Sat) and one day of complete rest (Sun). Game-simulation was used to match GTL of non-starters on game day.

Players were expected to participate in all practices and also complete 2 to 3 S&C sessions per week. Coaching staff were solely responsible for the football-specific elements of practice session planning. Physical conditioning elements in these sessions were guided by the team's professional S&C coach who also constructed the resistance training programs. During the competitive season the weekly training plan varied slightly depending on game day scheduling. All practice sessions were completed on modern artificial turf at the U of S football stadium.

5-3-4. Procedures - Measures of Internal Load

Session-RPE. All daily GTLs were collected in accordance with Foster et al. (12) original equation (Eq. 5-1) and relevant literature (33).

$$\text{Training Load (AU)} = \text{Intensity (RPE)} * \text{Duration (mins)}$$

[Equation 5-1]

Player RPE was verbally collected 30 min after completion of each session and/or game using the FMB scale. Practice and S&C session duration was defined as the time elapsed from the beginning of warm-up until the completion of the last training component prescribed by the S&C or head coach. Duration for competitive games was defined as time elapsed from kickoff to the final whistle.

Neuromuscular Fatigue Measures. Weekly NMF fatigue measures were collected 48 h post competitive game using a Bertec Na4060-10 force platform and protocols detailed below. A standardized dynamic warm-up (10 min) and three maximal CMJs were performed wearing athletic footwear followed by a barefoot 60-s postural sway task. Custom MATLAB (Mathworks) scripts created were used to compute NMF parameters.

Countermovement Jump. With no direction regarding speed or depth, players fixed hands on hips and were instructed to jump as high as possible. Knowledge of performance was permitted between jumps and the trial with the greatest takeoff velocity (TOV) was used for analysis. Ground reaction

force (GRF) data was used to obtain peak vertical force (PF). Takeoff velocity was obtained through calculation of the velocity profile which was combined with GRF data to obtain PP. Jump initiation was defined as the point where the force-curve dropped below a threshold of 2.5% bodyweight at the start of the counter-movement and take-off was calculated when the force dropped to zero (25).

Postural Sway Assessment. Players were instructed on the sharpened Romberg task whereby they stood with the heel of the non-dominant foot in front of the toe of the dominant foot and asked to place hands on the hips with elbows flexed (36). Once established in this position on the force plate, players were instructed to look straight ahead and stand as still as possible. A 65s data capture then began. After 5s elapsed the players were cued visually to close their eyes and the remaining 60s of data was used for analysis. Noise cancelling headphones streaming white noise were worn to nullify auditory distractions.

Postural sway was quantified through calculation of the area covered by a player's Center of Pressure (CoP) in line with equations reported previously (8-*Ch.IV*). In order to reduce the high variability due to initial balance adjustments and any short duration extreme excursions of the CoP, the CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Therefore, the adjusted CoP data included 95% of the original data points (CoP_A).

5-3-5. Reliability

All forty participants completed the NMF monitoring battery twice within 24hrs (T₀, T₂₄) prior to the commencement of pre-season practices and the mean used as baseline (Wk₀). Test-retest reliability was assessed between T₀ and T₂₄ using the intra-class correlation coefficient (ICC), technical error of the measurement (TEM) and percent change from T₀ (Table 5-1). Good reproducibility was shown for all measures (ICC $r = 0.95$ to 0.99) supporting previous reliability assessment from our laboratory (8-*Ch.IV*). Relatively large TEM ranges of CoP (9.3 to 27.9%) were expected as a minimum difference of 10-30% has been reported necessary to depict a measurable change in postural sway (2).

Table 5-1. Test-retest reliability of indirect neuromuscular fatigue variables assessed using time points 24 hours before (T_0) and immediately before (T_{24}) pre-season commencement. Data from all 40 participants was analyzed using the intra-class correlation coefficient (ICC), technical error of the measurement (TEM), and a one sample t-test of percent change from T_0 ran against zero.

Postural Sway	CoPx (mm)	CoPy (mm)	CoPSD_x (mm)	CoPSD_y (mm)	CoP_A (mm²)
T_0	36.9±7.8	27.9±10.2	9.5±2.1	7.3±2.9	852.1±461.3
T_{24}	37.4±8.9	26.8±9.2	9.6±2.4	6.9±2.3	834.3±457.4
<i>Change (%)</i>	1.3±18.1	-4.4±12.8	1.0±10.3	-7.4±17.1	-2.1±8.4
<i>t-test (p)</i>	0.91	0.22	0.926	0.13	0.234
<i>ICC range</i>	0.88 - 0.97	0.93 - 0.98	0.91 - 0.97	0.85 - 0.96	0.98 - 0.99
<i>TEM (%)</i>	15.5	19.0	14.6	27.9	9.3

CMJ	TOV (m/s)	PP (W)
T_0	2.64±0.19	5535.9±792.5
T_{24}	2.62±0.25	5523.2±727.1
<i>Change (%)</i>	-0.3±2.8	-0.2±4.5
<i>t-test (p)</i>	0.469	0.841
<i>ICC range</i>	0.97-0.99	0.95-0.99
<i>TEM (%)</i>	3.6	6.0

CMJ = Countermovement jump; TOV = Take-Velocity; PP = Peak Power; CoPSD_{x/y} = Center of Pressure standard deviation along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoPx/y = Center of Pressure displacement along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoP_A = Adjusted area covered by CoP trajectory. CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Values are means ± SD.

5-3-6. Statistical Analyses

All raw data was log transformed and individual Pearson's product moment correlations between weekly GTL, postural sway (CoP_A) and CMJ variables (PP,TOV) were computed for each player using the number of weekly data collections as cases according to the methods of Clarke et al. (7-Ch.III).

Differences between groups (starters vs non-starters) was examined over time (Wk₁ to Wk₁₀) for CMJ performance and postural sway through comparison of percent change from baseline. A two-way group × week factorial analysis of variance (ANOVA) was utilized to analyze data. This between-between design was the preference in place of the more logical repeated measures analysis due to the weekly fluctuation of group size (Table 5-2) as well as several missing data points. GTL group differences were also examined using a between-between two-way factorial ANOVA (group × week) but with the raw log transformed data as the assumption of

normal distribution was not met. Alpha for ANOVA tests was set at $p < 0.05$ and effect size (ES) was calculated using partial eta squared (η_p^2).

Table 5-2. Week-by-week player status, training week length (days) and game descriptors of the 2012 CIS football season.

Weekly/Game Descriptors				Player Status (N=40)		
Wk	Length (Days)	Game		Active (S/NS/NoCMJ)	Inactive	Out
		Location	Result			
Wk0	0	H	Base	20/20/0	0	0
Wk1	9	H	W _{Ex}	19/19/0	2	0
Wk2	7	H	W	17/11/1	11	1
Wk3	8	A	L	15/18/1	6	1
Wk4	7	A	W	15/17/1	7	1
Wk5	6	H	L	17/12/2	10	1
Wk6	8	A	L	12/13/3	13	2
Wk7	6	H	Bye	15/18/4	5	2
Wk8	7	H	W	18/11/0	8	3
Wk9	8	A	W	15/13/4	9	3
Wk10	6	H	W	18/14/0	5	3
Averages				15.6/15.0/1.2	7.7	1.7

Active = Number of players physical able to practice, compete and perform NMF monitoring for that week; Inactive = Number of players either physically unable to practice, compete and perform NMF monitoring for that week or classified as unused substitutes for that week's game (e.g. < 2 Quarters involvement) and not included in that week's analysis; Out = Cumulative number of players with season ending injuries and no longer included in analysis; Wk = Week; S = Starters (>2 Quarters game involvement); NS = Non-starters (not on game roster); NoCMJ = Number of players that completed a whole week of practice, competition and postural sway measure but did not to perform a countermovement jump (CMJ); H = Home; A = Away; W = Win; L = Loss; W_{Ex} = Win of Exhibition game; Grey highlight = Bye week

In order to gain more insight into the practical significance of the findings additional ES estimates were included on Figure 5-2 for NMF measures in the form of meaningfully percent change boundaries. Effect size boundaries were based on typical within-individual coefficient of variation (CV) determined during baseline testing. Multiplying the CV by modified standardized effect factors of 0.3, 0.9 and 1.6 provided estimates to determine small, moderate and large changes in the NMF measures (16,38).

5-4. RESULTS

Statistically significant individual correlations ($p < 0.01$) between global TL with TOV ($r = -0.66$, r range: -0.21 to -0.98), PP ($r = -0.69$, r range: -0.41 to -0.90) as well as CoP_A ($r = 0.69$, r range: 0.45 to 0.89) were found (Table 5-3, Fig. 5-2.).

Table 5-3. Average individual correlation coefficients (r) between weekly Global Training Load (GTL) and two neuromuscular fatigue (NMF) metrics. Across 10 weeks of the season an average of 30 players per week (15 starters & 15 non-starters) contributed 286 data points.

NMF Metric	Correlation with Global TL			
	Min	Max	Avg	SD
Postural Sway				
CoP _A (mm ²)	0.45	0.89	0.68*	0.12
CMJ				
TOV (m/s)	-0.21	-0.98	-0.66*	0.20
PP (W)	-0.43	-0.92	-0.69*	0.12

CoP_A = Adjusted Center of Pressure; CMJ = Countermovement Jump; TOV = Takeoff velocity; PP = Peak Power. * Statistically significant ($p < 0.01$).

Factorial ANOVA tests revealed a significant main effect of week for PP ($F_{(9,246)} = 9.0$; $p < 0.01$; $\eta_p^2 = 0.25$), TOV ($F_{(9,246)} = 8.5$; $p < 0.01$; $\eta_p^2 = 0.24$), CoP_A ($F_{(9,266)} = 11.6$; $p < 0.01$; $\eta_p^2 = 0.28$) and GTL ($F_{(9,266)} = 58.6$; $p < 0.01$; $\eta_p^2 = 0.67$). No group main effects (p range: 0.22 to 0.75) or group by week interactions were found (p range: 0.37 to 0.92) for any NMF metrics or GTL (Fig. 5-3). For full non-significant statistical results see Appendix B.

Bonferroni adjusted post hoc pairwise comparisons revealed that GTL during Wk₁ (9506.1 ± 960.2 AU) and Wk₇ (1852.0 ± 572.3 AU) was significantly different from all other weeks ($P < 0.01$). Week 6 (5076.1 ± 372.1 AU) was also significantly different from all weeks apart from Wk₃ (4506.9 ± 484.9 AU) ($p < 0.05$).

Post hoc analysis for NMF measures showed that CoP_A collected during Wk₁ was significantly larger than all other weeks ($135.6 \pm 23.6\%$). Compared to baseline, Wk₁ PP and TOV

values were the lowest reported across the season and were significantly lower than seven out of the 10 weeks (all $p < 0.05$).

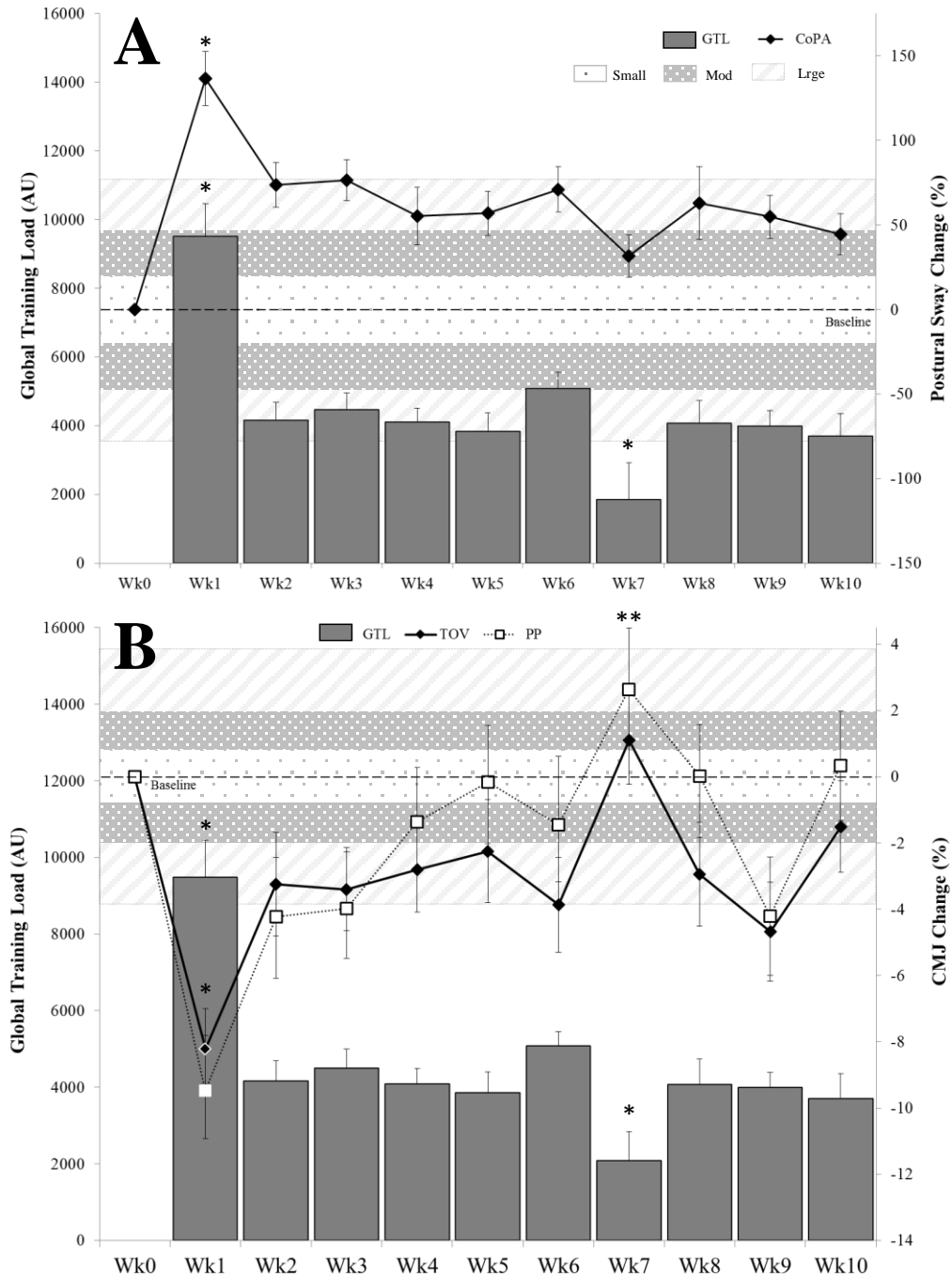


Figure 5-2. Fluctuation of weekly Global Training Load (GTL) and percent change from baseline of neuromuscular fatigue indicators **A**) postural sway and **B**) countermovement jump variables. CoP_A = Adjusted area covered by center of pressure trajectory; TOV = Takeoff velocity; PP = Peak Power. Values are means \pm SE. Effect size boundaries (16); CoP_A = Small (16.2%), Mod (48.8%), Large (86.8%). CMJ = Small (0.7%), Mod (2.1%), Lrg (3.9%). * Significantly different than all 10 weeks ($p < 0.05$). ** Significantly different from 9 out of 10 weeks ($p < 0.05$).

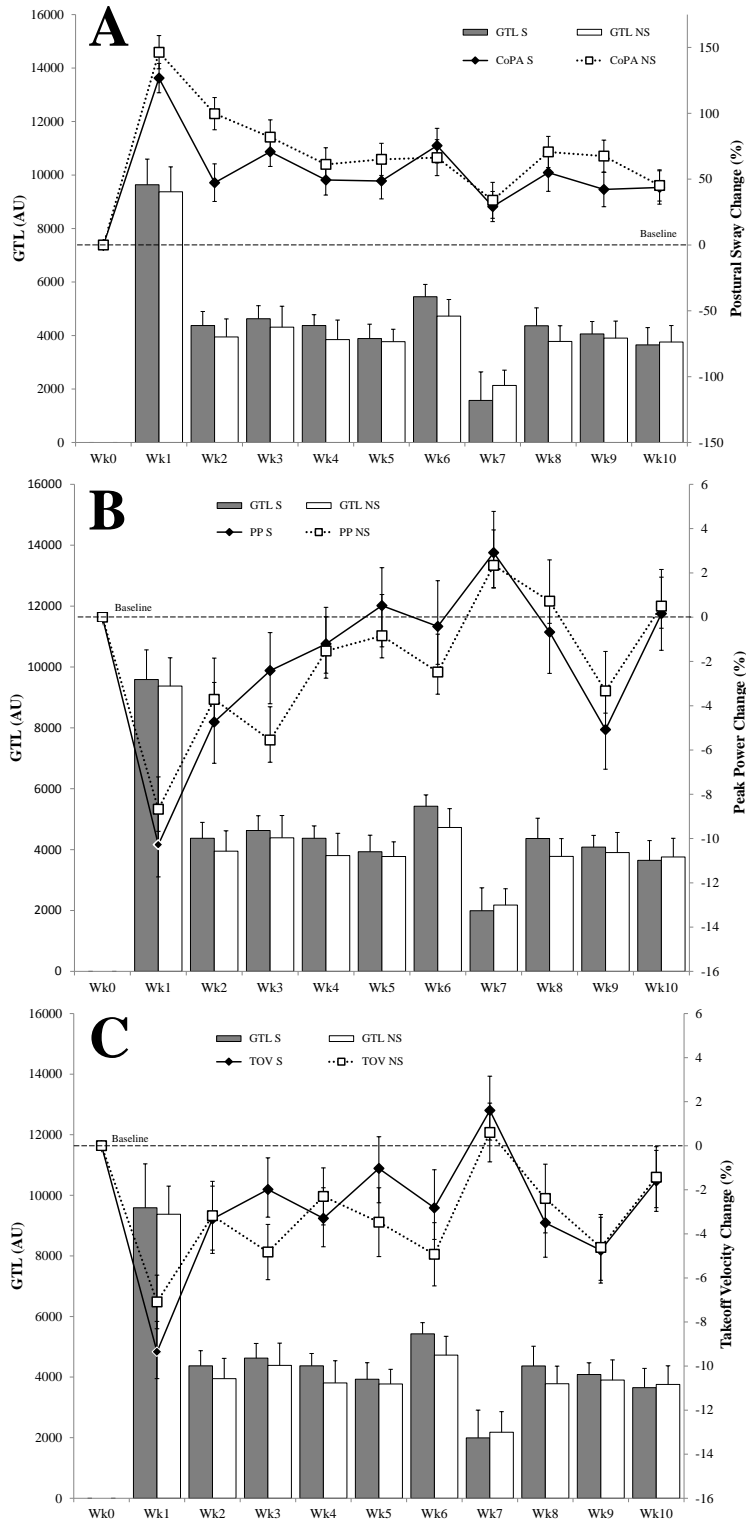


Figure 5-3. Starters (S) vs. non-starters (NS) comparison of weekly Global Training Load (GTL) and percent change from baseline of neuromuscular fatigue indicators **A)** postural sway and countermovement jump variables, **B)** Peak power (PP), **C)** Takeoff Velocity (TOV). CoP_A = Adjusted area covered by center of pressure trajectory; Values are means \pm SE.

5-5. DISCUSSION

The primary aim of this study was to investigate the sensitivity of postural sway, represented by CoP_A , to the fluctuating GTLs experienced by Canadian football players over the time-course of a competitive season. As hypothesized significant correlations were demonstrated between weekly GTL and postural sway that were further supported by similar significant associations between GTL and the more established NMF measure of CMJ PP and TOV (Table 5-3). Our secondary aim was to investigate any potential differences in season-long NMF profiling between starters and non-starters of the weekly game. In opposition to our hypothesis no significant differences in magnitude or direction of the studied NMF indicators were observed at any time point between these player groups (Fig. 5-3).

5-5-1. Mechanisms of Fatigue

Previously the physiological NMF mechanisms responsible for the deleterious changes of CMJ and postural sway in Canadian football players immediately following a fatigue inducing simulated game were found to be both peripheral and central in origin (8-*Ch.IV*). Acute peripheral fatigue post-exercise is associated with local glycogen depletion, metabolite accumulation and muscle damage (21). In the current study, due to the short intense bouts and high degree of eccentric contractions seen in football combined with the standardized 48 h timeframe prior to collection, it is likely that the involvement of metabolic factors was less than muscle damage at time of NMF assessment (1,15). Therefore, depending on recovery effectiveness, it is reasonable to suggest that any observed CMJ impairment can be attributed to structural compromise of excitation-contraction coupling (5). Likewise, the acute peripheral mechanism for any diminished postural sway is most likely attributable to inflammatory induced dysfunction of muscle mechanoreceptors (29). Despite studies citing a less than optimal neural drive as the driver of reduced CMJ and balance ability, identifying specific mechanisms of central fatigue is complex in applied sport settings (8-*Ch.IV*,14,30). Based on this relevant literature a combination of reduced proprioceptive signaling, interrupted voluntary stabilization and diminished motor control accuracy may have been responsible for the detrimental changes to both CMJ and postural sway. While from the current data it is impossible to distinguish the relative contributions of central and peripheral mechanisms for the evidenced NMF, it is clear that both neuromuscular and

somatosensory control pathways were altered over the time-course of the season in response to fluctuating GTL demands (Fig. 5-2).

Most previous investigations of balance and CMJ response to simulated- or game-induced NMF have done so over relatively short time periods (8-*Ch.IV*,30,42). There is little, if any research that extends across entire competitive seasons or extensive training periods. As acute responses may be unrepresentative of long-term changes this remains a major practical limitation of not only the existing postural sway literature, but a number of other dose-response indicators used by sport scientists today. For example, the current recommendations regarding time required for recovery to baseline of physiological monitoring markers such as HR recovery are based on studies examining passive recovery following a single exercise bout (31). However, the high training frequencies and short time frames between games associated with competitive football seasons do often not allow 48-72h of passive recovery (7-*Ch.III*). While regular monitoring of CMJ PP has proven very effective in evidenced based guidance of recovery over the course of a 22 match Australian Rules football season (10), there remains uncertainty regarding the expected pattern of season-long postural sway responses in collision-based team sport athletes. To this end, the current study provides a unique and valuable insight into the practical application and potential limitations of monitoring postural sway in real-world high performance settings as well amassing additional support for season-long CMJ tracking.

5-5-2. Recovery-time course of NMF measures

Based on the first week's (Wk₁) measurements it appears that both postural sway and CMJ metrics show most significant decrements following periods of extreme training and are arguably indicative of neuromuscular overreaching (10,26). Wk₁ represented a deliberate pre-season overloading strategy whereby two full contact sessions per day were incorporated by the coaches to increase GTL, which is a common pre-season preparation approach in CIS football. Given effective periodization the expectation would be for the players to rebound, which to a degree was witnessed with a recovery trend towards baseline of NMF metrics once the regular season began (Wk₂). The CMJ metrics recovered to within ~1% of baseline after Wk₅ and went on to show a slight improvement following the Wk₇ bye. Similarly, postural sway exhibited a trend back towards baseline across the whole season but failed to fully recover at any time point (Fig. 5-2). This prolonged recuperation of CMJ and season-long suppression of postural sway could be the

result of inappropriate periodization (26). Therefore, our findings provided strong support for coaches' to be well versed in the intricacies of training stimulus residuals (i.e. time required to recovery from previous sessions) and has implications for season-long program design in high level collision-based team sports.

Disparity in the recovery-time course of postural sway and CMJ following the Wk₁ overload may in part be explained by the degree of sensitivity to NMF in the somatosensory and neuromuscular control pathways. Postural control relies more heavily on the somatosensory system (32) and the prolonged suppression of CoP_A may have resulted from a heightened impairment of somatosensation over a football season compared with neuromuscular pathways predominantly assessed by a CMJ. Support for this hypothesis may be found in the repeated and extensive stimulation experienced by structures in the sole of players' feet while performing aggressive football-specific running movements. As evidenced by postural control assessment in runners, Leper et al. (21) suggested that changes in proprioceptive information or a decrease in effector system efficiency due to muscle fatigue accumulation has the potential to impair the postural regulation loops by impacting tendons, joint receptors and cutaneous mechanoreceptors in the feet which play a vital role in maintaining balance. Extensive impairment of postural sway over many weeks seen in the present study may therefore be a result of inadequate time for the somatosensory system to recover particularly the effector system within the players' feet.

Recovery or time to restoration of homeostasis post exercise, relies on a multitude of integrated physiological mechanisms and is influenced by factors including training intensity (27), training history and energetic profile (3,37), cardiovascular fitness (31), sleep and lifestyle factors such as psychological stress (33). Contributions of these factors were not examined in our study; however, discussing a footballer player's expected energetic profile may provide further explanation as to the recovery-time course differences seen between CMJ and postural sway over the season. The energetic profile of an athlete refers to the nature of adaptive response to training and is therefore highly influenced by a combination of training history and genetics (3). In comparison to more aerobically dependent athletes, athletes who rely predominantly on anaerobic energy contributions induce greater acute NMF, parasympathetic suppression, metabolic responses and larger performance decrements post exercise (6,22) but also show greater ability to recover the neuromuscular system (20). The apparent recovery capacity of the CMJ variables seen

in our study (Fig. 5-2) is a possible reflection of these well-trained power athletes' ability to cope with neuromuscular overload despite ongoing high training frequencies. Additionally, the incorporation of regular S&C sessions to activate, enhance and promote neuromuscular activation may have also provided further bias towards CMJ recovery and enhancement.

5-5-3. Global Training Load Composition: Starters vs. Non-Starters

A secondary aim of the current study was to identify any differences in NMF patterning between those players who competed in the weekly game versus those who did not (i.e. starters vs. non-starters). The stress of competitive game intensity and collision experienced by weekly starters was predicted to result in more muscle damage, increased localized as well as systematic inflammation leading to either more pronounced or persistent NMF. However, while successful in matching weekly GTL, no significant differences between starters and non-starters were observed in any NMF measures across the whole 11-week season (Fig. 5-3). The results suggest therefore, that while the NMF measures in the current study are sensitive to football-specific exercise; in isolation they are not sensitive enough to distinguish a training load elicited from a simulated-game compared to a competitive game. Interestingly, in the period since initial conception and data collection for this study (2012), Johnston et al. (18) reported a significant amount of upper body fatigue following rugby league matches as well as observed differences between the time-course of NMF assessed by plyometric press-up and CMJ performance. In explanation, the authors pointed to the differing movement characteristics under-taken by the lower body (i.e. lower force, high velocity) and upper body (i.e. higher force, low velocity) of rugby players during a match. Furthermore, plyometric press-up performance was thought to be more heavily influenced by muscle damage and soreness as the upper body is known to be involved in a greater number of collisions compared with the lower body during rugby match play (18). Taking this into consideration with the current findings, it can be speculated that a difference between starters and non-starters may well have been found with the incorporation of an upper body NMF metric such as the plyometric press up. In hindsight, it is acknowledged that upper body NMF monitoring and subjective assessments of muscle soreness may have been more sensitive to competitive exposures (18,33) nonetheless, the current observations remain important in terms of in-season physical readiness (i.e. fitness maintenance). For example, as long as GTL

is matched with football specific exercise such as a G-Sim, any in-season deterioration of fitness often seen in fringe players or non-starters can potentially be avoided (7-*Ch.III*).

Matching weekly GTL for all players within a football team can also be highly advantageous in guiding the interruption of athlete monitoring. To explain, in the current study a time point of particular interest was the reduction in CMJ performance after Wk₉ (Fig. 5-2), which despite not reaching significance, dropped below the “large” meaningful change boundary and thus merited further investigation. Travel fatigue was originally thought to have hindered CMJ recovery (9) as the Wk₉ game was played away from home requiring a 9-hour bus journey in both directions. However, two factors confound this explanation: firstly, CoP_A in the starters continued a recovery trend with slight improvement from Wk₈ and secondly, GTL matched non-starters who did not travel also experienced a comparable reduction in CMJ performance. Commonality for all players was a coach instigated surface switch from artificial turf to natural grass during that entire training week in preparation for the Wk₉ opposition who played on a grass field. Compared to natural grass surfaces, it is known that higher game speeds are generated on artificial turf due to greater peak torque forces and rates of torque increase (stiffness) between the shoe and playing surface (13,41). Therefore, as this was the only week (Wk₉) to be completed on grass, a surface associated with lower load generation, the decline in CMJ performance may have been due to alterations in muscle stiffness and stretch reflex regulation leading to a deterioration in the force potentiation mechanisms involved in the stretch-shortening cycle (19).

5-5-4. Conclusion

Fluctuations of neuromuscular and somatosensory responses were elicited in line with the variations in GTL experienced over a competitive CIS football season. Whether the NMF evident is influenced more by central or peripheral factors cannot be determined from our results, although compromise of E-C coupling and dysfunction of mechanoreceptors resulting from muscle damage may be responsible for the decrements observed. Following the relatively extreme GTLs experienced during the pre-season (Wk₁), the response of both CoP_A and CMJ metrics indicate neuromuscular overload. The pattern of recovery seen in CMJ performance suggests that players were in a compromised neuromuscular state for 8 out of the 11 weeks of the season. The response of CoP_A post Wk₁ suggests that a player’s balance ability was suppressed across the entire season most likely due to inadequate recovery of the somatosensory system. Disparity between the

recovery-time courses of the NMF metrics may be explained by heightened sensitivity of somatosensory pathways to football induced NMF as well as the energetic profile of football players which lends itself to enhanced tolerance of high neuromuscular load. Further investigation of postural sway monitoring in collision-based team sports is warranted particularly the response of CoP_A in relation to more precise training load measures such as GPS metrics of impact frequency and magnitude.

5-5-5. Practical Application

Increased CoP_A and a reduction in CMJ PP and TOV compared with baseline suggests inadequate recovery of somatosensory and neuromuscular pathways. Weekly monitoring of these variables and comparing responses to individual baseline measures may provide valuable periodization guidance in an effort to optimize performance throughout a football season. With the inevitability of minor injuries hampering CMJ collection, postural sway provides a valid alternative to enable continued monitoring of recovery status. While postural sway should not replace CMJ, the addition of this supplementary NMF measure allows for regular uninterrupted monitoring over the time-course of a competitive season as well as enabling increased evidence accrual for the instigation of interventions aimed to enhance recovery such as training load reduction or improved recovery modalities.

5-6. REFERENCES

1. Allen, D, Lamb, G, and Westerbland, H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Reviews* 88: 287-332, 2008.
2. Birmingham, TB. Test-retest reliability of lower extremity functional instability measures. *Clin J Sport Med* 10(4): 264–268, 2000.
3. Bouchard, C, Sarzynski, MA, Rice, TK, Kraus, WE, Church, TS, Sung, YJ, Rankinen, T. Genomic predictors of the maximal O₂ uptake response to standardized exercise training programs. *J App Physiol* 110(5): 1160-1170, 2011.
4. Brito, J, Fontes, I, Ribeiro, F, Raposo, A, Krstrup, P, and Rebelo, A. Postural stability decreases in elite young soccer players after a competitive soccer match. *Phys Ther Sport* 13(3): 175–179, 2012.
5. Bruton, JD, Lännergren, J, and Westerblad, H. Mechanisms underlying the slow recovery of force after fatigue: importance of intracellular calcium. *Acta Physiol Scand* 162(3): 285–293, 1998.
6. Buchheit, M, Hader, K and Mendez-Villanueva, A. Tolerance to high intensity intermittent running exercise: do oxygen uptake kinetics really matter? *Front Physiol* 3(406): 1-13, 2012
7. Clarke, N, Farthing, JP, Lanovaz, JL, and Krentz, JR. Direct and indirect measurement of neuromuscular fatigue in Canadian football players. *App Physiol Nutri Metabol* 40(5): 464-473, 2015.
8. Clarke, N, Farthing, JP, Norris, SR, Arnold, BE, and Lanovaz, JL. Quantification of training load in Canadian football: application of session-RPE in collision-based team sports. *J Strength Cond Res* 27(8): 2198-2205, 2013.
9. Cormack, S. The effect of regular travel on periodisation. *Strength Cond Coach* 9: 19-24, 2001
10. Cormack, SJ, Newton, RU, McGuigan, MR, and Cormie, P. Neuromuscular and endocrine responses of elite players during an Australian Rules football season. *Int J Sports Physiol Perform* 3(4): 439–453, 2008
11. Dick, R, Ferrara, MS, Agel, J, Courson, R, Marshall, SW, Hanley, MJ, and Reifstack, F. Descriptive epidemiology of collegiate men’s football injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train* 42(2): 221–233, 2007.
12. Foster, C, Florhaug, JA, Franklin, J, Gottschall, L, Hrovatin, LA, Parker, S, Doleshal, P, and Dodge, C. A New Approach to Monitoring Exercise Training. *J Strength Cond Res* 15(1): 109-115, 2001.
13. Gains, GL, Swedenhjelm, AN, Mayhenw, JL, Bird, HM, and Houser, JJ. Comparison of speed and agility performance of college football players on field turf and natural grass. 2010. *J Strength Cond Res* 24(10): 2010.

14. Girard, O, Racinais, S, Micallef, J-P, and Millet, GP. Spinal modulations accompany peripheral fatigue during prolonged tennis playing. *Scand J Med Sci Sports* 21(3): 455–464, 2011.
15. Hoffman JR, Kang J, Ratamess NA, Faigenbaum AD. Biochemical and hormonal responses during an intercollegiate football season. *Med Sci Sports Exerc* 37(7): 1237–1241, 2005.
16. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41(1): 3-13, 2009.
17. Hrysomallis, C. Preseason and midseason balance ability of professional Australian footballers. *J Strength Cond Res* 22(1): 210-211, 2008.
18. Johnston, RD, Gibson, NV, Twist, C, Gabbett, TJ, MacNay, SA, MacFarlane NG. Physiological responses to an intensified period of rugby league competition. *J Strength Cond Res* 27(3): 643–654, 2013.
19. Komi, PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech* 33, 1197-1206, 2000.
20. Krustup, P, Ørtenblad, N, Nelson, J, Nybo, L, Gunnerson, TP, Iaia, FM, et al. Maximal voluntary contraction force, SR function and glycogen resynthesis during the first 72 h after a high-level competitive soccer game. *Eur J Appl Physiol* 111(12): 2987-2995, 2011.
21. Lepers, R, Bigard, AX, Diard, JP, Gouteyron, JF, and Guezennec, CY. Posture control after prolonged exercise. *Eur J Appl Physiol Occup Physiol* 76(1): 55-61, 1997.
22. McDonald, KG, Grote, S, and Shoepe, TC. Effect of training mode on post-exercise heart rate recovery of trained cyclists. *J Human Kin* 41(1): 43-49, 2014.
23. McLellan, CP, and Lovell, DI, and Gass, GC. Biochemical and endocrine responses to impact and collision during elite rugby league match play. *J Strength Cond Res* 25(6): 1553–1562, 2011.
24. McLellan, CP, and Lovell, DI, and Gass, GC. Markers of postmatch fatigue in Professional rugby league players. *J Strength Cond Res* 25(4):1030–1039, 2011.
25. Meylan, C, Nosaka, K, Green, J, and Cronin, J. The effect of three different start thresholds on the kinematics and kinetics of a countermovement jump. *J Strength Cond Res* 25(4): 1164–1167, 2011.
26. Moore, CA, and Fry, AC. Nonfunctional Overreaching During Off-Season Training for Skill Position Players in Collegiate American Football. *J Strength Cond Res.* 21(3): 793–800, 2007.
27. Niewiadomski, W, Gasiorowska, A, Krauss, B, Mroz, A, and Cubulski, G. Suppression of heart rate variability after supramaximal exertion. *Clin Physiol Func Imaging* 27(5): 309-319, 2007.
28. Pau, M, Ibba, G, and Attene, G. Fatigue-induced balance impairment in young soccer players. *J Athl Train* 49(4): 454-456, 2014.

29. Rhea, MR, Hunter, RL, and Hunter, TJ. Competition modelling of American football: Observational data and implications for high school, collegiate, and professional player conditioning. *J Strength Cond Res* 20(1): 58–61, 2006.
30. Ribeiro, F, Santos, F, Gonçalves, P, and Oliveira, J. Effects of volleyball match-induced fatigue on knee joint position sense. *Eur J Sport Sci* 8(6): 397–402, 2008.
31. Seiler, S, Haugen, O, and Kuffel, E. Autonomic recovery after exercise in trained athletes: intensity and duration effects. *Med Sci Sports Exerc* 39(8): 1366, 2007.
32. Shaffer, SW, and Harrison, AL. 2007. Aging of the somatosensory system: A translational perspective. *Physical Therapy* 87(2): 193-207, 2007
33. Singh, F, Foster, C, Tod, D, and McGuigan, MR. Monitoring different types of resistance training using session rating of perceived exertion. *Int J Sports Physiol Perform* 2(1): 34-45, 2007.
34. Skein, M, Duffield, R, Minett, GM, Snape, A, and Murphy, A. The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. *Int J Sports Physiol Perform* 8(5): 556-564, 2013.
35. Smith, D. A framework for understanding the training process leading to elite performance. *Sports Med* 33: 1103-1126, 2003.
36. Spiliopoulou, SI, Amiridis, IG, Tsigganos, G, Economides, D. and Kellis, E. Vibration Effects on Static Balance and Strength. *Int J Sports Med* 31: 610–616, 2010.
37. Tucker, R and Collins, M. What makes a champion? A review of the relative contribution of genes and training to sporting success. *Brit J Sports Med* 46(3). 555-561, 2012.
38. Twist, C and Highton, J. Monitoring fatigue and recovery in rugby league players. *Int J Sports Physiol Perform* 8: 467-474, 2013.
39. Wellman, AD, Coad, SC, Goulet, GC, and McLellan, CP. Quantification of competitive game demands of NCAA division I college football players using global positioning systems. *J Strength Cond Res* 30(1): 11-19, 2015.
40. Wellman, AD, Coad, SC, Goulet, GC, Vernon, GC, and McLellan, CP. Quantification of accelerometer derived impacts associated with competitive games in NCAA division I college football players. *J Strength Cond Res* E Pub 2016
41. Williams, S, Hume, PA, and Kara, S. A Review of Football Injuries on Third and Fourth Generation Artificial Turfs Compared with Natural Turf. *Sports Med* 41(11): 903-923, 2011.
42. Zech, A, Steib, S, Hentschke, C, Eckhardt, H, and Pfeifer, K. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. *J Strength Cond Res* 26(4): 1162–1168, 2012.

CHAPTER VI

SUMMARY, RECOMMENDATIONS & CONCLUSIONS

6-1. SUMMARY OF FINDINGS

The aim of this thesis was to provide a body of research investigating effective monitoring of the training dose-response relationship in Canadian football as well as furthering our understanding of the players' neuromuscular fatigue (NMF) response to both acute and extended periods of football specific training and competition.

6-1-1. Chapter III, Study 1 - *Quantification of training load in Canadian football: Application of Session-RPE in collision-based team sports.*

Due to the lack of published research in Canadian football, the first task was to provide a practical and reliable method to quantify the dose of training or internal training load (TL) experienced by the players in this unique collision-based sport. Certainly within the collegiate ranks, there is a tendency for football coaches to react using intuition in order to manipulate training intensity or duration rather than following a specific plan. However, perception and intuition of even experienced coaches is arguably not the most reliable method for accurately monitoring internal TL especially when considering the complexity of physical components and interactions seen within even a basic football program (e.g. technique, agility, power and strength). For this reason, chapter 2 set out to validate Session-RPE (sRPE) as an inexpensive and highly practical method of quantifying internal TL in Canadian football players. Session-RPE was collected over an 11-week season and through comparison with two criterion heart rate (HR)-based internal TL metrics, significant ($p < 0.01$) individual player correlations were found between all three methods (r range: 0.65 to 0.91). To our knowledge this was the first study to validate the sRPE method in Canadian Football and subsequently opened up a number of potential avenues for investigation, since there was no constraint of expensive and invasive HR monitors that decrease potential sample size dramatically.

6-1-2. Chapter IV, Study 2 - *Direct and Indirect measurement of neuromuscular fatigue in Canadian football players.*

During the season over which the first study in Chapter III was completed, a pilot investigation was initiated to track the response of countermovement jump (CMJ) performance using a force plate. The intention was not only to familiarize and habitualize the team with regular monitoring but also to further understanding regarding the practical limitations of the methodology. It became quickly apparent that the ability to consistently track this maximal form of NMF monitoring was challenging due to the number of minor injuries that prevented players committing fully to the CMJ despite training and playing in the competitive game each week. Chapter IV attempted to address this issue by introducing a novel and submaximal form of NMF monitoring to the sport of Canadian football. Postural sway (PS), quantified by adjustments in center of pressure (CoP_A), was assessed in players using a force plate immediately before and immediately following a fatigue inducing simulated Canadian football game (G-Sim). A significant increase in CoP_A (95.2%; $p < 0.05$) following the G-Sim suggests that PS was negatively affected and thus sensitive to football specific acute fatigue in this group. The truly novel aspect of the study was the observed congruency with direct measures of NMF as well as a CMJ performance decline. Specifically, with the detection immediately post G-Sim of low frequency fatigue and a reduction in the ratio between maximal voluntary and electrically-stimulated torques (-12.1%) this study provided direct evidence of both peripheral and central NMF mechanisms in football players. Although it was not prudent to comment on the relative contributions of these mechanisms, this is one of the few studies that compared direct and indirect measures of NMF, and therefore accrues further support for the often assumed narrative that functional performance tests are reflective of fatigue-induced alterations in both neuromuscular and somatosensory pathways. More importantly, a submaximal method of measuring NMF in Canadian football players was introduced with great potential as an indicator of acute fatigue and warranted further investigation particularly over extended training periods.

6-1-3. Chapter V, Study 3 – *Novel approach to neuromuscular fatigue monitoring of competitive collegiate season in Canadian football players.*

One of the largest gaps in the literature surrounding fatigue monitoring is the understanding of responses during and following extensive periods of high frequency training. This is particularly relevant to the weekly structure of a Canadian football season as competitive games, which elicit the highest weekly stress, are often separated by 5 to 7 days of practice. In these circumstances, a reliable NMF monitoring system is vital, but even if a system is in place, it remains common practice for interpretation of these responses to be conducted citing research from acute fatiguing studies. As acute responses may misrepresent the accumulative effect of fatigue, this type of practice may well unintentionally impact coaching decisions in regards to providing adequate, or in most cases; inadequate time for physical recovery. Investigating the use of monitoring tools and parameters in applied settings across entire seasons is therefore critical, but more so it is important to amass knowledge as to the NMF response and recovery profiles of football players during these periods. To this end, the primary goal of Chapter V was to compare the response profile of PS and the empirically supported CMJ to all fluctuating Global training load (GTL) stressors placed on players across an 11-week competitive Canadian football season. On an individual level significant corresponding correlations ($p < 0.01$) were evident with GTL increase and performance deterioration in both CMJ (r range: -0.21 to -0.98) and PS (r range: 0.45 to 0.89). This led to the conclusion that not only is CMJ valuable for tracking neuromuscular changes in applied Canadian football settings, but also that quantifying balance is a valid and alternative NMF monitoring tool which is extremely useful under circumstances where maximal monitoring is inhibited by minor injury.

The secondary aim of Chapter V was to elucidate any potential discrepancy in football player NMF response to- or recovery from- a regular season week that either included or did not include a competitive game. By retrospectively assigning players as starters or non-starters on a weekly basis players exposed to the competitive game (starters) were predicted to exhibit either more pronounced or persistent NMF compared with the GTL matched non-starters. Contrary to this initial theory no significant difference between the PS and CMJ performance response to GTL was seen between groups at any time point during the season. Both NMF measures, while sensitive to football-specific fatigue, were not sensitive enough to distinguish between GTLs elicited by

actual or simulated game play. Implications of such findings are important in terms of maintaining in-season fitness as coaches can expose all players on a squad to similar physical stress by replacing a competitive game with a G-Sim (e.g. matching weekly GTL). The findings also raise the question for future research as to what fatigue measure or method would best differentiate between competitive (contact) and simulated (non-contact) football stress.

6-2. PRACTICAL APPLICATION & RECOMMENDATIONS

Based on the findings presented in this thesis, the following practical recommendations are made for coaches' and practitioners working not only in football but also other collision-based team sports with similar challenges. It is important to acknowledge firstly that although the studied cohort was considered high performance a number of these applications can, and are encouraged to be used across all levels of football player. Secondly, since thesis data collection ended in 2013 a number of studies advancing our knowledge in collision-based team sport monitoring have also been completed. Relevant findings from these investigations are therefore discussed within our recommendations to provide the reader with all the most up to date information required in developing a monitoring system for football players and programs.

6-2-1. Monitoring Systems

Implementation of a reliable, valid and practical monitoring system is recommended throughout the off-, pre- and in-season that consistently identifies the TL or “dose” that players are exposed too, as well as the adaptation or “response” to that TL.

The power of monitoring lies in consistency. In order to develop knowledge of player response to all stressors, players must first be exposed to all stressors and the response carefully tracked. Over time a comprehensive training does-response relationship could be established and potentially used to pre-empt mistakes, maximize performance and inform the coach as to the validity of their program on individual players.

Recommendations:

- Daily collection of dose or TL data is recommended and response/performance indicators should be collected at minimum on a weekly basis.

- Standardized timing of collection is crucial. Longer or irregular intervals between tests may mask important trends.
- Familiarization, habitualisation and understanding of all monitoring tools by players and coaches is essential for “buy-in”, consistency and accurate interpretation.

6-2-2 Training Load or “Dose” Monitoring

The emergence of TL monitoring in team sports has exponentially grown owing to the need to monitor individual response to training. The combination of internal (sRPE) and external (GPS) TL is important for practitioners in understanding all loads obtained during the course of a season (23). While acknowledging that GPS equipment is highly expensive and requires a certain level of expertise, sRPE is valid, cost effective and a very useful subjective tool that is recommended as a minimum requirement of all monitoring systems.

In order to provide a more detailed quantification of internal TL during team-sport training an interesting new slant on the sRPE method, known as Differential-RPE (dRPE), has been recently presented (20). Intended as a supplement to sRPE, and calculated in the same way, dRPE is suggested to provide additional information on the specific mediators of load within a single session by differentiating session ratings for breathlessness (sRPE-B), leg muscle exertion (sRPE-L), upper body muscle exertion (sRPE-U), and cognitive/technical demands (sRPE-T [20]). Despite some authors questioning the practical relevance of these measures (12,18) others recommend dRPE to be a worthwhile addition to the monitoring of training (11,20) and match (19,33) loads in team sport.

Recommendations:

- Use sRPE to quantify player internal TL amassed by all program modalities including football practice, competition, cross-training, S&C and others. Summation of all these modality TLs is referred to as Global TL.
- Differential-RPE may be adopted to provide more detailed quantification of internal TL but only if the specific outcome is defined e.g. do not collect data just for sake of collecting data.

- Caution the use of dRPE until sRPE and other more important monitoring tools have been habitualized and are well established within the team. Overwhelming players with monitoring will negatively affect buy-in and consistency (24)
- Completely replacing sRPE with dRPE is not advised
- If financially feasible, GPS technology is recommended to quantify external load.
- If no GPS data is available another option may be to use the external load prescribed by the coaches e.g. the training plan or program. This is a form of capturing external load, albeit less accurate. Additionally, asking the coach's to provide an RPE for each session on the program will enable you to calculate a TL using sRPE that is representative of their session intent. As a practitioner you now have the ability to compare "Prescribed" (Coach) vs "Actual" (Player) TLs. As per sRPE methodology showing players the coach's RPE values is not recommended as it has the potential to create bias.
- Carefully monitor TL distribution at various points during the season as a form of program validation. Off- and pre-season TLs usually compromise of conditioning and skills. In-season focus moves to competition and recovery.

6-2-3. Neuromuscular Fatigue or "Response" Monitoring

Regardless of sport, the ultimate response monitoring tool will always be the competitive performance. To be able to quantify this in football, however, is fraught with difficulty as just tracking team wins and losses may not truly reflect on an individual player's performance in that game. For this reason, consistent tracking of the performance changes in maximal CMJ and balance are highly recommended to provide an indication of physical (neuromuscular or somatosensory) status or response.

Johnson and colleagues (16) observed a more pronounced NMF in the upper body (UB) compared with lower body (LB) of elite rugby players following competitive match play. In explanation, the authors suggested that the prolonged decline in plyometric press up (UB NMF) compared with CMJ (LB NMF) performance post-game was due to a more frequent exposure of the upper extremities to collisions during rugby competition. Recognizing that Canadian football players wear more UB protective equipment and that the distribution and frequency of collision

exposure has yet to be documented in football, it seems reasonable to venture that measures of UB NMF may well have been more sensitive to a competitive football game than a CMJ.

Recommendations: Countermovement Jump

- Maximal CMJ is recommended as the primary functional performance test to monitor NMF
- Peak power (PP) of a CMJ is more sensitive to NMF than jump height and where possible therefore, instrumentation which allows measurement of PP such as a force plate is recommended
- Consider the use of an explosive upper body NMF test such as a plyometric push-up particularly during the competitive season (16)

Recommendations: Postural Sway

- Postural sway quantified by tracking center of pressure (CoP) during a 60s eyes-closed balance task can be implemented as supplementary NMF monitoring tool but requires a force plate.
- The bilateral Romberg-sharpened task (27) is recommended as a single leg task, similar to maximal CMJ, can be hampered by injury, are less reliable, and require more than double the collection time.
- As explained in Chapter IV, in order to achieve moderate to good reproducibility with PS (ICC = 0.73 to 0.99) it is recommended that CoP data be adjusted to exclude the 5% of CoP locations that are the farthest from the center of the CoP range (CoP_A [6-Ch.IV]).
- Although PS would not be recommended to replace CMJ, in a scenario when CMJ participation is not possible, having PS tracked in parallel offers a regular alternative for continuous response or NMF monitoring.

Recommendations: Reliability and Detecting Meaningful Change

- Test-retest reliability data of all indirect NMF variables recommended are available in appendix C.
- Since typical variation in CMJ and PS assessment are substantially different between players, it is crucial to define thresholds for meaningful changes using individual data.

- It is recommended that effect size boundaries be calculated by multiplying the typical within-individual coefficient of variance by the modified standardized effect factors of 0.3, 0.9 and 1.6 (14). These boundaries provide estimates to determine small, moderate and large changes (30).

6-2-4. Athlete Self-Reported Measures

While monitoring of objective response measures has been the focus of this thesis, it is important to acknowledge the crucial role that athlete self-reported or subjective measures can play in establishing an individual player's stress tolerance threshold (25). Figure 6-1 shows the weekly data collected from a modified Recovery-cue questionnaire (Appendix D [1]) that was implemented for the experimental group (n=40) during the season long study reported in Chapter V.

By studying the responses of all self-report measures across the CIS season (Fig. 6-1), it is clear that a dose-response relationship with GTL exists. These observations are supported by the individual correlations presented in Table 6-1. Ratings of Perceived effort, Perceived recovery, along with Physical recovery, Recovery efforts and Sleep quality all reported significant ($p < 0.01$) negative associations with GTL (r range: -0.51 to -0.86) as well as PS (r range: -0.50 to -0.61). These associations are emphasised following the two GTL extremes of pre-season camp (Wk₁) and the bye week (Wk₇). Following the intensive 8 day long pre-season camp of Wk₁, which not only incorporated gruelling two-a-day collision-based sessions but also the additional stress of final roster selection, self-reported measures were negatively affected. Whereas, following the bye week, which included 4 days off from football and university life during the Thanksgiving holiday, those same measures were reported to be positively affected.

Interestingly, on average no significant correlations were found with CMJ PP. Further, the constructs of Social recovery and Self-regulation were found to have no relationship with any dose or response variables measured in the study. For the purpose of explaining the importance of self-reported constructs that may not be directly related to either dose or response metrics, self-regulation data was split into starters and non-starters (Fig. 6-1 A). The question for this construct was "Have you achieved your football goals this week?" and a distinct divide in negative and

positive responses can be seen between those players who were selected to play in the weekly game (*positive*) and those who did not make the roster (*negative*). Although not included as part

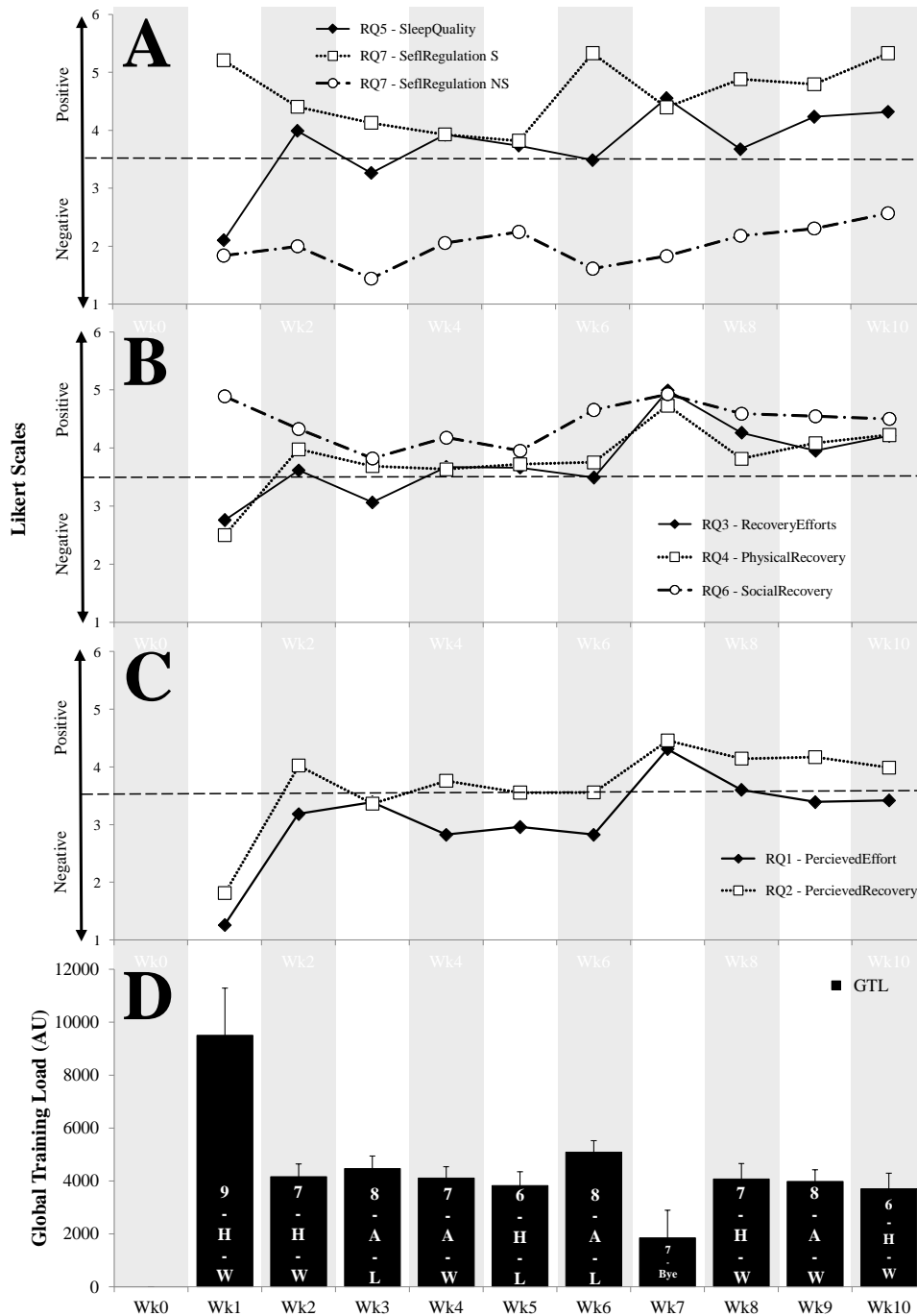


Figure 6-1. Weekly athlete self-reported measures of **A)** Sleep Quality, Self-Regulation; **B)** Recovery Efforts, Physical Recovery, Social Recovery; **C)** Perceived Effort and Perceived Recovery compared with **D)** fluctuation of weekly Global Training Load (GTL) across an 11 week competitive Canadian football season. H = Home game; A = Away game; W = Game Win; L = Game loss; Bye = No game; S = Starter; NS = Non-Starter; **D)** Numbers in columns represent days in that training week defined as game day to game day. Values are means \pm SE.

of the Chapter V study because of volume of data, the purpose is to make practitioners and coaches aware that physiological or mechanical load from football practise and competition is not the only source of stress on players that can affect performance. Well-being and mood disturbances of individual players are also responses that must be integrated and tracked in applied monitoring practice (25); in recognising that the most powerful evidenced-based data revolves around the individual player (n=1). No research is more relevant than the data collected on the individual player and team that is being monitored.

Recommendations:

- Subjective measures are useful for monitoring player’s holistic response to training and non-training stressors for practitioners and coaches to employ
- Subscales which evaluate non-training stress, well-being and mood disturbances as well as fatigue and physical recovery are valuable to incorporate and apply on a regular basis alongside other monitoring tools.

Table 6-1. Individual correlation coefficients (r) between seven modified Recovery-Cue components with Global Training Load (TL) and two neuromuscular fatigue indicators (CMJ and Postural Sway). 286 comparisons were analysed.

Recovery-Cue Component	Correlations with Modified Recovery-Cue											
	Global TL (AU)				Postural Sway (CoPA)				CMJ Peak Power (W)			
	Min	Max	Avg	SD	Min	Max	Avg	SD	Min	Max	Avg	SD
RQ1 - Perceived Effort	-0.98	-0.49	-0.86*	0.10	-0.87	-0.32	-0.61*	0.15	-0.24	0.83	0.49	0.30
RQ2 - Perceived Recovery	-0.98	-0.16	-0.78*	0.15	-0.90	-0.21	-0.58*	0.19	-0.19	0.90	0.46	0.28
RQ3 - Recovery Efforts	-0.95	0.24	-0.65*	0.22	-0.91	0.31	-0.50*	0.26	-0.25	0.86	0.46	0.26
RQ4 - Physical Recovery	-0.97	-0.22	-0.76*	0.16	-0.84	-0.17	-0.55*	0.16	-0.26	0.90	0.47	0.33
RQ5 - Sleep Quality	-0.85	0.35	-0.51*	0.24	-0.89	-0.01	-0.50*	0.24	-0.23	0.80	0.32	0.30
RQ6 - Social Recovery	-0.65	0.92	0.09	0.38	-0.64	0.83	0.11	0.39	-0.93	0.56	0.03	0.40
RQ7 - Self Regulation	-0.80	0.72	0.02	0.14	-0.89	0.65	0.01	0.40	-0.66	0.75	0.09	0.43

CoPA = Adjusted Center of Pressure; CMJ = Countermovement Jump; W = Watts * statistically significant (p <0.01).

6-2-5. Matching Training Loads

One of the original motives behind this body of work was to gain insight into the variation in TL distribution across the year (off-, pre- and in-season) as well as highlight positional or hierarchical load differences particularly through competition periods. During the off- and pre- season the TL tends to be similar throughout the positions and individuals as the attention is on conditioning, skills and general schemes of play. Once the in-season begins, the focus turns to competition and preparing the 1st team players as best as possible.

It is during this in-season period where the potential risk of detraining the 2nd string players and non-starters rises. To explain, those players who are designated as 2nd string players spend the majority of football practices shadowing those players ahead of them on the depth chart. During competitive games 2nd string players are substitutes that tend to be used sparingly (<1Quarter), and during practice the priority for physical repetitions of plays lies with the starters. Physical work or TL is therefore minimal for this group of players. Non-starters are regularly used as the “Show” team during the practices, whereby they mimic the upcoming opposition’s defense or offense to prepare the 1st string players. By completing a similar number of physical repetitions in practice, TL in these groups remains high at the beginning of the week. However, they receive no competition stimulus and in some cases have 2 to 3 days of complete rest at the back end of weeks where games are played away from home. Despite mandatory S&C sessions, over the course of an 11 week season this type of hierarchical TL distribution can lead to physical detraining, which becomes an important performance consideration when injuries occur to 1st string players (e.g. 2nd string not physically ready to compete).

Recommendations:

- Include weekly TL matching or “top up” sessions to avoid the negative effects associated with detraining, which include both performance decrements and increased threat of injury (9). Those football players at particular risk are either non-starters or those who participate in less than one quarter of the weekly game.
- Chapter IV provides a detailed description of a simulated game session designed to mimic the physiological demands of a Canadian football game-play.

6-3. LIMITATIONS & FUTURE RESEARCH

Similar to many investigations in high performance sport, and despite the novel findings, this thesis effectively represents a case study of a single team competing in Canadian football at the collegiate level. Our findings are essentially generalizable to this group of players and specific to the philosophy and style of the coaching staff. As such, further research is required to depict a broader overview of the TL distribution and NMF responses to training and competing in Canadian football. Furthermore, on an individual level, more information on position, impact exposure, training history, years of game experience and injury would provide a greater understanding of the training dose-response relationship in football. To clarify, monitoring and tracking responses at the individual level is always preferred in applied high performance settings as opposed to team level responses, which can lead to trend misinterpretation and misguided program design. The following presents areas and ideas of future research to positively impact performance in football.

Neuromuscular fatigue monitoring

- A large portion of this thesis has formed the basis of support for a submaximal NMF monitoring tool within collision-based team sports (6-*Ch.IV*), but further research is needed to confirm the capabilities of the PS within other sports and cohorts.
- CMJ and PS were selected as the primary NMF response measures, the measurement of upper body NMF using a plyometric push-up has shown potential as a useful fatigue marker following a competitive rugby league game (16). Whether the plyometric push-up is sensitive enough to track NMF in Canadian football players both acutely, chronically and post-game warrants investigation.
- Based on our findings and previous research (6-*Ch.IV,7,22*) PP of CMJ has been identified as the most congruent vertical jump parameter with changes in NMF. Further examination as to the most appropriate measure of CMJ performance is recommended as single-point concentric-based variables (e.g. peak power or force and height) are thought to be less sensitive to NMF compared to movement strategy-based variables (e.g. Force at zero velocity or Eccentric duration [20]).

Assessing Meaningful Change

- While it is recommended to carefully monitor changes in NMF status across the course of the season, more information is needed to establish thresholds of negative changes requiring intervention. This will require consistent monitoring of players that experience multiple periods of overreaching (Functional and Non-functional), which is difficult to achieve without placing individual athletes at risk.
- Once more accurate and appropriate thresholds are established, it will be important to determine whether manipulation of TL in response to NMF (CMJ and PS) changes help in the recovery and adaptation of individual players, particularly over extensive periods of high frequency training such as a competitive season.

Global Positioning Systems: External Load & Impact indices

- The relationship between GPS indices (impact and external load) and all dose-response metrics discussed in this thesis requires investigation. The combination of internal and external TLs is gaining popularity in collision-based-team sports as inclusion of both explain a greater proportion of variance than any single measure (2,31).
- Through GPS data collection an in-depth analysis into the influence of collision on football players is warranted. Specifically, quantification of frequency, intensity and distribution of force trauma during competitive game-play can enhance our understanding of Canadian football demands. Previous studies in rugby league (21) and American football (32) provide evidence as to the value of such information.

Cognitive Load

- As with many high profile sports, Canadian football requires a significant amount of strategizing and tactical awareness within games as well as a substantial amount of time spent off the field for mental preparation (e.g. team meetings, video study [13]). Using subjective methods such as dRPE, which has the ability to quantify the specific mediators of load within a session (20), examination of the cognitive or technical load placed on players in varying positions and roles would be an interesting avenue to explore particularly

in terms of recovery. For example, do Quarterbacks require more time to allow for mental recovery?

- The pathway to professional football (either American or Canadian) runs through the collegiate system. Investigating the impact of non-training stressors and cognitive load on student athletes is another viable area of future research.

Statistical modelling: Training Load – Injury Relationship

- A major limitation of the season long study presented in chapter IV was a lack of injury occurrence data. Similar to those models developed in rugby league (8), further work is needed to establish the influence of TL on training injury and performance.
- Multiple seasons worth of monitoring data would be required to assess and begin to accurately model acute-chronic TL ratios, injury prevalence and their relationship with NMF and performance (4,9).

6-4. CONCLUSION

Recent evidence suggests that athletes, coaches and practitioners are engaging more in a scientific approach to high performance monitoring (13,29) and this thesis provides insight for both the applied and theoretical sport science community.

6-4-1. Theoretical synopsis

Illustration and support for a two-factor training after-effect model (fitness-fatigue), as opposed to single unified response (supercompensation), can be seen throughout the findings. Following acute (*Ch.III*) and weekly (*Ch.IV*) exposure of high internal TLs both CMJ and PS responded with a similar initial fatigue response (negative performance), followed by two differing recovery profiles. In both studies, performance of PS recovered at a slower rate than the CMJ, highlighted by a failure of PS values to return to baseline at any measured time point. In contrast, CMJ performance returned to baseline within 24hrs of the acute G-Sim and, although was suppressed during the first few weeks of the season, eventually showed improvement after the relatively low TL of the bye week. This enhancement compared to baseline would be indicative of fatigue dissipation and a manifestation of the fitness after-effect (positive performance). It is clear that not

only do the results support the presence of TL induced fitness and fatigue after-effects but also for the existence of multiple specific-after effects (5).

Initially proposed by Chiu and colleagues (5, Fig 2-3) in their revision of fitness-fatigue model, the possibility of multiple specific fitness and fatigue after-effects offers a partial explanation as to observed difference in CMJ and PS recovery profile following exposure to high TLs. In accepting the logic that PS relies more heavily on the somatosensory system (26) than a predominantly neuromuscular reliant CMJ, then the differing recovery time-course of these parameters provide evidence of a specific neuromuscular after-effect as well as a somatosensory after-effect. While neuromuscular recovery in the season-long study may well have been aided by regular S&C sessions, the combined fatigue and fitness response for somatosensory system remained compromised (negative) throughout. Conceptually, these differences in recovery are considered residual training effects and serve to support the basis for sequential training. Sequential training suggests that the rate of decay of a residual training effect can be modulated with either minimal training stimulus or through the periodic dosing of the specified training factor. The return to baseline of CMJ performance concomitant with neural promoting S&C sessions in the season-long study can be seen as evidence for the inclusion of specified training factors during extended competitive seasons.

6-4-2. Applied synopsis

In football, consistent and reliable monitoring of the training dose-response relationship remains a challenge for numerous reasons inherent within the collision-based sport. Based on the findings, sRPE, CMJ and PS have the potential to overcome a number of these challenges and accurately monitor changes in TL and NMF status on a regular basis in football players. Importantly, this research also implies that in isolation no single parameter can consistently specify TL intolerance or predict accumulative fatigue. Therefore, the recommended focus of practitioners and coaches wishing to monitor football or, in fact, any collision-based team sport lies within a combination of objective (e.g. CMJ, PS and GPS) and subjective (e.g. sRPE and Wellness questionnaires) tools selected to reliably quantify both dose of- and response to- training, non-training and competitive stressors.

Taken together, the research presented has broadened the understanding of how to begin implementing an effective and practical monitoring system within Canadian football and serves to illustrate a players' neuromuscular and somatosensory response to a sport with unique demands. More importantly, we acknowledged the use of Canadian football as a vehicle to elucidate challenges evident in many other collision-based team sports. This work has the potential for widespread impact and application in numerous other sports with similar demands and challenges. While further work is required to determine the best combination, the parameters investigated show promise that can help begin to reliably establish the training dose-response relationship and predict changes in performance of collision-based team sport athletes over competitive periods.

6-5. REFERENCES

1. Botterill, C, and Wilson, C. (2002) *Overtraining: Emotional and interdisciplinary dimensions*. In: Enhancing recovery: Preventing underperformance in athletes. Ed: Kellman, M. Champaign, IL: Human Kinetics. 143-159
2. Bradley, WJ, Cavanagh, BP, Douglas, W, Donovan, TF, Morton JP, and Close, GL. Quantification of training load, energy intake, and physiological adaptations during a rugby preseason: A case study from an elite European rugby union squad. *J Strength Cond Res* 29(2): 534-544, 2015.
3. Busso, T. and Thomas, L. Using mathematical modelling in training planning. *Int J Sports Physiol Perf* 1: 400-405, 2006.
4. Carey, DL, Blanch, P, Ong K-L, Crossley, KM, Crow, J, and Morris, ME. Training loads and injury risk in Australian football – differing acute:chronic workload ratios influence match injury risk. *Brit J Sports Med* 1: 1-7, 2016.
5. Chiu, LZ, and Barnes, JL. The fitness-fatigue model revisited: Implications for planning short- and long term training. *Strength Cond J* 25(6): 42-51.2003
6. Clarke, N, Farthing, JP, Lanovaz, JL, and Krentz, JR. Direct and indirect measurement of neuromuscular fatigue in Canadian football players. *Appl Physiol Nutr Metabol* 40(5): 464-473, 2015.
7. Cormack SJ, Newton RU, McGuigan MR, et al. Neuromuscular and endocrine responses of elite players during an Australian Rules football season. *Int J Sports Physiol Perform* 3: 439-453, 2008.
8. Gabbett, TJ, and Domrow, N. Relationships between training load, injury, and fitness in sub-elite collision sport athletes collision sport athletes. *J Sports Sci* 25(13): 1507-1519, 2007.
9. Gabbett, TJ. The training-injury prevention paradox: should athletes be training smarter and harder? *Brit J Sports Med* 50: 273-280, 2016.
10. Gathercole, R, Sporer, B, and Stellingwerff, T. Countermovement jump performance with increased training loads in elite female rugby athletes. *Int J Sports Med* 36: 722-728, 2015.
11. Gil-Rey, E, Lezaun, A, and Los Arcos, A. Quantification of the perceived training load and its relationship with changes in physical fitness performance in junior soccer players. *J Sports Sci* 33(20): 2125–2132, 2015.
12. Green, JM, McIntosh, JR, Hornsby, J et al. Effect of exercise duration on session RPE at an individualized constant workload. *Eur J Appl Physiol* 107(5): 501–507, 2009.
13. Halson, SL. Monitoring training load to understand fatigue in athletes. *Sports Med* 44(S2): 139–47, 2014.
14. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41(1): 3-13. 2009.
15. Impellizzeri, FM, Rampini, E and Marcora, SM. Physiological assessment of aerobic training in soccer. *J Sport Sci* 23(6): 583-592, 2005.

16. Johnston, RD, Gibson, NV, Twist, C, Gabbett, TJ, MacNay SA, and MacFarlane NG. Physiological responses to an intensified period of rugby league competition. *J Strength Cond Res* 27(3): 643–654, 2013.
17. Lambert, MI, and Borresen, J. A theoretical basic of monitoring fatigue: A practical approach for coaches. *Int J Sports Sci Coaching* 1(4): 371–375, 2006.
18. Los Arcos, A, Mendez-Villanueva, A, Yanci, J, et al. Respiratory and muscular perceived exertion during official games in professional soccer players. *Int J Sports Physiol Perform* 11(3): 301–304, 2016.
19. Los Arcos, A, Yanci, J, Mendiguchia, J et al. Rating of muscular and respiratory perceived exertion in professional soccer players. *J Strength Cond Res* 28(11): 3280–3288, 2014.
20. McLaren, S.J., Smith, A., Spears IR, Spears, and Weston, M. A detailed quantifications of differential ratings of perceived exertion during team-sport training. *J Sci Med Sport* 20(3): 290-295, 2017.
21. McLellan, C.P., and Lovell, D.I, and Gass, G.C. 2011. Biochemical and endocrine responses to impact and collision during elite rugby league match play. *J Strength Cond Res* 25(6): 1553–1562, 2011.
22. McLellan, CP, and Lovell, DI. Neuromuscular responses to impact and collision during elite rugby league match play. *J Strength Cond Res* 26(5): 1431–1440, 2012.
23. Ritchie, D, Hopkins, WG, Bucheit, M, Cordy, J, and Barlett, JD. Quantification of training and competition load across a season in an elite Australian football club. *Int J Sports Physiol Perform* 11: 474-479, 2016.
24. Saw, AE, Main LC, and Gatin, PB. Monitoring athletes through self-report: Factors influencing implementation. *J Sports Sci Med* 14: 137-146, 2015.
25. Saw, AE, Main LC, and Gatin, PB. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *Brit J Sports Med* 50: 281-291, 2016
26. Spiliopoulou, SI, Amiridis, IG, Tsigganos, G, Economides, D. and Kellis, E. Vibration Effects on Static Balance and Strength. *Int J Sports Med* 31: 610–616, 2010.
27. Taha, T and Thomas, SG. Systems modelling of the relationship between training and performance. *Sports Med* 33(14): 1061-1073. 2003.
28. Taylor K, Chapman D, Cronin J, et al. Fatigue monitoring in high performance sport: a survey of current trends. *J Aust Strength Cond* 20: 12–23, 2012.
29. Twist, C and Highton, J. Monitoring fatigue and recovery in rugby league players. *Int J Sports Physiol Perform* 8: 467-474, 2013.
30. Weaving, D, Marshall, P, Earle, K, Nevill, A, and Abt, G. Combining internal- and external-training-measures in professional rugby league. *Int J Sports Physiol Perform* 9: 905-912, 2014.
31. Wellman, AD, Coad, SC, Goulet, GC, and McLellan, CP. Quantification of competitive game demands of NCAA division I college football players using global positioning systems. *J Strength Cond Res* 30(1): 11-19 2015.

32. Weston, M, Siegler, J, Bahnert, A, et al. The application of differential ratings of perceived exertion to Australian Football League matches. *J Sci Med Sport* 18(6):704–708, 2015.

APPENDIX A

METHODOLOGICAL CONSIDERATIONS

Below are summary tables presenting the major pros, cons and methodological considerations when implementing the monitoring tools discussed in the Chapter II Literature review. More specific collision-based sport considerations are eluded to at the bottom of each table.

Table A-1. Methodological considerations for using objective and subjective training load monitoring tools

TRAINING LOAD

Training Load – TRIMP (HR Response)

- Equation relies on weighting factors, the origins of which have been criticised (9)
- HR monitor, run the risk of losing data should the instrument fail or HR monitor not available or practical for that particular training session
- Please see Heart Rate Table A-3

Session-RPE

- Inexpensive and easily administered to large group of athletes
- RPE has a remarkable value as a psychophysiological integrator – indicator of holistic stress
- Robust relationship between RPE and measures of intensity
- Ability to produce arbitrary unit for all training modalities e.g. Global Training Load
- Familiarisation and understanding is needed as it is a subjective measure
- Appropriate instructions and the original CR-10 or CR-100 point scale must be used (7)

Collision-based sport considerations

- Lambert & Borresen (9) suggested - Session RPE may cater for how players' feels, but the underlying physiological stress arising from the collisions may not be well represented with score
 - Impellizzeri et al. (7) - counterpoint: Session-RPE validated in both rugby codes (5,6,8)
 - Match session-RPE moderately correlated ($r = 0.54$) to number of completed tackles in game pro rugby league (4)
-

Table A-2. Methodological considerations for monitoring functional performance in athletes

FUNCTIONAL PERFORMANCE TESTS

- Allows easy and regular implementation of testing throughout differing training phases
- Large groups can be assessed in minimal time
- Individual assessment of training responses can be achieved due to minimal equipment and time demands
- Performance indicators are more relevant to sports performance and can provide useful information for the coaches and athletes even if no negative adaptations are apparent
- Limited information regarding the cause of performance reduction obtained

Vertical Jumps

- Majority of studies report “good” reliability in jump parameters
- The relationship between typical error and smallest worthwhile change in performance has only been reported in the sport of rugby league (15)
- No consensus as to which vertical jump parameter is the most appropriate in tracking fatigue
- Large diversity of jump parameter response to fatigue is problematic and needs further work (15)

Collision-based sport considerations

- High probability of injury has the potential to negatively effective consistency maximal functional performance tests such as vertical jumps.
-

Table A-3. Methodological considerations for monitoring athletes using heart rate metrics

HEART RATE

- HR is probably one of the most accessible physiological measures available (1)
- HR monitors are generally affordable and necessitate minimal interference to training
- Reductions in HR_{max} has been suggested as a good marker of overreaching and/or overtraining (1,3)
 - Caution - reduction in HR during or after exercise may also occur as a positive training response due to improvements in cardiovascular efficiency. Accuracy of measuring changes in HR and HRR may be therefore be compromised (3,10)
- The day-to-day variability in HR is relatively high (10).
 - From test to test, a change in HRR > 6 bpm or in submax HR > 3 bpm can be regarded as a meaningful change under controlled conditions (10)
 - Submax HRR testing protocols should target exercise intensities ranging in between 86 – 93 % of HR max. This intensity is associated with least day-to-day variation (11)
- Most evidence for using HRV shows elevations in already overtrained individuals. To date minimal evidence exists supporting its use as an early indicator of maladaptation to training
- The smallest meaningful change in submax HR indices during regular training has so far only been established for youth (adolescent) soccer players (2)
 - More work is needed to quantify these values in other populations
- Most HR studies have investigated responses to increases in endurance training only, although some investigations have been conducted with team sport athletes
- Variations in muscle glycogen and diet can affect lactate concentration, so conditions prior to submax tests require strict standardisation for repeatable measures (12)

Collision-based sport considerations

- Commercially available HR monitors are worn on the chest and non-compressible
 - Injury to players are possible with direct contact on HR monitor and buy-in may be subsequently affected
 - High probability of HR monitor being damaged due to collision and a subsequent loss of data
-

Table A-4. Methodological considerations for using athlete self-report measures

ATHLETE SELF-REPORT MEASURES

- A simple and cost-effective approach to monitoring an athlete's response to training (13)
- Evidence that subjective measures of perceptual ratings of fatigue and recovery are just as valid, if not more sensitive for detecting changes in TL than objective measures (12)
- Less evidence available regarding relationship with subjective measures & changes in performance (13)
- Daily use can provide good longitudinal data
- Athletes can become habituated or anticipate the responses that will lead to favourable outcomes (12)
- Efficacy is dependent on how they are implemented and used
- Influencing factors of the implementation and compliance of ASRM (14)
 - Measurement factors
 - *Accessibility and timing/frequency of completion*
 - *Design which obtains quality, meaningful data with minimal burden*
 - *Careful consideration of the questions, number of questions, effective utilization of technology along with incidence of feedback to athlete (12)*
 - Social environmental factors
 - *Buy-in and reinforcement*
 - *Organization promotes use through ongoing investment in staff and resources*
 - *Establishing a positive culture through education and trust in the process*
 - *Culture is further supported by the perceptions and actions of the end-users (e.g. feedback that is acted upon to improve training and eventually performance)*
- Ultimately the implementation of ARSM will be unique to the sports program and their short and long-term goals
- Implementation practices may also be further tailored to meet the needs of individuals within the program

Collision-based sport considerations

- Promising tool for regular, guaranteed uninterrupted monitoring of players who's probability of injury is high which can hamper some objective measures
-

APPENDIX A - REFERENCES

1. Bosquet, L, Merkari S, Arvisais D, et al. Is heart rate monitoring a convenient tool to monitor over-reaching? A systematic review of the literature. *Brit J Sports Med* 42: 709-714, 2008.
2. Buchheit, M, Mendez-Villanueva, A, Quod, MJ, et al. Determinants of the variability of heart rate measures during a competitive period in young soccer players. *Eur J Appl Physiol* 109(5): 869-878, 2010.
3. Coutts AJ, Reaburn P, Piva T, et al. Changes in selected biochemical, muscular strength, power, and endurance measures during deliberate overreaching and tapering in rugby league players. *Int J Sport Med* 28: 116-124, 2007a
4. Coutts, AJ, Sirotic, AC, Knowles, H, and Catterick, C. *Monitoring training loads in professional rugby league*. In: Reilly, T, and Korkusuz, F, eds. *Science and Football VI*. London, UK: Routledge, 2008. pp. 272-277.
5. Cunniffe, B, Griffiths, H, Proctor, W, Davies, B, Baker, JS, and Jones, KP. Mucosal Immunity and Illness Incidence in Elite Rugby Union Players across a Season. *Med Sci Sports Exer* 2: 388-397, 2010.
6. Gabbett, T, and Domrow, N. Relationships between training load, injury, and fitness in sub-elite collision sport athletes collision sport athletes. *J Sports Sci* 25(13): 1507-1519, 2007.
7. Impellizzeri, FM, Borg, E, and Coutts, AJ. Intersubjective comparisons are possible with an accurate use of the Borg CR scales. *Int J Sports Physiol Perform* 6:2-4, 2011.
8. Killen, NM, Gabbett, TJ, and Jenkins, DG. Training loads and incidence of injury during the preseason in professional rugby league players. *J Strength Cond Res* 24(8): 2079-2084, 2010.
9. Lambert, MI, and Borresen, J. Measuring training load in sports. *Int J Sports Physiol Perform* 5: 406-411, 2010.
10. Lamberts, R, and Lambert, M. Day-to-day variation in heart rate at different levels of submaximal exertion: implications for monitoring training. *J Strength Cond Res* 23(3): 1005-1010, 2009.
11. Lamberts, R, Maskell, S, Borresen, J, et al. Adapting workload improves the measurement of heart rate recovery. *Int J Sport Med* 32: 698-702, 2011.
12. Robson-Ansley, P, Gleeson, M, and Ansley, L. Fatigue management in the preparation of Olympic athletes. *J Sports Sci* 27(13): 1409-1420, 2009.
13. Saw, AE, Main LC, and Gastin, PB. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *Brit J Sports Med* 50, 281-291, 2016.
14. Saw, AE, Main, LC, and Gastin, PB. Monitoring athletes through self-report: Factors influencing implementation. *J Sports Sci Med* 14, 137-146 2015.

15. Twist, C, and Highton, J. Monitoring fatigue and recovery in rugby league players. *Int J Sports Physiol Perform* 8: 467-474, 2013.

APPENDIX B

CHAPTER V - STATISTICS

Full non-significant statistics from Chapter V: Novel approach to neuromuscular fatigue monitoring of a competitive collegiate season in Canadian football players.

Group main effect:

- PP ($F_{(1,246)} = 0.099$; $P = 0.753$; $\eta_p^2 = 0.013$)
- TOV ($F_{(1,246)} = 0.039$; $P = 0.844$; $\eta_p^2 = 0.02$)
- CoPA ($F_{(1,266)} = 1.094$; $P = 0.375$; $\eta_p^2 = 0.013$)
- Log10GTL ($F_{(1,266)} = 1.456$; $P = 0.229$; $\eta_p^2 = 0.012$)

Group x week interaction:

- PP ($F_{(9,246)} = 0.422$; $P = 0.923$; $\eta_p^2 = 0.015$)
- TOV ($F_{(9,246)} = 0.789$; $P = 0.627$; $\eta_p^2 = 0.11$)
- CoPA ($F_{(9,266)} = 1.084$; $P = 0.375$; $\eta_p^2 = 0.21$)
- Log10GTL ($F_{(9,266)} = 1.090$; $P = 0.371$; $\eta_p^2 = 0.15$)

APPENDIX C

COMBINED TEST-RETEST RELIABILITY

Combined test-retest reliability data of all indirect NMF variables measured in this thesis. Total samples size of 55 players.

Table C-1. Test-retest reliability of indirect neuromuscular fatigue variables assessed using time points 24 hours before (T_0) and immediately before (T_{24}) pre-season commencement. Data from all 55 participants was analyzed using the intra-class correlation coefficient (ICC), technical error of the measurement (TEM), and a one sample t-test of percent change from T_0 ran against zero.

Postural Sway	CoPx (mm)	CoPy (mm)	CoPSD_x (mm)	CoPSD_y (mm)	CoP_A (mm²)
T _{Base}	37.5±9.4	27.4±9.9	9.6±2.5	7.1±2.8	868.4±527.2
T _{Pre}	38.2±11.4	26.3±8.3	9.7±3.1	6.7±2.1	843.1±487.1
Change (%)	1.0±13.3	-3.6±12.8	1.5±9.6	-5.1±15.2	-2.4±8.6
t-test (p)	0.834	0.365	0.684	0.479	0.291
ICC range	0.88 - 0.99	0.73 - 0.99	0.91 - 0.99	0.73 - 0.98	0.94 - 0.99
TEM (%)	13.8	19.7	13.5	24.9	12.2

CMJ	TOV (m/s)	PP (W)	PF (Nm)
T _{Base}	2.81±0.19	5587.1±901.8	2479.9±343.5
T _{Pre}	2.80±0.23	5620.7±855.1	2493.1±350.6
Change (%)	0.5±2.3	1.1±3.8	0.3±6.1
t-test (p)	0.377	0.465	0.637
ICC	0.95-0.99	0.94-0.99	0.77-0.94
TEM (%)	4.1	5.8	8.7

CMJ = Countermovement jump; TOV = Take-Velocity; PP = Peak Power; CoPSD_{x/y} = Center of Pressure standard deviation along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoPx/y = Center of Pressure displacement along Anterior/Posterior(y) and Medio/Lateral(x) axis; CoP_A = Adjusted area covered by CoP trajectory. CoP data was adjusted to exclude the 5% of CoP locations that were the farthest from the center of the CoP range. Values are means ± SD.

APPENDIX D

MODIFIED RECOVERY STRESS QUESTIONNAIRE FOR ATHLETES

Player:

1, How much effort was required to complete my workouts last week?

<i>Hardly any effort</i>	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4	4	4	4
	3	3	3	3	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1	1
<i>Excessive Effort</i>	0	0	0	0	0	0	0	0	0	0	0
Week	0	1 UofA	2 UofM	3 UBC	4 UofR	5 UofC	6 BVE	7 UofM	8 UBC	9 UofA	10

2, How recovered did I feel before my workouts last week?

<i>Energized/recharged</i>	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4	4	4	4
	3	3	3	3	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1	1
<i>Still not recovered</i>	0	0	0	0	0	0	0	0	0	0	0
Week	0	1 UofA	2 UofM	3 UBC	4 UofR	5 UofC	6 BVE	7 UofM	8 UBC	9 UofA	10

3, How successful was I at rest and recovery activities last week?

<i>Successful</i>	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4	4	4	4
	3	3	3	3	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1	1
<i>Not successful</i>	0	0	0	0	0	0	0	0	0	0	0
Week	0	1 UofA	2 UofM	3 UBC	4 UofR	5 UofC	6 BVE	7 UofM	8 UBC	9 UofA	10

4, How well did I recover physically last week?

<i>Always</i>	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4	4	4	4
	3	3	3	3	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1	1
<i>Never</i>	0	0	0	0	0	0	0	0	0	0	0
Week	0	1 UofA	2 UofM	3 UBC	4 UofR	5 UofC	6 BVE	7 UofM	8 UBC	9 UofA	10

5, How Satisfied and relaxed was I as I fell asleep in the last week?

<i>Always</i>	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4	4	4	4
	3	3	3	3	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1	1
<i>Never</i>	0	0	0	0	0	0	0	0	0	0	0
Week	0	1 UofA	2 UofM	3 UBC	4 UofR	5 UofC	6 BVE	7 UofM	8 UBC	9 UofA	10

6, How much fun did I have last week?

<i>Always</i>	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4	4	4	4
	3	3	3	3	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1	1
<i>Never</i>	0	0	0	0	0	0	0	0	0	0	0
Week	0	1 UofA	2 UofM	3 UBC	4 UofR	5 UofC	6 BVE	7 UofM	8 UBC	9 UofA	10

7, How convinced was I that I could achieve my goals during performance last week?

<i>Always</i>	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4	4	4	4
	3	3	3	3	3	3	3	3	3	3	3
	2	2	2	2	2	2	2	2	2	2	2
	1	1	1	1	1	1	1	1	1	1	1
<i>Never</i>	0	0	0	0	0	0	0	0	0	0	0
Week	0	1 UofA	2 UofM	3 UBC	4 UofR	5 UofC	6 BVE	7 UofM	8 UBC	9 UofA	10

Figure D-1. The Recovery Stress questionnaire for athletes was modified and administered weekly before neuromuscular fatigue monitoring to gather subjective data during Chapter V (1).

APPENDIX D - REFERENCES

1. Kellman, M, and Kallus, W. *Recovery-Stress Questionnaire for Athletes*. Champaign, IL: Human Kinetics, 2001.