Peak Running Intensities of Professional Football

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy
to
Institute of Sport, Exercise and Active Living
Victoria University, Melbourne
October, 2016

Jace Angus Delaney
Bachelor of Exercise and Sports Science
Bachelor of Exercise and Sports Science (Honours)

ABSTRACT

The use of global positioning systems (GPS) in team sports is now widespread, providing coaches with a useful tool for accurately quantifying the physical demands of training and competition. A number of training load metrics have been identified using these systems, however it was previously unclear which variables were most appropriate for use in a team-sport setting. Furthermore, traditional match analysis techniques do not accurately detect within-match fluctuations in running intensity that may provide insight into developing specific training and recovery methodologies. This series of studies first established the peak running intensities achieved during professional rugby league competition, using a novel moving average technique. This method outlined a considerable oversight in traditional methods, where the peak periods of play may have been missed. Secondly, these studies investigated the contextual factors affecting running intensity within interchange rugby league players. Next, the importance, reliability and usefulness of acceleration-based measures using GPS technology within team sports were evaluated. A comprehensive assessment of the peak running intensities achieved during team-sport competition was then performed, with particular reference to the football codes. Lastly, a novel application of power law analysis was used to quantify the relationship between running intensity and the duration of the moving average applied. This series of studies provides coaches with a precise overview of the true peak intensities of competition, and furthermore presents a simple, practical tool for estimating match running intensity as a function of time. As a result, coaches may provide players with an environment where technical, competitive and physical traits can be developed concurrently, using specific methodologies such as small-sided games. If athletes are exposed to the rigors of competition during training they will become more resilient, and when faced with these situations during a match, these events will be less "catastrophic".

STUDENT DECLARATION

I, Jace Delaney, declare that the PhD thesis by publication entitled Peak Running Intensities of Professional Football is no more than 100,000 words in length, including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

[redacted]

Jace A Delaney

30/6/2017

Date Submitted

Peak Running Intensities of Professional Football

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy
to
Institute of Sport, Exercise and Active Living
Victoria University, Melbourne
October, 2016

Jace Angus Delaney
Bachelor of Exercise and Sports Science
Bachelor of Exercise and Sports Science (Honours)

ABSTRACT

The use of global positioning systems (GPS) in team sports is now widespread, providing coaches with a useful tool for accurately quantifying the physical demands of training and competition. A number of training load metrics have been identified using these systems, however it was previously unclear which variables were most appropriate for use in a team-sport setting. Furthermore, traditional match analysis techniques do not accurately detect within-match fluctuations in running intensity that may provide insight into developing specific training and recovery methodologies. This series of studies first established the peak running intensities achieved during professional rugby league competition, using a novel moving average technique. This method outlined a considerable oversight in traditional methods, where the peak periods of play may have been missed. Secondly, these studies investigated the contextual factors affecting running intensity within interchange rugby league players. Next, the importance, reliability and usefulness of acceleration-based measures using GPS technology within team sports were evaluated. A comprehensive assessment of the peak running intensities achieved during team-sport competition was then performed, with particular reference to the football codes. Lastly, a novel application of power law analysis was used to quantify the relationship between running intensity and the duration of the moving average applied. This series of studies provides coaches with a precise overview of the true peak intensities of competition, and furthermore presents a simple, practical tool for estimating match running intensity as a function of time. As a result, coaches may provide players with an environment where technical, competitive and physical traits can be developed concurrently, using specific methodologies such as small-sided games. If athletes are exposed to the rigors of competition during training they will become more resilient, and when faced with these situations during a match, these events will be less "catastrophic".

STUDENT DECLARATION

I, Jace Delaney, declare that the PhD thesis by publication entitled Peak Running Intensities of Professional Football is no more than 100,000 words in length, including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Jace A Delaney

Date Submitted

DEDICATIONS AND ACKNOWLEDGEMENTS

LIST OF PUBLICATIONS ARISING FROM THIS THESIS

Peer-reviewed Articles

Delaney, J. A., Scott, T. J., Thornton, H. R., Bennett, K. J., Gay, D., Duthie, G. M., & Dascombe, B. J. (2015 – Chapter 3). Establishing duration specific running intensities from match-play analysis in rugby league. *Int J Sports Physiol Perform, 10*(6), 725-731. doi: 10.1123/ijspp.2015-0092.

Delaney, J. A., Thornton, H. R., Duthie, G. M., & Dascombe, B. J. (2016 – Chapter 4). Factors that influence running intensity in interchange players within professional rugby league. *Int J Sports Physiol Perform*, *11*(8), 1047-1042. doi: 10.1123/ijspp.2015-0559.

Delaney, J. A., Thornton, H. R., Cummins, C. J., & Duthie, G. M. (2017 – Chapter 5). Importance, reliability and usefulness of acceleration measures in team sports. *J Strength Cond Res.* (Published Ahead of Print). doi: 10.1519/JSC.0000000000001849.

Delaney, J. A., Duthie, G. M., Thornton, H. R., Scott, T. J., Gay, D., & Dascombe, B. J. (2016 – Chapter 6). Acceleration-based running intensities of professional rugby league match play. *Int J Sports Physiol Perform*. *11*(6), 802-809. doi: 10.1123/ijspp.2015-0424.

Delaney, J. A., Thornton, H. R., Pryor, J. F., Stewart, A. M., Dascombe, B. J., & Duthie, G. M. (2016 – Chapter 7). Duration specific running intensities of international Rugby competition: Implications for training prescription. *Int J Sports Physiol Perform.* (Published Ahead of Print). doi: 10.1123/ijspp.2016-0469.

Delaney, J. A., Thornton, H.R., Burgess, D. J., Dascombe, B. J., & Duthie, G. M. (2017 – Chapter 8). Duration-specific running intensities of Australian Football match play. *J Sci Med Sport.* (Published Ahead of Print). doi: 10.1016/j.jsams.2016.11.009.

Delaney, J. A., Thornton, H.R., Rowell, A. E., Dascombe, B. J., Aughey, R. J., & Duthie, G. M. (2017 – Chapter 9). Modelling the decrement in running intensity within professional soccer players. *Sci Med Football.* (Accepted for Publication).

Delaney, J. A., Thornton, H. R., Scott, T. J., Ballard, D. A., Duthie, G. M., Wood, L. G., & Dascombe, B. J. (2016 – Appendix 2). Validity of skinfold-based measures for tracking changes in body composition in professional rugby league players. *Int J Sports Physiol Perform, 11*(2), 261-266.

Conference Proceedings

Delaney, J. A., Thornton, H. R., & Duthie, G. M. Modelling peak running intensity in football. Poster presentation at the Australian Strength and Conditioning Association Conference, Melbourne, 2016. (Appendix 1)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

%	Percentage
%BF	Percentage body fat
~	Approximately
<	Less than
>	Greater than
±	Plus/minus
≤	Less than or equal to
≥	Greater than or equal to
↑	Increase
↓	Decrease
2C	2 compartment
3C	3 compartment
4C	4 compartment
Acc	Acceleration
af	Forward acceleration
AF	Australian football
AFL	Australian football league
Ave Acc	Average acceleration
Ave Acc/Dec	Average acceleration/deceleration
Ave Dec	Average deceleration
AveP$_{met}$	Average metabolic power
BD	Body density
BIA	Bioelectrical impedance analysis
BMC	Bone mineral content
C	Celcius
CD	Central defender
CI	Confidence interval
CK	Creatine kinase
CL	Confidence limit

CM	Central midfielder
cm	Centimetre
COM	Centre of mass
CV	Coefficient of variation
Dec	Deceleration
df	Degrees of freedom
DXA	Dual x-ray absorptiometry
EC	Energy cost
EF	Edge forwards
EqD	Equivalent distance
EqM	Equivalent mass
EqS	Equivalent slope
ES	Effect size
EWMA	Exponentially weighted moving average
FB	Fullbacks
FFM	Fat-free mass
FFSTM	Fat-free soft tissue mass
FM	Fat mass
g	Gravity
g'	Vectoral sum of forward acceleration and gravity
GPS	Global positioning systems
H	Horizontal
HA	Halves
HDOP	Horizontal dilution of precision
HK	Hookers
HPD	High-power distance
HPR	High-power running
hr	Hour
HS	High speed
HSD	High-speed distance

HSR	High-speed running
Hz	Hertz
ICC	Intraclass correlation coefficient
IFT	30:15 Intermittent Fitness Test
Kg	Kilogram
km	Kilometre
$km \cdot h^{-1}$	Kilometres per hour
La	Lactate
LF	Loose forwards
LM	Lean mass
LMI	Lean mass index
LPM	Local positioning measurement
m	Metre
$m \cdot min^{-1}$	Metres per minute
m·s-1	Metres per second
MAS	Maximal aerobic speed
MF	Middle forwards
MID	Midfielders
min	Minute
$mmol \cdot L^{-1}$	Millimole per litre
MobB	Mobile backs
NRL	National Rugby League
OB	Outside backs
ºC	Degrees celcius
p	Alpha
P_{met}	Metabolic power
r	pearson's correlation coefficient
R^2	Pearson's r squared
RHIE	Repeated high-intensity efforts
RKS	Rucks

RMANOVA	Repeated measures analysis of variance
s	Second
SD	Standard deviation
SEE	Standard error of the estimate
SkF	Skinfold-based prediction equation
SSG	Small-sided games
STR	Striker
SWC	Smallest worthwhile change
SWD	Smallest worthwhile difference
T	Terrain
T5	Tight 5
tan	Tangent
TB	Tall backs
TE	Typical error
TEM	Typical error of measurement
TF	Tall forwards
USG	Urine specific gravity
v	Velocity
VHSD	Very-high-speed distance
VHSR	Very-high-speed running
vIFT	Maximum speed attained before exhaustion during the 30:15 Intermittent Fitness Test
W	Watts
$W \cdot kg^{-1}$	Watts per kilogram
WD	Wide defender
WM	Wide midfielder
WNG	Winger
yr	Year
Σ7	Sum of seven
χ2	Chi square statistic

Chapter 1

General Introduction

BACKGROUND

Team sports can be characterised by brief bouts of high-intensity running interspersed with longer periods of low-intensity activity (Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007). There is an abundance of literature pertaining to the analysis of match demands within professional team sports. Originally, time-motion analyses from video footage were used to quantify the physical requirements of competition, however advances in technology have permitted the accurate assessment of athletes' movement demands using global positioning system (GPS) technology. Originally designed for military purposes, this satellite-based navigational technology has grown in popularity in both the commercial and public arena. The system consists of 27 satellites which are constantly orbiting the earth, with signals transferred to and from receivers positioned locally. Using this signal, the GPS receiver is able to calculate distance to the satellite. Based upon the distance to at least four satellites, accurate information of the receiver's latitude, longitude and altitude can be computed (Larsson, 2003). In addition, speed is calculated by examining the frequency of the satellite signal, which is subject to change due to movement of the receiver, known as the Doppler shift method (Larsson, 2003). These techniques were first used for the tracking of athletes in 1997, and have since been used extensively by coaches, sports scientists, and athletes alike to quantify basic movement patterns, including speed, distance, acceleration and deceleration (Schutz & Chambaz, 1997).

Global positioning systems are now used extensively in team sports worldwide, such as rugby league, rugby union, Australian football (AF), cricket, hockey and soccer (Cummins, Orr, O'Connor, & West, 2013). Physical training can be described in terms of external load completed (i.e. work), and the psychobiological outcome that occurs as a consequence (i.e. internal response) (Impellizzeri, Rampinini, & Marcora, 2005).

Typically, the internal response to training is quantifying using a subjective well-being questionnaire, session rating of perceived exertion (sRPE), or a range of heart rate (HR) indices (Akenhead & Nassis, 2016). Global positioning systems (GPS) provide valuable information regarding the external demands imposed on the athletes, and can be used for assessing adherence to prescribed loads, or for attempting to reduce the risk of overtraining and soft-tissue injuries (Cummins et al., 2013). Furthermore, the collaboration of such objective assessments of external load with measures of internal load provides practitioners with a holistic approach for monitoring fatigue and optimising performance (Impellizzeri et al., 2005). As a result, coaches and practitioners are interested in quantifying the specific demands of competition, information which can then be utilised in the prescription of training that adequately prepares athletes for competition.

RESEARCH PROBLEM

During the opening keynote address of the first World Congress of Science and Football in 1987, similarities were drawn between each of the football codes, and it was highlighted that specific components of each sport were interrelated, and that the transfer of knowledge between the games should be encouraged (Douge, 1988). The four primary football codes represented in Australia are rugby league, rugby union, AF and soccer. Whilst there are obvious resemblances between the sports, their physical and physiological requirements differ substantially. For example, rugby league, rugby union and AF are collision sports, which allow the movement of the ball via both hand and foot. In contrast, soccer is primarily a non-collision sport, where players cannot touch the ball with their hands, with the exception of the goalkeeper. In the rugby codes, an “onside” rule applies, where players are not permitted to pass the ball in a forward direction, whilst both AF and soccer allow passing and kicking of the ball in any direction. Furthermore, rugby league, rugby union and soccer are played on rectangular fields of similar dimensions, where, in contrast, AF is played on an oval field, considerably larger than the other three codes. These differences have substantial implications for the physical requirements of the sports, and therefore it is important to assess the demands of each sport independently.

The vast majority of available literature has assessed the movement demands of team-sport competition in absolute terms, or relative to time spent on the field (Cummins et al., 2013). However, due to the stochastic nature of team-sports activity, large fluctuations in intensity occur throughout a match. These fluctuations have been attributed to a myriad of factors, including fatigue (Bendiksen et al., 2012), pacing (Edwards & Noakes, 2009), individual fitness (Gabbett, Stein, Kemp, & Lorenzen, 2013) and match situation (Carling & Dupont, 2011; Gabbett, 2013b). During team sports, the knowledge of the end point of exercise has been demonstrated as a major factor in the utilisation of physiological resources throughout a bout (Billaut, Bishop, Schaerz, & Noakes, 2011), thus having implications for sports involving regular interchanges such as rugby league or AF. Furthermore, athletes may self-regulate running intensity in preparation for an intense period, or to allow adequate recovery from a high-intensity bout (Waldron & Highton, 2014). These periods of intense activity have been associated with important match events such as point scoring opportunities (Austin, Gabbett, & Jenkins, 2011d), and therefore these periods may be critical to the outcome of the game (Spencer et al., 2004). Decreases in technical performance towards the latter stages of a match may indicate that cognitive abilities may be impaired due to a state of physiological fatigue (Rampinini, Impellizzeri, Castagna, Coutts, & Wisloff, 2009).

Moreover, reductions in skill performance during the period directly following the most demanding period of play have also been reported (Black, Gabbett, Naughton, & McLean, 2015; Kempton, Sirotic, Cameron, & Coutts, 2013). If athletes are prepared for these peak periods appropriately, the relative physiological cost of these bouts will be less, which may improve the technical performance of athletes during the ensuing stages of the match.

When prescribing training relative to match demands, it is important to obtain an accurate depiction of the most demanding periods of play to ensure athletes are exposed to these intensities during training. Small-sided games (SSG) have been suggested as an appropriate method for developing physical capacities, whilst concurrently improving athletes' technical and tactical abilities (Hill-Haas, Dawson, Impellizzeri, & Coutts, 2011). Whilst these methods provide athletes with a specific environment for the development of both physical and skill-based capacities concurrently, it is vital that they are monitored relative to the most demanding periods of play, to contextualise the running intensities achieved. However, there is a poor understanding of the peak periods of team-sport competition, and it may be that current practices are not adequately preparing athletes for competition. Therefore, there is a need to provide coaches and practitioners with a clear assessment of the peak demands of competition, in an attempt to maximise the development of their athletes for competitive match-play.

OBJECTIVES

Despite the previous assessment of temporal changes in running intensity within elite-level team-sport competition, there is a paucity of information regarding the true peaks in physical activity. Firstly, it was a goal of this series of studies to determine the peak running intensity of rugby league competition, identified as the greatest distance per unit of time (i.e. speed). Secondly, this research aimed to assess how rugby league players' running intensity is influenced by contextual factors, with particular reference to interchange players. In addition, this research aimed to assess the importance, reliability and usefulness of a range of acceleration-based variables, to determine the most appropriate metrics for following studies. Lastly, these investigations used GPS technology in an attempt to accurately assess the most demanding period of match-play across the four major football codes. Overall, these studies aimed to provide coaches with a simple, practical and meaningful method for both prescribing and monitoring of specific training methodologies, relative to the peak demands of competition. Exposure to these intensities during training may result in an increased readiness to perform when faced with these situations during match-play.

PURPOSE OF THE STUDIES

Chapter 3 – Establishing duration specific running intensities from match-play analysis in rugby league

- To establish the peak speed-based running demands of elite (National Rugby League; NRL) rugby league competition, using a moving average technique.
- To examine differences between positions and moving average durations.

Chapter 4 – Factors that influence running intensity in interchange players within professional rugby league

- To investigate the independent effects of a variety of factors running intensity within interchange rugby league players.

Chapter 5 – Importance, reliability and usefulness of acceleration measures in team sports.

- To determine the inter-unit reliability of acceleration-based measures using GPS technology.
- To identify the most appropriate training variables for use within a team-sports monitoring program.

Chapter 6 – Acceleration-based running intensities of professional rugby league match-play.

- To describe the acceleration-based duration-specific running demands of elite-level rugby league competition, for the development of precise training methodologies.
- To differentiate running intensities by position and moving average duration.

Chapter 7 – Peak running intensity of international rugby: Implications for training prescription.

- To quantify the peak speed- and acceleration-based running intensities achieved during international (Test matches) rugby competition.
- To present a position- and duration-specific framework of the peak running intensities of international rugby.

Chapter 8 – Duration-specific running intensities of Australian Football match-play.

- To determine the duration-specific running intensities of elite Australian Football competition.
- To differentiate running intensities by position and moving average duration.

Chapter 9 – Modelling the decrement in running intensity within professional soccer players.

- To establish both the peak capacity and rate of decline of running intensity within elite-level soccer players, using a power law analysis.
- To examine inter-positional differences in the peak running capacities achieved, and the rate of decline in running intensity, within this population.

RESEARCH PROGRESS LINKING THE MANUSCRIPTS

This research project firstly described the most intense periods of rugby league match competition, using a novel moving average approach (Chapter 3). Further, due to the unique role of interchange players within rugby league, the contributing factors to running performance amongst these athletes were investigated (Chapter 4). Next, several acceleration-based variables were compared to determine the most appropriate method for quantifying the acceleration profile of team-sport athletes during training and competition. As such, the importance of quantifying acceleration in team sports was determined, followed by an assessment of the ability of a range of commonly-used acceleration-based variables to detect positional differences during team-sports competition (Chapter 5). The findings of this study assisted in the selection of the most appropriate variables to be used for Chapters 6 to 9. The moving average technique proposed in Chapter 3 was then applied to a range of speed- and acceleration-based variables, across each of the four football codes studied (Chapters 6, 7, 8 and 9).

Moreover, Chapter 9 depicts an investigation between the duration of the moving average utilised, and the running intensity achieved, using a novel application of power law analysis.

Overall, the research undertaken in this thesis aimed to investigate the true peaks in running intensity achieved during professional team-sports activity, specific to football codes. There are several unique applications of these studies, including the presentation of a duration-specific moving average framework, in addition to the development of position-specific thresholds for peak match intensity. Furthermore, the novel use of power law analysis within this research adds to the current knowledge regarding team-sport match analysis techniques. Both in their individual and collective capacities, these studies contribute to the current understanding of the peak movement demands of team sports, and provide recommendations for the use of these methods in preparing athletes for the rigors of competition.

Chapter 2

Literature Review

INTRODUCTION

In a team-sport setting, the physical preparation of athletes is paramount to performance. To achieve this, coaches and practitioners require objective feedback on the physical demands of training and competition, to adequately periodise a preparation program. The emergence of global positioning systems (GPS) technology as an athletic monitoring tool has provided coaches, sports scientists and athletes alike with a method of accurately assessing the movement demands of training and competition (Schutz & Chambaz, 1997). This review will focus on the application of GPS technology in team sports, with particular reference to the four primary football codes in Australia – rugby league, rugby union, Australian football (AF) and soccer.

GLOBAL POSITIONING SYSTEMS

The development of portable GPS units has permitted the application of these technologies into a wider range of settings, such as sport, providing an additional means for quantifying and understanding the spatial context of physical activity (Cummins et al., 2013). Despite the practical application of these systems, there are several limitations that must be addressed. Given that GPS receivers calculate their position based on feedback from available satellites, the impairment of this transfer of data may affect its accuracy (Larsson, 2003). For example, tall buildings or structures may impede the signal, a common issue for sports that are regularly played in large stadiums. Further to this, although only four satellites are theoretically required to triangulate the position of a GPS receiver, there is a moderate, negative correlation between the number of available satellites, and the error in total distance measured (Gray, Jenkins, Andrews, Taaffe, & Glover, 2010). Similarly, the positioning and distribution of available satellites relative to the receiver is vital to the accuracy of the data (Witte & Wilson, 2004). It can therefore be seen that these systems are not without limitation, and these possible confounding factors must be addressed when interpreting GPS data.

There have been several technological advances in GPS over time, aimed at increasing the accuracy of the information provided by these systems. For example, original systems possessed a sampling rate of 1 Hertz (Hz; samples per second), but this rate has since increased to 5 Hz, 10 Hz and 15 Hz (Scott, Scott, & Kelly, 2016), theoretically providing a more accurate reflection of the movement of the receiver. In addition, GPS are often supplemented by the inclusion of a tri-axial accelerometer, where acceleration data in three planes (X, Y and Z) are recorded at a much higher sampling rate, typically 100 Hz (Waldron, Twist, Highton, Worsfold, & Daniels, 2011). Collectively, these devices are also capable of quantifying such events as physical contacts/collisions, changes of direction, foot strikes and falls (Cummins et al., 2013). Of recent popularity are the calculations of di Prampero et al. (2005), who presented a novel method of determining the energetic cost of running, through the integration of acceleration and speed measures, where the energetic cost is converted to an instantaneous power variable (termed as metabolic power, P_{met}). As a result of these technological developments, these systems have infiltrated the team-sports arena. However, the consideration of the validity and reliability of the GPS is vital when interpreting and comparing these data.

VALIDITY AND RELIABILITY

Validity

Validity refers to the ability of an instrument to accurately measure what it intends to measure (McDermott, 2009). This is typically assessed using the standard error of the estimate (SEE), typical error of measurement (TEM), the coefficient of variation (CV), or percentage difference from the criterion measure (Scott et al., 2016). In a team-sport setting, the data produced by GPS devices are critical in quantifying external loads, differentiating performances, and comparing positional demands (Cummins et al., 2013). Large measurement error could result in the misinterpretation of data, which in turn could lead to such issues as overtraining, or even underpreparing athletes. Therefore, it is critical that these devices are valid in their measurements.

Distance Validity

There is an abundance of literature assessing the validity of GPS for quantifying the movement demands in team sports (Scott et al., 2016). Primarily, these studies have suggested that all currently commercially available GPS (i.e. 1Hz, 5Hz, 10Hz and 15Hz) exhibit acceptable validity for assessing distances covered during team-sports activities (Johnston, Watsford, Kelly, Pine, & Spurrs, 2014; Petersen, Pyne, Portus, & Dawson, 2009; Portas, Harley, Barnes, & Rush, 2010; Vickery et al., 2014). For example, it was reported that both 1 Hz and 5 Hz GPS units were capable of accurately measuring distance covered during a soccer-specific running course (SEE = 1.3-3.0% and 1.5-2.0%, respectively) (Portas et al., 2010). Similar findings were recently reported during sport-specific movements using both 10 Hz and 15 Hz units (Johnston, Watsford, et al., 2014;

Vickery et al., 2014), supporting the use of GPS technology for quantifying total distance during team-sports training and competition.

Despite the validity of these units for assessing absolute movement demands, limitations exist for some devices during running over short distances, or at high speeds, particularly for systems exhibiting lower sampling rates (Scott et al., 2016). A recent study (Rampinini et al., 2015) investigated the ability of both 5 Hz and 10 Hz GPS units to measure distance covered running at high-speed (high-sped running, HSR; >4.17 $m \cdot s^{-1}$) and very high-speed threshold (very-high-speed running, VHSR; >5.56 $m \cdot s^{-1}$). It was revealed that when compared to the 5 Hz units, the 10 Hz units were able to more accurately assess both HSR (CV = 4.7% vs. 7.5%) and VHSR (CV = 10.5% vs. 23.2%). Interestingly, the increase in sampling rate from 10 Hz to 15 Hz has been shown to illicit no additional benefit (Johnston, Watsford, et al., 2014), though this may be due to the interpolation method used to establish 15 Hz data, as these units only exhibit true sampling rates of 5 Hz (Nagahara et al., 2016). Taken together, these findings demonstrate not only the effect of an increased sampling rate on the accuracy of these measures, but also the decreased validity of GPS for assessing higher-speed activities which are a common element of team sports.

Speed Validity

When assessing the running demands of team-sports competition, knowledge of the speed at which the movement is completed may provide further understanding of the intensity and quality of the bout. Therefore, the validity of such measures are vitally important when prescribing and monitoring an athletic conditioning program. Typically, the validity of GPS for assessing speed is quantified via comparisons with timing gates, a radar gun, or motion capture software (Scott et al., 2016). Only two studies have assessed the validity of 1 Hz units for measuring speed (Barbero-Alvarez, Coutts, Granda, Barbero-Alvarez, & Castagna, 2010; MacLeod, Morris, Nevill, & Sunderland, 2009). Strong relationships (correlation coefficient; r >0.9) have been reported between 1 Hz GPS units and speed assessed using timing gates during both a hockey simulation protocol (MacLeod et al., 2009) and 30 m sprints (Barbero-Alvarez et al., 2010), but this relationship deteriorated when assessing shorter (13 m), straight-line shuttle sprints, possibly due to the low sampling rate.

When quantifying speeds during straight-line sprinting efforts, 5 Hz units have been shown to possess moderate levels of validity (CV = 5.7-9.8%) (Waldron, Worsfold, Twist, & Lamb, 2011). Similar to the 1 Hz units, the relationship with the criterion improved as the length of the effort increased, suggesting 5 Hz units may not be sufficiently senstive when measuring speed over short efforts. Further to this, there has been data presented demonstrating poor validity (CV >10%) of these units when assessing constant speed efforts from a low to moderate starting speed (i.e. 1-5 $m \cdot s^{-1}$) (Varley, Fairweather, & Aughey, 2012). However, when the initial speed of these efforts rose above 5 $m \cdot s^{-1}$, the validity of these units was reported as good (CV = 3.6%). An increase in sampling rate to 10 Hz saw an improvement in validity for efforts starting at 1-3 $m \cdot s^{-1}$ (CV = 8.3%), 3-5 $m \cdot s^{-1}$ (CV = 4.3%) and >5 $m \cdot s^{-1}$ (CV = 3.1%). Despite the greater validity of 10 Hz units for measuring speed, the increase to 15 Hz has been shown to have little additional benefit (Scott et al., 2016).

Acceleration/Deceleration Validity

Acceleration can be defined as the rate of change in speed (Little & Williams, 2005), and therefore it can be seen that the validity of this measure hinges on the ability of a system to accurately assess instantaneous speed. Compared to the criterion measure (laser), 5 Hz units exhibited moderate to poor validity for the assessment of instantaneous speed during acceleration (Varley, Fairweather, et al., 2012). Interestingly, the validity of these units was better for efforts starting from a higher speed (i.e. >3 $m \cdot s^{-1}$; CV = 7.1-9.5%), when compared to efforts from a low initial speed (i.e. <3 $m \cdot s^{-1}$; CV = 14.9%). The authors also reported a benefit of an increase in sampling rate, with 10 Hz units exhibiting good to moderate validity during the same efforts (CV = 3.6-5.9%). This notion was more recently supported, with acceptable validity of 10 Hz devices reported for assessing speed during acceleration up to 4 $m \cdot s^{-2}$ (SEE = 0.12-0.19 $m \cdot s^{-1}$) (Akenhead, French, Thompson, & Hayes, 2014). However, these authors too observed an inverse relationship between the validity of the speed measurement and the degree of acceleration, particularly for when acceleration exceeded 4 $m \cdot s^{-2}$ (SEE = 0.32 ± 0.06 $m \cdot s^{-2}$). As a result, caution must be taken when relying on 10 Hz GPS devices to assess speed during maximal acceleration efforts.

Only one study has assessed the validity of GPS for measuring speed during deceleration, reporting overestimations of up to 19.3% when compared to a laser device sampling at 50 Hz (Varley, Fairweather, et al., 2012). It was observed that the magnitude of deceleration was on average 17% greater than that of acceleration, which may have contributed to the increased error. Given the inverse relationship between the validity of speed assessments during acceleration and the starting speed, it can be seen that GPS are negatively affected by a high rate of change in speed. The poor validity of GPS for quantifying acceleration or deceleration efforts of high magnitude suggest that caution must be taken when basing decisions upon these data.

Metabolic Power Model

The metabolic power method represents a theoretical model for the assessing the physiological demands of team sports, where the energetic cost of acceleration and deceleration efforts are accounted for (di Prampero et al., 2005; Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). This technique assumes the energetic cost of accelerated running on flat terrain to be equivalent to uphill running at a constant speed. More specifically, during sprinting, an athlete's body leans forward which results in an acute angle (α) with the ground, which becomes smaller the greater the acceleration (Figure 2.1, A). If the ground were then tilted upward (Figure 2.1, B), this would shift the position of the athlete's body to vertical, meaning that accelerated running can then be equated to running at a constant speed up this "equivalent slope" (EqS), where:

$$EqS = \tan(90 - \alpha)$$

(di Prampero et al., 2005)

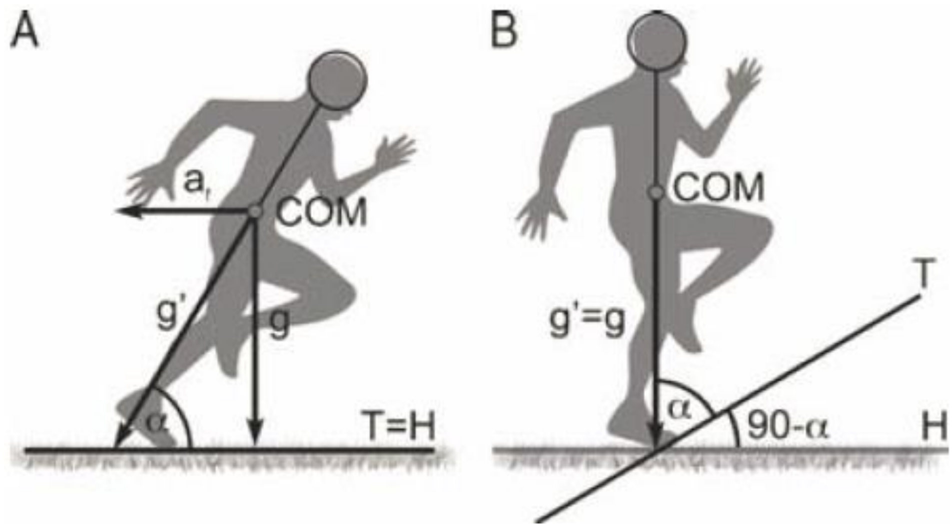

Figure 2.1: Simplified view of the forces acting on the body during accelerated running (Osgnach et al., 2010). COM = centre of mass of the body, T = terrain, H = horizontal, g = acceleration due to gravity, af = forward acceleration, g' = vectoral sum of forward acceleration and gravity.

Further, the force exerted by an athlete's muscles during sprinting is greater than the athlete's body mass, by the ratio of g'/g (Figure 2.1), known as the athlete's "equivalent mass" (EqM). Using EqS and EqM, estimations can be made as to the energetic cost (EC) of accelerated running, using the known energy cost of uphill running (Minetti, Moia, Roi, Susta, & Ferretti, 2002):

$$EC = (155.4EqS^5 - 30.4EqS^4 - 43.3EqS^3 + 46.3EqS^2 + 19.5EqS + 3.6)\ EqM$$

(di Prampero et al., 2005)

Put simply, this model attempts to quantify the energetic cost of accelerated/decelerated running by comparing the demands of accelerated running with the known cost of uphill running at a constant speed. The above equation provides an estimation of instantaneous energy cost based on the magnitude of acceleration. This instantaneous energetic cost can then multiplied by running velocity (v) to estimate P_{met} ($W \cdot kg^{-1}$).

$$P_{met} = EC\mathit{v}$$

(Osgnach et al., 2010)

Metabolic Power Limitations

Despite the proposed benefits of this model, it is not without limitation. Several issues must be considered in addition to the already known limitations associated with GPS technology, such as the decreased accuracy over short distances or at high speeds (Cummins et al., 2013; Scott et al., 2016). These issues are summarised below:

i. Firstly, using this model, the overall mass of the athlete is assumed to be located at the athlete's centre of mass. As a result, the contribution of the limbs to the energetics is ignored. Given that the energetic cost of accelerated running is equated to uphill running, it must be noted that the frequency of movement is much higher during accelerated running on flat terrain compared to uphill running (Osgnach et al., 2010). This model implies that the biomechanics of running (i.e. joint angles and torques) is the same in both conditions, though this is not necessarily the case (di Prampero, Botter, & Osgnach, 2015). As such, the estimated EC value for accelerated running must only be interpreted as a minimum value, as the effects of the movement of the limbs during sprinting would theoretically increase the instantaneous EC.

ii. The calculations presented by di Prampero et al. (2005) are based on data obtained using treadmill inclines of gradients <0.45. However, the authors observed maximum EqS values of 0.65-0.70 amongst medium-level sprinters. For these efforts where the EqS exceeds 0.45, estimations are based on assumptions of a similar relationship between uphill constant running and high-acceleration running. Although these efforts may represent a small percentage of the activity, this limitation must be considered.

iii. The calculated EqS of accelerated running is compared to constant running on flat terrain, where the EqS is assumed to be zero. However, during constant speed running, an athlete will have a small forward lean, even at low speeds (di Prampero et al., 2015). Conversely, given the reference value of the energetic cost of running was performed on flat terrain, this issue would theoretically not introduce large errors.

iv. Originally, the energetic model presented did not account for the energy required to overcome air resistance. However, modifications to this equation can be made to account for the resistance of air where required (di Prampero et al., 2015).

v. This model calculates energy expenditure according to the movement/acceleration of the athlete, though cannot account for energetically demanding non-locomotor movements such as kicking, jumping or tackling (Brown, Dwyer, Robertson, & Gastin, 2016; Highton, Mullen, Norris, Oxendale, & Twist, 2016).

In spite of these acknowledged limitations, this model still has theoretical benefits over traditional team-sport training and match analysis techniques. During competition, players are often restricted in their ability to cover distance at high speed, due to spatial constraints, or the presence of opposing players (Kempton, Sirotic, Rampinini, & Coutts, 2015). The integration of the bioenergetics of accelerated/decelerated running into traditional techniques hypothetically presents coaches with a more accurate understanding of the demands imposed on their athletes. Therefore, it would seem that the P_{met} method may be useful for quantifying the global demands of team-sports activity. However, for this theory to transfer into practice, the validity of this model must be considered.

Metabolic Power Validity

To determine if any increases in metabolic output occurred as a result of accelerated/decelerated running, the energtic cost of running at oscillating speeds was investigated (Minetti, Gaudino, Seminati, & Cazzola, 2013). Subjects were required to run at an average speed of 11 $km \cdot h^{-1}$, where the speed either remained constant, or fluctuated by ±1 to ±4 $km \cdot h^{-1}$. It was suggested that in this acceleration range, the energy cost of running is fundamentally independent of the acceleration value, possibly due to the equal proportions of accelerated and decelerated running in each condition. However, it was a requirement of this study that all participants exhibited post-exercise blood lactate values of <4 $mmol \cdot L^{-1}$, to confirm the aerobic nature of the activity. Given the large anaerobic contribution to team-sport exercise, these data have limited applicability in an environment that requires considerable high intensity activity.

Several studies have directly compared the estimated energy cost of running (via the method of di Prampero et al. (2005)), with indirect measurements of energy consumption made through the analysis of exercise and post-exercise oxygen kinetics (Buglione & di Prampero, 2013; Stevens et al., 2014). Amongst male amateur soccer players, the aerobic energy cost of constant and continuous shuttle running at a range of sub-maximal speeds (7.5-10.0 $km \cdot h^{-1}$) over 10 m has been monitored (Stevens et al., 2014), for comparison with the estimation calculations of di Prampero et al. (2005). For constant running, these calculations were found to over-estimate energy consumption by 6-11%, possibly due to small acceleration/decelerations present even when subjects are attempting to maintain a constant speed. In contrast, for shuttle running, estimated energy cost was lower (-13 to -16%) than the measured energy consumption. The authors suggested that small underestimations of distance, speed and acceleration by the movement tracking system used (Local Position Measurement; LPM) may have contributed to the differences in the observed shuttle running energetics. Taken together, these data indicate some degree of inaccuracy in the P_{met} method for determining the energy cost of constant and continuous shuttle running at primarily aerobic intensities.

In addition to quantifying aerobic energy consumption during shuttle running, the added contribution of anaerobic pathways has been assessed, through post-exercise oxygen kinetics (Buglione & di Prampero, 2013). Using shuttle distances between 8.5 and 22 m, these authors examined the oxygen consumption from exercise onset to termination, as an indication of aerobic energy consumption. In addition, anaerobic alactic energy expenditure was estimated from the oxygen kinetics during the first 6 minutes of recovery. Lastly, the anaerobic lactic contribution was estimated from net lactate (La) accumulation (measured via blood lactate) as a result of exercise. These three methods were then summated to give an overal energy cost of exercise, which could then be compared to metabolic estimations (di Prampero et al., 2005). Again, the metabolic calculations were shown to underestimate energy consumption, compared to the directly measured energy cost, when considering short shuttle distances. However, when the shuttle distance was lengthened, the model yielded much more accuarate values. These data have considerable application to team-sport training, as shuttle running is often prescribed over short distances of less than 40 m in length (Elferink-Gemser, Visscher, van Duijn, & Lemmink, 2006; Waldron, Worsfold, Twist, & Lamb, 2014; Zamparo, Zadro, Lazzer, Beato, & Sepulcri, 2014). In addition, team-sport activity often involves short sprints with multiple changes of direction (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010), meaning that the metabolic calculations of di Prampero et al. (2005) may not accurately capture the movement demands of certain team-sport athletes.

Recently, several authors have challenged the ability of the P_{met} method to estimate the energetic demands of team-sports activity using GPS technology (Brown et al., 2016; Buchheit, Manouvrier, Cassirame, & Morin, 2015; Highton et al., 2016). For example, using 4 Hz units, Buchheit et al. (2015) reported large underestimations of the net metabolic demands of a soccer-specific simulation protocol that included bouts of running at various speeds both with and without possession of a ball (i.e. dribbling), a pass and receive off a rebound wall, and a shot on goal. Similar findings were reported during a rugby league simulation protocol which incorporated simulated collision events, suggesting the P_{met} metric is inappropriate for quantifying the metabolic demands of team-sports activities (Highton et al., 2016). However, these findings are not surprising given the P_{met} technique estimates energy consumption based on the movement of the system, and therefore it is unable to quantify the energetic demands of non-locomotor activity such as kicking, passing and tackling or recovery phases where there is little or no movement of the subject.

In an attempt to assess the validity of the P_{met} calculations during walking, jogging and running, the energetic demands estimated using GPS technology have been compared with indirect open-circuit calorimetry (Brown et al., 2016). By excluding non-locomotor efforts such as kicking and jumping, these methods provide a strong indication of the accuracy of the P_{met} during movement patterns common to team-sports athletes. However, these authors also found a large to very large underestimations of the energetic cost of team-sport specific running (Cohen's *d* = 1.97-2.24). Interestingly, this method exhibited much stronger validity during constant jogging and running, which may be reflective of the methods used to develop the calculations, which included only constant speed running. Therefore, the authors suggested that this method cannot be recommended for the quantification of energy cost during intermittent running, such as that common to team-sport activity.

Despite the reported poor validity of the P_{met} metric in assessing the physiological cost of the movement patterns of team sports, it may be suggested that this variable could still be used as a global indicator of external load, which accounts for both accelerated, decelerated and speed-based running. In support of this notion, compared to the criterion method (radar), the accuracy of this calculation was good using both 5 Hz (CV = 4.5%) and 10 Hz (CV = 2.4%) units (Rampinini et al., 2015). Furthermore, distances covered at high and very-high P_{met} (>20 $W \cdot kg^{-1}$ and >35 $W \cdot kg^{-1}$, respectively) exhibited similar, if not stronger stability when compared to traditional HSR distances (CV = 4.5-11.6% vs. 4.7-23.2%). However, the combination of acceleration/deceleration and speed-based running into one metric may come at the cost of losing sight of the underlying mechanisms of the load (Buchheit et al., 2015), and therefore this measure cannot be used in isolation.

Reliability

Reliability refers to the reproducibility of values obtained from a test on repeat occasions, and is typically assessed using the CV, TEM, change in the mean, or test-retest correlation (intra-class correlation coefficient; ICC) (Hopkins, 2000b). Similarly to the validity of GPS, reliability is also affected by such factors as sampling frequency and speed of movement (Scott et al., 2016). When considering the use of GPS, the repeatability of output measures is critically important for comparisons both between and within players and sessions. Intra-unit reliability refers to the ability of a single unit to produce the same results on repeat occasions, and is essential for making comparisons between sessions for the same player. Equally important is the consistency of measures between units (inter-unit reliability), for comparisons between players within sessions. Therefore, it is important that the reliability of a system is known before such evaluations can be made with confidence.

Distance Reliability

Within the literature, it is the intra-unit reliability that attracts the most attention, as it allows session-to-session or game-to-game comparisons within the same player, provided they are wearing the same unit. Such knowledge is important for assessing whether changes in output are real, relative to the smallest deviation that is considered substantial, also known as the smallest worthwhile change (SWC; calculated as 0.2 × the between subject standard deviation [SD]) (Hopkins, 2000b). Overall, it seems that even at a low sampling rate of 1 Hz, GPS units are adequately reliable for the comparison of total distance between sessions (Scott et al., 2016). However, when assessing short efforts such as sprints, or sprints incorporating one or more changes of direction, the intra-unit reliability of GPS has been reported as moderate (CV >5%) to poor (CV >10%) (Jennings et al., 2010; Petersen et al., 2009). As such, GPS technology cannot be recommended for comparing distance covered during these efforts.

Inter-unit reliability is important for making comparisons between players within the same session, which may assist coaches in differentiating between high and low performers. Whilst the majority of the available research has discussed intra-unit reliability, it is imperative that the inter-unit reliability of a system is also assessed. This is particularly important for comparing positional demands during match play, or linking findings between research studies. Overall, the reliability of GPS for distance comparisons between subjects have been encouraging (CV <6%), across all sampling rates studied (Buchheit et al., 2015; Gray et al., 2010; Johnston, Watsford, et al., 2014; Johnston et al., 2012). These data provide coaches and practitioners with confidence when comparing total distance between subjects within the same session or protocol.

When assessing the movement demands of training and competition between or within sessions, knowledge of the high-intensity running load of individuals may provide insight into an athlete's injury risk (Duhig et al., 2016), or have implications for the athlete's recovery (Murray, Gabbett, & Chamari, 2014). Unfortunately, the reliability of GPS for assessing HSR has been relatively poor. For example, using 1 Hz GPS units, poor intra-unit reliability has been reported for assessing distance covered at both HSR (CV = 11.2-32.4%) and VHSR (CV = 11.5-30.4%) (Coutts & Duffield, 2010). Using similar thresholds, the inter-unit reliability of GPS has been assessed using 5 Hz, 10 Hz and 15 Hz units (Johnston, Watsford, et al., 2014; Johnston et al., 2012). Interestingly, the 10 Hz units were shown to exhibit the strongest reliability, with errors of 4.8% and 11.5% reported for distance covered over HSR and VHSR thresholds, respectively. The increase in sampling rate to 15 Hz had no additional benefit, with the reliability of these units actually worse than the 10 Hz units, and closely comparable to the 5 Hz units (CV = 7.6-12.7%). Again, this is not surprising, as the 15 Hz units truly sample at only 5 Hz, with the added 10 Hz achieved through an interpolation method. Taken together, it can be seen that whilst 10 Hz units may be the most appropriate for evaluating HSR within and between sessions, these comparisons must be made with caution.

Speed Reliability

The reliable assessment of speed is important for quantifying distance into discrete speed zones, which is common amongst team-sports research and practice (Aughey, 2011). Initially, it was reported that 1 Hz units possess acceptable intra-unit reliability for assessing both peak speed (CV = 1.2%, ICC = 0.97) and summated maximal speed (CV = 1.7%, ICC = 0.93) during a 30 m sprint (Barbero-Alvarez et al., 2010). Similarly, 5 Hz units have been shown to exhibit considerable reliability for assessing speed during sprint trials (CV = 0.78-2.06%) (Waldron, Worsfold, et al., 2011). When considering the inter-unit reliability of GPS, it was reported that speed assessed during a 10 m sprint was comparable between 10 Hz units (CV = 0.7-9.1%) (Akenhead et al., 2014). Taken together, it can be seen that GPS units up to 10 Hz are acceptable for the assessment of peak speed during straight-line sprinting both on repeat occasions, and between units during the same protocol. However, when changes of direction are incorporated into the sprint trials, the inter-unit reliability of both 5 Hz and 15 Hz units has been shown to be moderate to poor (CV = 7.5-33.4%), suggesting that these units are inappropriate for the assessment of speed during such tasks (Vickery et al., 2014).

Several studies have investigated the inter-unit reliability of GPS technology for assessing peak speed during a team-sport simulation protocol, reporting overall promising results. Using 5 Hz units, it was demonstrated that peak speed can be reliably assessed on repeat occasions (CV = 7.5%, ICC = 0.52) (Johnston et al., 2012). An increase in sampling rate to 10 Hz resulted in an increase in the reliability of peak speed during a team-sport protocol (TEM = 1.6%, ICC = 0.97), however when a 15 Hz system was assessed, this reliability degraded (TEM = 8.1%, ICC = -0.14), possibly due to the 5 Hz raw sampling rate of these units (Johnston, Watsford, et al., 2014). In a comprehensive assessment of the inter-unit reliability of 15 Hz GPS units, a recent study (Buchheit, Al Haddad, et al., 2014) attached 50 units from the same manufacturer to a custom-built sled, and found that the between-unit variation in peak speed was particularly small (CV = 1%), suggesting peak speed achieved during a team-sport session can be compared between players with confidence using these units.

Acceleration/Deceleration Reliability

To reliably assess the rate of change in speed (i.e. acceleration or deceleration), it is clear that the accurate assessment of instantaneous speed is pivotal. To investigate the inter-unit reliability of GPS for assessing instantaneous speed during acceleration and deceleration, Varley et al. (2012) fitted two GPS units (either 5 Hz or 10 Hz) concurrently to a single athlete, and evaluated the interchangeability of these measures between units. For the 5 Hz units, moderate to poor reliability was observed during acceleration, regardless of the starting speed (CV = 9.5-16.2%), and poor reliability during deceleration (CV = 31.8%). In contrast, the inter-unit reliability of 10 Hz units during acceleration was rated as good (CV = 1.9-4.3%), particularly for efforts from a higher initial speed, and moderate for deceleration efforts (CV = 6.0%). More recently, Akenhead et al. (2014) concurrently assessed two 10 Hz GPS units for measuring instantaneous speed during accelerations of varying magnitudes, reporting acceptable reliability (CV <10%) for accelerations ranging up to and beyond 4 $m \cdot s^{-2}$, but observed that the greatest stability was observed for efforts below 4 $m \cdot s^{-2}$ (CV = 0.7-3.9%). Taken together, these findings suggest that 10 Hz units are suitable for assessing instantaneous speed during acceleration and deceleration, but confidence in such measures deteriorate as the magnitude of the speed, or change in speed increases.

A common method for assessing the acceleration-based demands of team sports is to count the number of acceleration or deceleration efforts within discrete bands (Varley, Gabbett, & Aughey, 2014). However, only two studies have assessed the reliability of this method using GPS technology (Buchheit, Al Haddad, et al., 2014; Buchheit et al., 2015). Buchheit, Al Haddad, et al. (2014) concurrently assessed 50 GPS units sampling at 15 Hz (interpolated from 5 Hz) for quantifying the acceleration demands of a 30-minute team-sport simulation circuit. When considering acceleration efforts, very large between-model differences were observed for the number of efforts over both 3 $m \cdot s^{-2}$ (CV = 31%) and 4 $m \cdot s^{-2}$ (CV = 43%). Similarly, deceleration counts exhibited extremely poor reliability using the same magnitude thresholds (CV = 42% and 56%, respectively). These findings were more recently supported, with poor intra-unit reliability of accelerations and decelerations over 3 $m \cdot s^{-2}$ (CV = 84.7% and 58.1%, respectively) reported during a standardised team-sport simulation circuit (Buchheit et al., 2015). Whilst some of this error observed is likely due to natural variation of the athlete during the circuit, such high values are indicative of poor reproducibility of these measures using GPS technology. As such, there is a need to establish a more suitable method for the quantification of these requirements amongst team-sport athletes.

Metabolic Power Reliability

Only one study to date has assessed the reliability of the P_{met} for the assessment of the movement demands of team-sport athletes, using 4 Hz GPS units (Buchheit et al., 2015).

It was observed that when P_{met} was averaged over the duration of the activity, this measure exhibited moderate to high intra-unit reliability (CV = 9.3%, ICC = 0.57). However, the distance covered over a predefined threshold of 20 $W \cdot kg^{-1}$ was shown to exhibit extremely poor reliability (CV = 73.6%, ICC = 0.09). When monitoring distance covered over a predefined threshold, subtle changes in speed or acceleration (and therefore P_{met}) will determine whether an activity is considered as high-intensity (i.e. slightly above threshold) or low-intensity (slightly below threshold). As such, these fluctuations can have large effects on the total distance covered in these zones, despite a potentially non-substantial change in work (Buchheit et al., 2015). Whilst these authors conceded that the use of such a low sampling frequency (4 Hz) might be considered a limitation, their system exhibited validity comparable to that of both a 45 Hz LPM system, and 5 Hz GPS units. However, given the known poor reliability of 5 Hz systems for quantifying high-intensity movements such as these, it is not unexpected that a measure that depends on these metrics will lose sensitivity at high speeds or accelerations. In addition, the observed error in this variable may have been magnified by deviations of the athlete during the skill-based component of the circuit (i.e. ball handling), and therefore it would seem that the reliability of these metrics should be further assessed at higher sampling rates, and in more controlled conditions, before they are completely discarded from practice.

GLOBAL POSITIONING SYSTEMS IN FOOTBALL

In Australia, the four primary football codes represented are rugby league (NRL), rugby union (Super Rugby), Australian football (AFL) and soccer (A-league). There is an abundance of literature describing the physical demands of these sports, with a large focus of the application of GPS technology during competition, allowing comparisons to be made both between and within performances. Within these football codes, GPS speed and collision data are commonly classified into six activity bands, ranging from low to high intensity of effort or impact (McLellan, Lovell, & Gass, 2011), information that can be utilised for discriminating workloads or prescribing and monitoring training intensities (McLellan et al., 2011). In addition, these data can be compared with internal training load metrics such as heart rate or wellness questionnaires, to assess an individual's response to the prescribed external load (Halson, 2014). As such, the introduction of GPS into an athlete monitoring program may provide a holistic depiction of the training status of an athlete. For the purposes of this review, the application of GPS technology for the assessment of the movement demands of the four primary Australian football codes will be evaluated.

Total Distance

Since the introduction of GPS technology into team sports, total distance travelled has been the most commonly reported variable within research (Cummins et al., 2013). Amongst the rugby codes, professional players typically cover between 3500-8500 m, depending on position (Austin, Gabbett, & Jenkins, 2011a; Cahill, Lamb, Worsfold, Headey, & Murray, 2013; Cunniffe, Proctor, Baker, & Davies, 2009; Hausler, Halaki, & Orr, 2016). Across both sports, an increase in total distance was observed amongst backs when compared to forwards, which can be attributed to the greater time spent on the field amongst these players. In both codes, backs are not regularly interchanged throughout a match (Cummins et al., 2013). The similarities evident between these two sports are not surprising, given both codes originated from the same game.

In a study comparing the match demands of the Australian football codes, it was reported that that rugby league players covered substantially less distance (~6000 m) throughout a match when compared to AF (~12500 m) and soccer players (~10500 m) (Varley et al., 2014). Soccer is a non-contact sport, and the lack of physically demanding collisions, such as those common to rugby league, may allow players to cover more distance before the onset of fatigue. Furthermore, these players are permitted to pass the ball in all directions, presenting players with further opportunity to cover greater distances. Whilst AF is also characterised as a contact sport, players generally attempt to avoid contact with the opposition when in possession of the ball, and instead run into spaces where attacking kicks can be performed, without being impeded by the presence of other players (Davies, Young, Farrow, & Bahnert, 2013). In addition, the considerably larger field dimensions of an AF match put greater emphasis on the running demands of the game, resulting in a substantially larger workload during competition.

Relative Distance

Relative distance is calculated as the total distance travelled per minute of match play (i.e. $m \cdot min^{-1}$), and is typically referred to as a measure of match intensity, accounting for actual time on the field (Cummins et al., 2013). Such information is important for players that do not complete the full match (i.e. match duration is not consistent from week to week), such as interchange players. A recent review (Cummins et al., 2013) reported that despite the widespread application of GPS in team sports, very few papers reported on relative distance covered. Nonetheless, similar to the absolute demands of match play, positional differences in the relative demands of competition have been described amongst rugby union players, with backs covering 7.2% greater relative distance when compared to forwards (Cunniffe et al., 2009). During professional rugby league competition, it was observed that adjustables (halves and hookers) covered the greatest relative distance of any positional group (Twist et al., 2014). Therefore, it may be that reporting distances and workloads relative to time spent on the field may provide coaches and practitioners with further insight into the intensity of competition.

When controlling for match duration, it has been shown that rugby league and soccer players exhibit similar running intensities throughout competition (97 ± 16 m·min^{-1} vs 104 ± 10 m·min^{-1}) (Varley et al., 2014). These data would indicate that the decrease in absolute match demands observed amongst rugby league players was largely due to the decrease in time spent on the field (64.9 ± 18.8 vs 95.4 ± 1.8 minutes). However, these authors reported that even when controlled for match duration, AF players covered greater relative distance (129 ± 17 m·min^{-1}) when compared to both rugby league and soccer players (ES = 1.99 and 1.50, respectively). At the time of publication, these authors cited the unlimited interchange rule in AF as a potential contributing factor to the increase in match running performance amongst these players. This rule has recently been modified to limit the number of rotations permitted per match, however the effect of this rule change remains to be seen.

High-Speed Distance

Whilst the quantification of total and relative distance during team-sports competition provides a strong overview of the overall demands of the activities, differences in the high-intensity running profiles of these sports may be lost using these techniques. In a team-sport setting, players' movements are often separated into predefined speed bands, to provide further information on the physical demands imposed on the athlete (Aughey, 2011; Cummins et al., 2013). Throughout the literature, HSR demands have been reported relative to both absolute thresholds, or as a percentage of an individual's physical capacity (Carling, Bradley, McCall, & Dupont, 2016; Gabbett, 2015c). These methods have been shown to possess the capacity to differentiate positional demands during competition (Austin et al., 2011a; Coutts et al., 2015; Gabbett, Jenkins, & Abernethy, 2012b; Torreno et al., 2016). For example, during professional soccer, the centre back position has been shown to cover the least distance at HSR and VHSR, compared to any other positional group (Torreno et al., 2016). Similarly, amongst professional AF players, the HSR and VHSR demands of rucks are substantially lower than all other positions (Coutts et al., 2015). As such, these data provide coaches with information that could be useful in the prescribing training relative to the match-play requirements of individual positions.

In addition to the performance benefits associated with adequately preparing athletes for the specific demands of competition, HSR volumes have been previously linked to soft tissue injuries, such as hamstring strains (Duhig et al., 2016; Gabbett & Ullah, 2012). More specifically, it seems that the appropriate periodisation of HSR loads may attenuate the injury risks associated with unexpected spikes in volume (Hulin, Gabbett, Caputi, Lawson, & Sampson, 2016; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016). As a result, knowledge of the HSR demands of competition may allow coaches to foresee such spikes in training load, and manipulate the surrounding training sessions accordingly.

Acceleration/Deceleration

Within team sports, particularly the collision-dominant sports, players are often not afforded the opportunity to reach maximal speed due to spatial constraints imposed by field dimensions or opposing players (Kempton, Sirotic, Rampinini, et al., 2015). Therefore, the ability to generate speed over a short distance or duration is vital for successful field sport performance (Lockie, Murphy, Knight, & Janse de Jonge, 2011). Despite the uncertainty surrounding the reliability of GPS for assessing acceleration/deceleration demands (Buchheit, Al Haddad, et al., 2014), the evaluation of these capacities is commonplace amongst team sports (Aughey, 2011). For example, it has been observed that players of a higher calibre possess greater acceleration abilities compared to their less-skilled counterparts (Cometti, Maffiuletti, Pousson, Chatard, & Maffulli, 2001; Gabbett, Jenkins, & Abernethy, 2011c), demonstrating the importance of this capacity amongst team-sport athletes. Furthermore, acceleration efforts are known to be physically demanding (Cavagna, Komarek, & Mazzoleni, 1971) and therefore knowledge of these demands during competition may assist in the development of specific training drills that replicate the physical requirements of competition.

During competitive match play, the acceleration requirements of AF, rugby league and soccer have been compared, using a count method (Varley et al., 2014). It was observed that of the three codes, AF players completed the most acceleration efforts (>2.78 $m \cdot s^{-2}$) throughout a match (ES = 0.56-0.72). The increase in the absolute number of accelerations amongst AF players is likely due to an increase in playing time compared to the other sports. However, when reported relative to playing time, the acceleration requirements of rugby league were shown to be much higher (ES = 1.03-1.72). This is interesting, given that these authors reported that rugby league players exhibited the lowest absolute demands of the three codes. Rugby league match play involves a unique variation of the “onside” rule, where players are required to retreat 10 m to the defensive line at the end of each play, before moving forward off the line for each ensuing play (Meir, Colla, & Milligan, 2001). Suggestively, this rule imparts a substantial acceleration/deceleration load on these athletes, a notion which is supported by the increased relative acceleration demands observed amongst these athletes (Varley et al., 2014).

Compared to the considerable physiological cost of accelerated running, deceleration is a far less taxing movement (di Prampero et al., 2015). However, despite this decreased energetic cost, the eccentric contractions that occur during deceleration may have implications for acute muscle damage (Young, Hepner, & Robbins, 2012). Following an elite junior AF match, match activity profiles were compared with post-match creatine kinase (CK) concentration, a known indicator of muscle damage (Newham, Jones, & Edwards, 1983; Nosaka & Newton, 2002). It was observed that players who exhibited higher CK concentration also completed significantly more moderate (1-3 $m \cdot s^{-2}$) and high intensity (3-15 $m \cdot s^{-2}$) deceleration efforts (ES = 1.46 and 1.29, respectively), which suggests that knowledge of the deceleration requirements of competition may assist in the development of specific recovery protocols. However, a limitation of this study was that it assessed just 15 athletes for one match, and therefore these findings require support from longitudinal studies exhibiting a larger sample size.

Despite the proposed benefits of quantifying acceleration/deceleration activity during completion, the limitation of the methods used to do so must be acknowledged. In addition to the questionable validity and reliability for quantifying these efforts, particularly at high intensities, it may be that the “count” method typically employed in research and practice might not be the most appropriate method for assessing these demands. By counting the number of efforts over a predefined threshold, subtle changes in acceleration that would otherwise be considered practically insignificant (i.e. 0.1 $m \cdot s^{-2}$) may determine whether an effort gained classification as an acceleration or deceleration (Buchheit et al., 2015). Currently, the alternative techniques for assessing acceleration/deceleration activity are scarce, and coaches are restricted to simply acknowledging the poor accuracy of the methods presently available. As such, there is a need to establish a more appropriate method for the quantification of the acceleration/deceleration demands of team-sport activity.

Metabolic Power

During professional soccer compeition, ~98% of maximal accelerations commence from an initial speed lower than what would be considered high-speed running (>4.17 $m \cdot s^{-1}$), whilst ~85% of maximal accelerations do not cross the high-speed threshold at all (Varley & Aughey, 2013). As such, there is a need to quantify all high-intensity movements, whether they are high-speed running bouts, or accelerations performed at low speeds. The P_{met} measure theoretically possesses the ability to account for these actions collaboratively, though the validity of this method has been challenged as a true indication of the physiological cost of team-sports activity (Brown et al., 2016; Buchheit et al., 2015; Highton et al., 2016). Nonetheless, this variable exhibits considerable stability (Rampinini et al., 2015), and therefore may be a more appropriate method of quantifying the external running demands of team sports, regardless of the metabolic cost of the activity.

Recently, the high-intensity running demands of professional rugby league were analysed, by comparing the distance covered at high speed (HSR; >14 $km \cdot h^{-1}$) with distance covered at high P_{met} (HPR), using a threshold of 20 $W \cdot kg^{-1}$ (Kempton, Sirotic, Rampinini, et al., 2015). This threshold was chosen to be reflective of the metabolic equivalent of constant speed running at high-speed threshold (Osgnach et al., 2010). The authors reported substantial underestimations of high-intensity activity using HSR (37-76%) and attributed these differences to the specific match-play requirements of each position. These findings are in support of previous research (Gaudino et al., 2013), where HPR distance was substantially higher (62-84%) than HSR distance during professional soccer training. In contrast to these findings, amongst AF players, distance covered over HPR threshold was actually slightly lower (1.5-7.5%) when compared to the equivalent HSR threshold (Coutts et al., 2015), indicative of the lesser reliance on acceleration qualities in professional AF. Taken together, it would seem that quantifying distances over HPR threshold may provide additional information on the physical demands for some but not all team sports.

As discussed, a common problem with the assessment of high-intensity activity is the decreasing reliability of GPS for detecting these efforts. Only one study has assessed the reliability of P_{met} measures of high-intensity movement, indicating that a drill average ($AveP_{met}$) was a far more stable measure (CV = 9.3%) when compared to distance covered above HPR threshold (CV = 73.6%), and therefore may be a more appropriate measure to quantify the intensity of an activity (Buchheit et al., 2015). As such, this method has been shown to differentiate positions amongst soccer (Gaudino et al., 2013), rugby league (Kempton, Sirotic, Rampinini, et al., 2015) and AF players (Coutts et al., 2015). Furthermore, P_{met} averaged over a match was shown to delineate between elite and sub-elite AF players (ES = 0.49) (Johnston, Watsford, Austin, Pine, & Spurrs, 2015). However, whilst this method might represent a more stable indication of match intensity compared to high-intensity running distances, averaging the demands over an entire period may come at the cost of a loss of sensitivity to within match fluctuations, and therefore this must be considered.

IDENTIFYING PEAKS IN RUNNING INTENSITY

The majority of the available literature that has quantified the peak demands of team-sport competition has done so with reference to fatigue or pacing, assessing temporal changes in running intensity, prior to and following the peak period. During team sports, athletes may self-regulate running intensity in preparation for an intense period, or to allow adequate recovery from a high-intensity bout (Waldron & Highton, 2014). These periods of intense activity have been associated with important match events such as point-scoring opportunities (Austin et al., 2011d), and therefore these periods may be critical to the outcome of the game (Spencer et al., 2004). Decreases in technical performance as towards the latter stages of a match may indicate that cognitive abilities may be impaired due to a state of physiological fatigue (Rampinini et al., 2009). Moreover, reductions in skill performance during the period directly following the most demanding period of play have also been reported (Black et al., 2015; Kempton et al., 2013). By preparing athletes for these periods appropriately, the relative physiological cost of these bouts will be less, which may improve the technical performance of athletes during the ensuing stages of the match. Therefore, it is vital that the most demanding periods of competition are assessed accurately, and the prescription and monitoring of training reflects these intensities. Small-sided games have been suggested as an appropriate method for developing physical capacities, whilst concurrently improving athletes' technical and tactical abilities (Hill-Haas et al., 2011). Whilst these methods provide athletes with a specific environment for the development of both physical and skill-based capacities concurrently, it is vital that they are monitored relative to the most demanding periods of play, to contextualise the running intensities achieved.

Discrete Periods

In order to identify the most demanding period of competition, research has typically separated match play into discrete periods lasting between five and 15 minutes in duration (Austin & Kelly, 2013; Barrett et al., 2015; Bradley & Noakes, 2013; Carling & Dupont, 2011; Kempton et al., 2013; Kempton, Sirotic, & Coutts, 2015; Mohr, Krustrup, & Bangsbo, 2003; Varley, Elias, & Aughey, 2012). Such methods allow for the assessment of temporal changes in running intensity throughout an on-field stint, within a half or quarter of play, or across an entire match. A minimum of a 5-minute period has been recommended, as this duration has been suggested to be robust enough to account for random changes in situational variables (i.e. possession, match score) that might prevent the identification of typical match fluctuations if a shorter period were to be used (Waldron & Highton, 2014). However, using pre-defined discrete periods may underestimate the true peak in running intensity, as the most intense period may overlap two successive blocks (Bradley, Di Mascio, Peart, Olsen, & Sheldon, 2010; Varley, Elias, et al., 2012), and therefore other methods may be more appropriate.

Moving Average Analysis

To accurately assess the peak movement demands of competition, a moving average method has been presented (Varley, Elias, et al., 2012), where match data can be analysed using a rolling time scale, to give a more accurate depiction of the most intense running demands of competition. Compared to a rolling average technique, the more traditional pre-defined block method has been shown to underestimate the peak period of high-speed running during professional soccer by up to 25% (Varley, Elias, et al., 2012). Furthermore, the difference between methods was magnified when considering the decrement in running intensity from the peak to the ensuing 5-minute period, with underestimations of up to 53%. These data outline a limitation of using pre-defined blocks to quantify the peak intensity of team sports, and therefore the moving average method may be a more appropriate method.

FACTORS AFFECTING RUNNING PERFORMANCE

Team sports can be characterised by brief bouts of high-intensity running interspersed with longer periods of low-intensity activity (Rampinini et al., 2007). Whilst individual fitness characteristics may influence a player's overall capability to perform at high intensities during competition (Gabbett et al., 2013), the within-match variations in intensity cannot be overlooked. During team-sport matches, an athlete's running profile typically fluctuates in response to a number of factors, including fatigue (Bendiksen et al., 2012), pacing (Edwards & Noakes, 2009) and match situation (Carling & Dupont, 2011). As such, expressing match intensity as a whole-match average is inappropriate, as this method lacks the sensitivity to detect the most demanding periods of play (Glaister, 2005). This has implications for the prescription of training, as drills based on whole-match averages may substantially underprepare athletes for the rigors of competition. Therefore, to understand the fluctuations in running intensity within team sports, it is essential to first consider the contributing factors that are at play.

Fatigue

In a team-sport setting, fatigue manifests as a decrease in maximal force or power output that occurs as a result of sustained exercise, and is reflected in a decline in performance (Reilly, 1994). This decrease in performance is exhibited by the self-regulated decrease in movement intensity during a match (Waldron & Highton, 2014). This decline in running intensity can be quantified as a progressive decrease across successive segments during a match, and has been evidenced extensively in rugby league (Kempton et al., 2013; Kempton, Sirotic, & Coutts, 2015; Sykes, Twist, Nicholas, & Lamb, 2011; Waldron, Highton, Daniels, & Twist, 2013), rugby union (Lacome, Piscione, Hager, & Bourdin, 2014; Roberts, Trewartha, Higgitt, El-Abd, & Stokes, 2008), AF (Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010; Wisbey, Montgomery, Pyne, & Rattray, 2010) and soccer (Barrett et al., 2015; Bradley & Noakes, 2013; Carling & Dupont, 2011). Whilst this decline is likely the result of a number of game-related factors (Bradley & Noakes, 2013), associations have been made with a lowering of muscle glycogen during the latter stages of a match (Krustrup et al., 2006). Furthermore, a 2ºC drop in muscle temperature has been observed following a passive recovery half-time break, which resulted in a 2.4% decrease in sprint performance (Mohr, Krustrup, Nybo, Nielsen, & Bangsbo, 2004). Conversely, second half sprint performance was less affected for athletes who performed low-intensity activities at half time, possibly due to an increased oxygen uptake, which allowed faster recovery between sprint efforts (Bangsbo, Krustrup, Gonzalez-Alonso, & Saltin, 2001).

More specifically, Mohr et al. (2003) originally noted a phenomenon whereby a brief period of decreased running intensity (comparative to the match average) occurs directly following the most intense period of the match. During this phase, athletes may limit the number of physiological disturbances they expose themselves to, in an attempt to regenerate energy stores for ensuing high-intensity bouts (Furlan et al., 2015). A number of studies have reported decreases in HSR in the period directly following the peak 5-minute period during professional soccer match play (Bradley & Noakes, 2013; Carling & Dupont, 2011; Mohr et al., 2003). Similarly, transient reductions in rugby league performance have been observed, with decreases in both total distance covered and the number of collisions in the periods following the peak 5-minute block (Kempton et al., 2013), providing preliminary evidence of a state of fatigue. It has been suggested that physiological factors may contribute to this decrease, such as disturbances in muscle ion homeostasis, leading to an impaired excitation of the sarcolemma (Mohr, Krustrup, & Bangsbo, 2005). However, ball-in-play time has been shown to be substantially greater during the peak periods of physical activity when compared to subsequent blocks, which would suggest that players have more opportunities to generate physical output during these periods (Carling & Dupont, 2011; Kempton et al., 2013), demonstrating that fatigue is not the only factor at play.

Match Situation

The running intensity achieved by team-sport athletes is affected by an array of external factors, making physical performance data difficult to interpret. For example, during professional rugby league match play, the running demands of defensive play are substantially higher than when attacking (Gabbett, Polley, Dwyer, Kearney, & Corvo, 2014). Furthermore, factors such as the opposition team's strength (Kempton & Coutts, 2015), and the score line (Lago & Martin, 2007) have been shown to influence the running intensity achieved. It is therefore clear that physical output during competition cannot be considered in isolation, and statistical analyses that control for such external factors may be beneficial.

There is an abundance of literature demonstrating substantial differences in the activity profiles of team-sports athletes playing different positions (Cummins et al., 2013). Although individual positions typically exhibit differences in physical capacities from one another (Johnston, Gabbett, & Jenkins, 2014; Stolen, Chamari, Castagna, & Wisloff, 2005), the variation in physical output between positions during competition is largely due to situational and tactical influences (Bradley & Noakes, 2013). Most commonly these differences are reported as whole-match averages, and therefore differences in peak intensities achieved between positions might be blunted as a result. Considering only the peak 5-minute period of professional soccer competition, players have been categorised according on their HSR profile, as “low”, “moderate” or “high” (Bradley & Noakes, 2013). It was shown that the “high” group was primarily composed of midfielders, and this was attributed to the position-specific tactical requirements of this position. Similarly, the “low” group included the highest proportion of central defenders, who typically remain in the defensive half of the field, even when the ball progresses forward.

Further to the tactical requirements of individual positions, it may be that game situation (i.e. stage of the match, score line etc.) also contributes to the fluctuating activity profile of team-sports athletes. Declines in both physical output and technical involvements have been reported towards the end of the match during professional soccer (Bradley & Noakes, 2013; Carling & Dupont, 2011) and rugby league competition (Austin & Kelly, 2013; Kempton et al., 2013; Sykes et al., 2011). Although there may be a component of fatigue involved, this decrease could be a result of players intentionally “slowing down” the match, to protect a lead. During rugby league match play, players often deliberately kick the ball into touch, or force a goal-line restart to cause a break in play prior to the restart, reducing ball-in-play time and thus the physical demands of this period (Kempton et al., 2013). In contrast, peak periods of physical activity have been associated with an increase in ball-in-play time (Carling & Dupont, 2011; Gabbett, 2015a). Whilst these findings are not surprising, such periods of back-and-forth play are reflective of the most intense period of the match, and therefore athletes must be adequately prepared for these demands through appropriate training prescription.

Pacing

It has been suggested that team-sport athletes typically regulate their efforts and involvements during matches bases on macro-, meso- and micro-pacing strategies (Edwards & Noakes, 2009). In these terms, macro-pacing reflects the pacing ‘schema’ of the athlete, where athletes are suggested to develop a performance ‘template’, which sets the expected distribution of energy distribution throughout an exercise bout (de Koning et al., 2011; St Clair Gibson et al., 2006; Tucker & Noakes, 2009). Furthermore, within-match modulation occurs between halves (i.e. meso) or on a continual basis (i.e. micro), which is suggested to be dependent upon the degree of homeostatic disturbance, such as poor fluid balance (Waldron & Highton, 2014). This theory was originally presented with specific reference to dehydration, but has since enhanced the understanding of “transient fatigue”, which is likely reflective of a fine (micro) self-regulation of movement intensity in response to match situation (Edwards & Noakes, 2009). Such occurrences are evident following the peak period of a match, though it is difficult to ascertain the proportion of this decrease that was an unplanned physiological response, or a result of a deliberate strategy by the player to conserve energy for following bouts (Aughey, 2010). Indeed, a player's individual pacing strategy may be dependent on their individual tasks during a match, posing yet another complexity to this model. For example, players who are substituted throughout a match may have prior knowledge of their bout duration, and therefore compete at a higher intensity earlier in the match compared to a player who is expected to complete the full match. As such, the activity profiles exhibited by these players will differ substantially, and therefore these players must be physically prepared accordingly.

In a review of the pacing strategies employed by team-sports athletes, the typical pacing profile of a number of team sports has been described (Waldron & Highton, 2014). Full-match soccer players can be characterised as exhibiting a "slow-positive" schema, whereby running intensity decreases steadily across a match. This "slow-positive" pacing profile was similar across all four football codes studied (i.e. soccer, rugby league, rugby union and AF), though subtle differences between sports exist, particularly in response to the substitution rules each sport adhered to. For example, during soccer, substitute players typically enter the match in the final 15-25 minutes of play, allowing them compete at a higher intensity when compared to full-match players (Bradley & Noakes, 2013; Carling, Espie, Le Gall, Bloomfield, & Jullien, 2010; Mohr et al., 2005). In rugby league, although a "slow-positive" profile is similarly evident, the interchange rule permits up to 8-12 replacements each match, which allows hit-up forwards to complete the match in two bouts of ~20 minutes (Waldron et al., 2013). This permits these players to adopt a "one bout, all out" pacing strategy during their first stint, before a stepwise reduction in running intensity is typical of the following bout (Waldron et al., 2013). In contrast, AF players are permitted a high number of substitutions, allowing players to sustain a high running intensity throughout the match (Mooney, Cormack, O'Brien, & Coutts, 2013). Collectively, it can be seen that the pacing strategies utilised by team-sports athletes are largely dependent on the positional tactics of the team, and therefore training prescription should be individualised to reflect these inter-positional differences.

Individual Fitness Characteristics

Fitness characteristics are considered important determinants of physical performance within team sports (Impellizzeri & Marcora, 2009), and have been associated with match running performance in AF (Mooney et al., 2011), soccer (Castagna, Impellizzeri, Cecchini, Rampinini, & Alvarez, 2009) and rugby league (Kempton & Coutts, 2015). Due to the intermittent nature of team sports, well-developed aerobic abilities may assist in an accelerated rate of energy restoration between high-intensity efforts (Tomlin & Wenger, 2001). However, it is important to account for playing position when considering this relationship, as different competition requirements may lead to different contributions of fitness characteristics to match performance. For example, during AF, players benefit from superior aerobic capacities, due to both the large distances covered, and the need for rapid recovery between high intensity bouts (Gray & Jenkins, 2010). In contrast, for rugby league forwards, strength and power abilities may be more important, as they assist in dominating collision-based events such as tackles and hit-ups (Gabbett, Jenkins, & Abernethy, 2011a). It can be seen that differences in the physical and physiological requirements of team-sport competition may lead to variations in the peak running intensities achieved, and therefore it may be beneficial to consider such peaks relative to playing position.

CONCLUSIONS

The acceptable validity and reliability of GPS for quantifying team-sports movement demands suggests that they can be used to assess the activity profiles of training and competition. However, to do so with confidence, it is vital that the most appropriate measures for within- and between-subject comparisons are selected. In particular, when quantifying high-intensity activity, the accuracy of these devices seems to decline, implicating training prescription based on these values, and this must be taken into consideration when using these data in practice. When prescribing training, data obtained from matches are useful in replicating the physical demands of competition. Further, the activity profile of team sports is one of stochasticity, with fluctuations observed throughout a match due to a variety of factors. As such, it is vital that the peaks in intensity are quantified, to allow for the prescription and monitoring of training relative to the most demanding periods of play. Throughout research, match intensity has typically been quantified using whole-match or whole-period averages, and therefore fluctuations in running intensity may be missed. Further research into the peak demands of competition is therefore warranted, which will contribute to the development of more effective conditioning programs.

Chapter 3

Establishing duration specific running intensities from match-play analysis in rugby league

Delaney, J. A., Scott, T. J., Thornton, H. R., Bennett, K. J., Gay, D., Duthie, G. M., & Dascombe, B. J. (2015). Establishing duration specific running intensities from match-play analysis in rugby league. *Int J Sports Physiol Perform, 10*(6), 725-731. doi: 10.1123/ijspp.2015-0092.

.

ABSTRACT

Rugby league coaches often prescribe training to replicate the demands of competition. The intensities of running drills are often monitored in comparison to absolute match-play measures. Such measures may not be sensitive enough to detect fluctuations in intensity across a match, or to differentiate between positions. ***Purpose:*** To determine the position and duration-specific running intensities of rugby league competition, using a moving average method, for the prescription and monitoring of training. ***Methods:*** 15 Hz Global Positioning System (GPS) data were collected from 32 professional rugby league players across a season. The velocity-time curve was analysed using a rolling average method, where maximum values were calculated for ten different durations: 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 minutes for each player across each match. ***Results:*** There were large differences between the 1 and 2-minute rolling average and all other rolling average durations. Smaller differences were observed for rolling averages of a greater duration. Fullbacks maintained a greater velocity compared to outside backs, middle and edge forwards over the 1 and 2-minute rolling averages (effect size [ES] = 0.8-1.2). For rolling averages 3 minutes and greater, the running demands of the fullback were greater compared to middle forwards and outside backs (ES = 1.1-1.4). ***Conclusions:*** These findings suggest that the running demands of rugby league fluctuate vastly across a match. Fullbacks were the only position to exhibit a greater running intensity than any other position, and therefore training prescription should reflect this.

INTRODUCTION

The use of Global Positioning Systems (GPS) to quantify the physical demands of competition has become increasingly popular in team sports such as rugby league (Aughey, 2011). During a rugby league match, players typically cover 5000-8000 m, depending on position played (Gabbett, 2013a), or level of competition (McLellan et al., 2011), which equates to an average relative distance ranging from 80-100 $m \cdot min^{-1}$. Further, players complete a repeated high intensity effort approximately once every 7 minutes, which include high impact physical collisions (Austin et al., 2011d). Despite the physical demands of rugby league being well established, it is often difficult to develop specific training methodologies that accurately replicate the oscillating intensities of rugby league match play.

Traditionally, coaches have had to rely upon data that resembles the absolute running demands of competition to monitor the training intensities of team-sport athletes (Casamichana, Castellano, & Castagna, 2012; Gabbett, 2010; Gabbett & Mulvey, 2008). However, these methods may substantially underestimate the running requirements of the most intense periods of match play. For example, Carling and Dupont (2011) reported professional midfield soccer players to cover greater distances in the first 15 minutes of a match compared to the last 15 minutes (1919 ± 125 vs. 1775 ± 158 m). A similar trend was observed amongst professional rugby league players, where players covered the greatest relative distance ($m \cdot min^{-1}$) during both the first 10-minute (Austin & Kelly, 2014) and 5-minute (Kempton et al., 2013) block of each 40-minute half, possibly due to a greater time of ball-in-play during this period. The varying running demands observed throughout team-sport competition suggest that absolute match demands may not adequately capture peaks in match-play intensity.

It has been previously suggested that declines observed in running performance in team sports are a result of both progressive and transient fatigue experienced throughout a match (Mohr et al., 2003). However, such claims are often based using data collected from predefined periods of play (i.e. 0-5 minutes, 5-10 minutes, etc.). It might be that the most intense period of a match does not fall completely within one of these blocks, and therefore these methods may underestimate the running demands of competition. To account for this issue, Varley et al (2012) utilised a rolling average method to determine the maximum distance covered in a 5-minute block during an elite soccer match at high speed (>4.17 $m \cdot s^{-1}$), for comparisons with the traditional 5-minute block method. It was observed that the traditional method underestimated peak high-speed distance by 20-25%, suggesting that the rolling average method was able to better discriminate the most intense period of running throughout the match. Similarly, amongst professional rugby league players, Austin and Kelly (2014) reported the maximum work rate of a 10-minute block to be 115 $m \cdot min^{-1}$ and 120 $m \cdot min^{-1}$ for forwards and backs respectively, substantially higher than the mean values for the entire match (85 ± 4 and 86 ± 5 $m \cdot min^{-1}$ for forwards and backs, respectively). As such, exercise prescribed based on pre-defined periods of the match may not satisfactorily reflect the most intense periods of play.

Using a similar method, Furlan et al. (2015) observed large variations in the relative running intensities throughout a rugby sevens match that have been previously unaccounted for using traditional absolute measures. It was shown that the peak 2-minute period, identified using a moving average, was immediately followed by a large reduction in running intensity (effect size [ES] = 2.92, *almost certainly* large effect). Similarly, Kempton et al. (2015) observed a significant decline from the peak 5-minute period to the subsequent 5-minute period (ES = 1.72) in professional rugby league competition. These fluctuations may be suggestive of a self-regulated pacing strategy, where athletes attempt to minimise the number of physiological disturbances as they recover from an intense exercise bout (Furlan et al., 2015), or simply reflective of regression to the mean (Galton, 1886). Therefore, it would seem beneficial for coaches to prescribe training intensities using methods that are more sensitive to determine within match fluctuations, to appropriately prepare athletes for the most demanding periods of play.

When describing rugby league match demands, it is ideal to quantify individual positions separately, due to the different locomotive requirements of each position (Austin & Kelly, 2014; Gabbett, Jenkins, et al., 2012b; Waldron, Twist, et al., 2011). However, previous research has been unclear as to whether positional differences exist in relative running intensities ($m \cdot min^{-1}$) across a rugby league match. Positional differences have been reported in some (Austin & Kelly, 2014; Gabbett, 2013a; Gabbett, Jenkins, et al., 2012b; McLellan et al., 2011; Twist et al., 2014), but not all studies (Gabbett, 2013a; Gabbett, Jenkins, et al., 2012b; McLellan et al., 2011). Despite these inconsistencies, when considering distances covered at high speed, differences between positions become much clearer. For example, Waldron et al. (2011) reported that whilst outside backs covered significantly less relative distance over a English Super League match than middle forwards (89 ± 4 vs. 95 ± 7 m), they covered far greater distance sprinting (316 ± 117 vs. 119 ± 86 m). Such data suggests large fluctuations in the speed profile of each position may exist. As a result, prescribing training based on total match intensities may not be sensitive enough to replicate the most intense periods of match play across the varying positions.

Alternatively, a more practical method would be to develop position-specific speed-based movement indicators to ensure players meet the desired intensities during rugby league training. Although the physical demands of rugby league competition have been well established, there is a lack of research that has documented the specific running demands that can be used for subsequent prescription of training intensities. The use of a rolling average method has allowed researchers to identify the most intense period of competition, for a pre-defined moving average length. Such data has significant practical application for the prescription of training, allowing coaches to monitor training drills according to these match demands. However, subsequent training prescription is limited to the pre-determined moving average length (commonly 5 minutes). Therefore, the purpose of this study is to determine the position and duration-specific running intensities of rugby league competition, using a moving average method. This will provide valuable data for the prescription and monitoring of players during rugby league training drills.

METHODS

Design

An observational GPS analysis was used to develop duration and position-specific velocity based movement indicators. Data was collected across the 2014 National Rugby League (NRL) competitive season. Prior to the commencement of the study, all subjects were informed of the aims and requirements of the research, and informed consent was obtained. The Institutional Human Ethics Committee approved all experimental procedures.

Subjects

Data was collected from 32 professional rugby league players (26.0 ± 4.8 yr, 99.1 ± 9.6 kg, 1.84 ± 0.06 m) from the same club during 20 matches throughout the 2014 National Rugby League (NRL) season (9 wins, 11 losses, final position 12th). Between matches, players typically completed 2-3 field sessions and 1-2 resistance-based sessions, combined with 1-2 recovery sessions. Each match was 80 minutes in duration that was separated into two 40-minute halves. Players were grouped by playing position, and the number of observations per position are as follows: fullbacks (n = 18), outside backs (n = 76), halves (half-back and five-eighth; n = 39), middle forwards (props and locks; n = 98), edge forwards (second rowers; n = 44) and hookers (n = 27). The mean (± SD) number of observations per player was 10.2 ± 6.4.

Methodology

The running demands of players during matches were recorded using a portable GPS unit that possessed a raw sampling rate of 5 Hz (SPI HPU, GPSports, Canberra, Australia). The GPS unit was worn in a customised padded pouch in the player's jersey and positioned in the centre of the upper back area, slightly superior to the scapulae. To minimise the effect of inter-unit error, each player was allocated the same unit for the entire season. The validity and reliability of these GPS units have been previously established (Johnston, Watsford, et al., 2014). The number of satellites and horizontal dilution of precision (HDOP) during match play were 8.1 ± 1.4 and 1.1 ± 0.1, respectively.

Following the completion of each match, GPS data were analysed using the appropriate proprietary software (Team AMS, Canberra, Australia). A total of 297 files were collected across the 2014 NRL season. Files were trimmed so that only match time was included in analysis. Velocity-time curves were linearly interpolated to 15 Hz, and a fourth-order Butterworth filter applied with a 1 Hz cut-off frequency. These files (n = 297) were then processed using customised MATLAB® software (Version 8.4.0.150421, MathWorks Inc, MA, USA) that was developed to specifically allow for the computation of a moving average for each player's relative distance covered ($m \cdot min^{-1}$). This was the only extracted variable considered by the present study. To assist in the development of speed-based movement indicators, rolling moving averages were calculated across ten different durations (1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 minutes) for each player across each match, and the maximum value for each duration was recorded. For example, for a 1-minute rolling average, the software identified the 900 consecutive data points (i.e. 15 samples per second for 60 seconds) where the subject exhibited the greatest relative distance. For a 2-minute rolling average, 1800 samples were used, and so on. Descriptive statistics were then calculated relative to playing position. Values were averaged across all observations per positional group for between-group comparisons.

Statistical Analyses

Data distribution was assessed for normality using the Kolmogorov-Smirnov test to determine whether parametric or non-parametric statistical methods were appropriate. A repeated-measures analysis of variances (RMANOVA) was used to determine differences between maximum relative distances calculated from all maximal moving average lengths (i.e. 10 x 10). Where necessary, a Bonferroni post-hoc test located significant differences between groups. Effect sizes (ES) were used to describe differences in running intensities between moving average lengths. Statistical significance was set at $p < 0.05$. Effect sizes of 0.2-0.6, 0.6-1.2 and >1.2 were considered small, moderate and large, respectively (Hopkins, Marshall, Batterham, & Hanin, 2009). Furthermore, a customised spreadsheet (Microsoft Excel; Microsoft, Redmond, USA) was used to calculate the chance that the observed difference between moving averages was practically significant, using a threshold of 10 $m \cdot min^{-1}$ (Hopkins, 2006). This threshold represented the smallest difference that would practically have any application in the prescription and monitoring of rugby league training. Quantitative chances of real differences in variables were assessed qualitatively as: <1%, *almost certainly not*; 1-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, possibly; 75-97.5%, *likely*; 97.5-99% *very likely*; >99%, *almost certainly* (Hopkins et al., 2009). A difference was considered substantial when the likelihood that the true value was greater than the practical threshold exceeded 75%. This method was then repeated for comparisons between positions. Statistical analyses were performed using SPSS v. 22.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Running Demands by Moving Average Duration

Table 3.1 shows all pairwise comparisons between rolling average durations. All comparisons between rolling average durations were significant, with the exception of the 9 vs. 10-minute comparison (mean difference 1.3 ± 1.3 $m \cdot min^{-1}$, *almost certainly* trivial). Figure 3.1 illustrates a substantial increase in maximal relative distance covered as the length of the rolling average used decreased, relative to the longest window (10 minutes). Quantitative analysis revealed that there were *likely* moderate to large differences between the 1 and 2-minute rolling averages and all other rolling average durations, but the magnitude of these differences decreased as the length of the rolling averages increased.

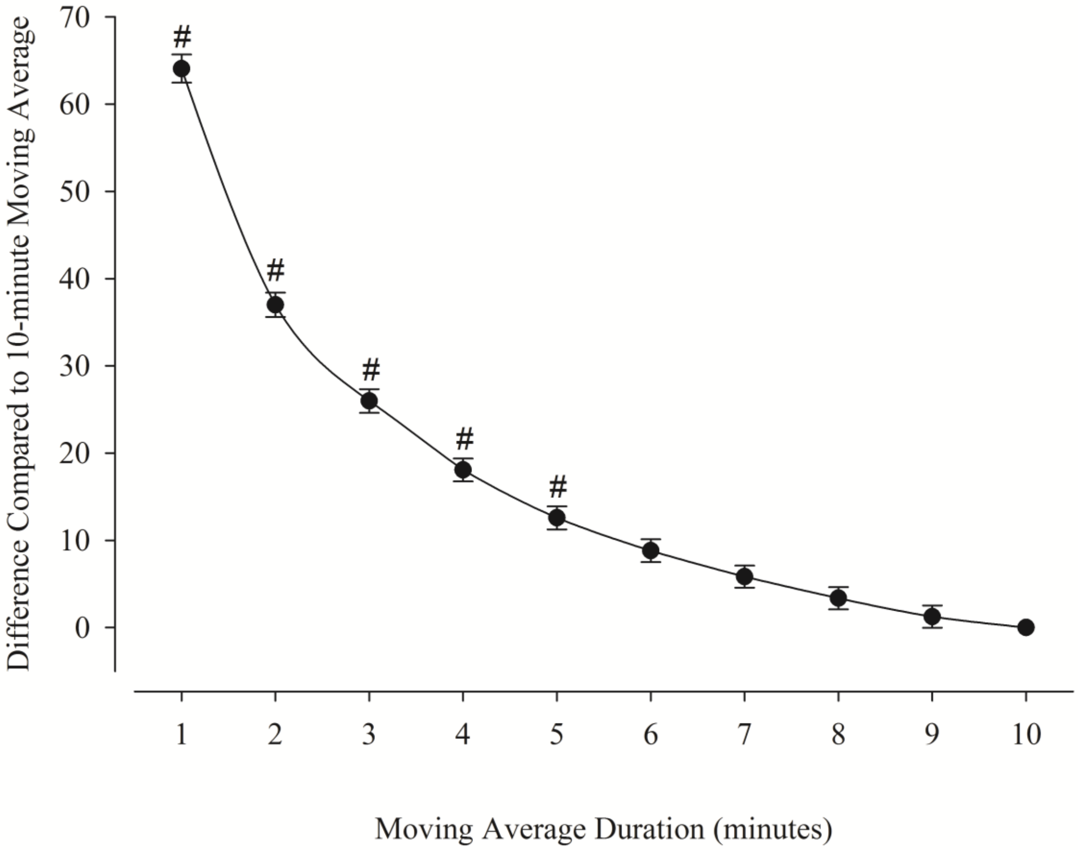

Figure 3.1: Maximum relative distance (m·min^{-1}) of rugby league match play by rolling average duration. Data are presented relative to 10-minute rolling average (mean difference ±90% CL). # = substantially different from 10-minute rolling average.

Table 3.1: Comparisons between maximum relative distances ($m \cdot min^{-1}$) for rolling averages of different durations (±90% CL).

	1	2	3	4	5	6	7	8	9
2	27.1; ±1.7** *Almost certainly* large ↑								
3	38.1; ±1.7** *Almost certainly* large ↑	11.0; ±1.5** *Likely* moderate ↑							
4	46.0; ±1.7** *Almost certainly* large ↑	18.9; ±1.4** *Almost certainly* large ↑	7.9; ±1.4** *Almost certainly* moderate ↑						
5	51.5; ±1.7** *Almost certainly* large ↑	24.4; ±1.5** *Almost certainly* large ↑	13.4; ±1.4** *Almost certainly* large ↑	5.5; ±1.4** *Almost certainly not* moderate ↑					
6	55.3; ±1.7** *Almost certainly* large ↑	28.2; ±1.4** *Almost certainly* large ↑	17.2; ±1.4** *Almost certainly* large ↑	9.3; ±1.4** *Unlikely* moderate ↑	3.8; ±1.4** *Almost certainly not* small ↑				
7	58.2; ±1.6** *Almost certainly* large ↑	31.2; ±1.4** *Almost certainly* large ↑	20.1; ±1.4** *Almost certainly* large ↑	12.2; ±1.3** *Almost certainly* large ↑	6.7; ±1.3** *Almost certainly* moderate ↑	3.0; ±1.3** *Almost certainly not* small ↑			
8	60.7; ±1.6** *Almost certainly* large ↑	33.6; ±1.4** *Almost certainly* large ↑	22.6; ±1.6** *Almost certainly* large ↑	14.7; ±1.3** *Almost certainly* large ↑	9.2; ±1.3** *Unlikely* moderate ↑	5.4; ±1.3** *Almost certainly not* moderate ↑	2.5; ±1.3* *Almost certainly not* small ↑		
9	62.8; ±1.6** *Almost certainly* large ↑	35.7; ±1.4** *Almost certainly* large ↑	24.7; ±1.4** *Almost certainly* large ↑	16.8; ±1.3** *Almost certainly* large ↑	11.3; ±1.3** *Likely* moderate ↑	7.5; ±1.3** *Almost certainly not* moderate ↑	4.6; ±1.3** *Almost certainly not* small ↑	2.1; ±1.3* *Almost certainly not* small ↑	
10	64.1; ±1.6** *Almost certainly* large ↑	37; ±1.4** *Almost certainly* large ↑	26; ±1.4** *Almost certainly* large ↑	18.1; ±1.3** *Almost certainly* large ↑	12.6; ±1.3** Almost certainly large ↑	8.8; ±1.3** *Unlikely* moderate ↑	5.8; ±1.3** *Almost certainly not* moderate ↑	3.4; ±1.3** *Almost certainly not* small ↑	1.3; ±1.3 *Almost certainly not* trivial ↑

* Significant difference, $p < 0.05$ between rolling average lengths; ** Significant difference, $p < 0.001$ between rolling average lengths. Data are presented as mean ±90% CL, likelihood of effect, size and direction of effect ± ↑ or ↓.

Running Demands by Position

Maximum relative distances covered for each position can be seen in Table 3.2. Middle forwards covered significantly less relative distance than all other positions, besides outside backs for all moving averages. Fullbacks exhibited a greater relative distance than all other positions when the moving average duration was set at 1 and 2 minutes. For the moving averages between 5 and 10 minutes, fullbacks covered the greatest relative distance compared to hookers, outside backs, middle and edge forwards. For the 4 and 5-minute rolling averages, the fullbacks' running demands were significantly higher than all positions besides halves. Halves and hookers covered a greater relative distance than outside backs across moving averages of 3 and 4 minutes, whilst a greater relative distance was observed in halves compared to outside backs for averages of 5-10 minutes in length.

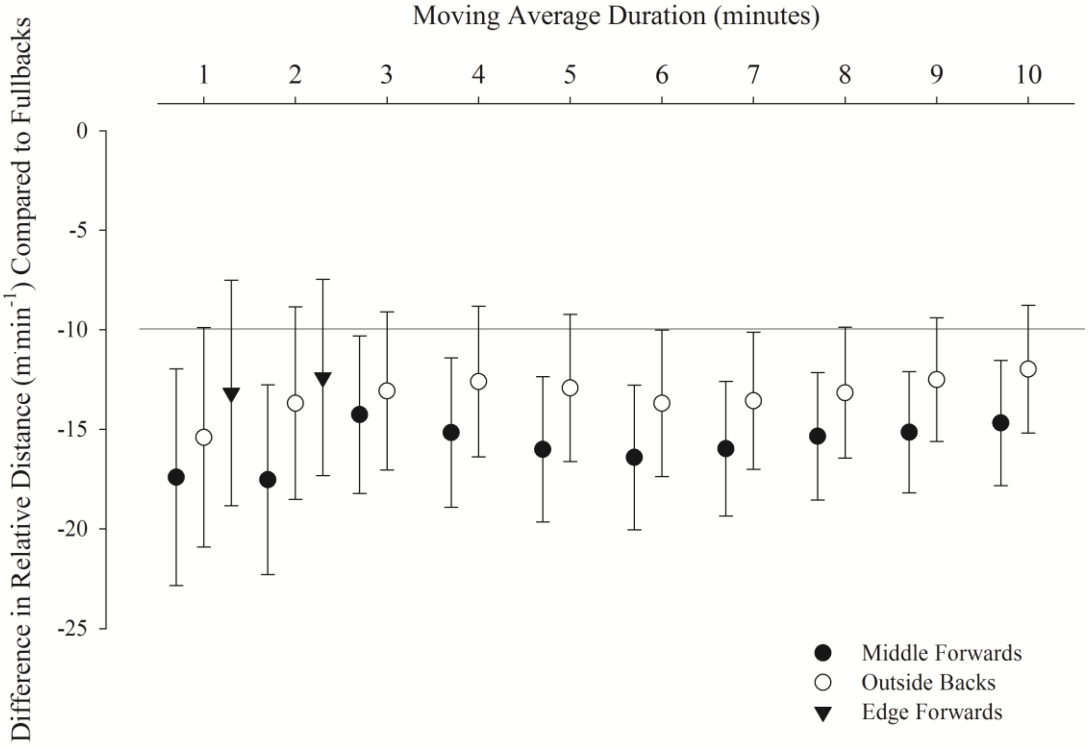

Figure 3.2: Practically significant differences in maximum relative distance between positions. Data are presented relative to the Fullback position (mean difference ±90% CL).

Table 3.2: Maximum relative distances ($m \cdot min^{-1}$) of professional rugby league players by position for each moving average duration (± SD).

Window Length (minutes)	Fullback	Halves	Hooker	Edge Forwards	Outside Backs	Middle Forwards
1	172 ± 18^{abcde}	156 ± 15^{e}	161 ± 18	159 ± 13	159 ± 17	154 ± 16
2	144 ± 16^{abcde}	130 ± 12^{e}	135 ± 16	132 ± 10^{e}	135 ± 15	127 ± 12
3	131 ± 13^{cde}	118 ± 11^{de}	125 ± 15^{de}	121 ± 10	125 ± 15	116 ± 12
4	123 ± 12^{cde}	111 ± 11^{de}	117 ± 15^{de}	113 ± 8^{e}	116 ± 15	108 ± 12
5	118 ± 12^{bcde}	105 ± 11^{de}	112 ± 15^{e}	108 ± 8^{e}	110 ± 15	102 ± 12
6	115 ± 12^{bcde}	101 ± 10^{de}	109 ± 14^{e}	104 ± 8^{e}	106 ± 15	99 ± 11
7	112 ± 11^{bcde}	98 ± 10^{d}	106 ± 14^{e}	101 ± 9^{e}	103 ± 14	96 ± 10
8	109 ± 10^{bcde}	96 ± 10^{d}	103 ± 14^{e}	99 ± 8^{e}	100 ± 14	93 ± 10
9	106 ± 10^{bcde}	94 ± 10^{de}	101 ± 13^{e}	97 ± 8^{e}	98 ± 14	91 ± 10
10	105 ± 10^{bcde}	93 ± 10^{de}	100 ± 13^{e}	95 ± 7^{e}	97 ± 14	90 ± 10

[a] = significantly different from halves. [b] = significantly different from hookers. [c] = significantly different from edge forwards. [d] = significantly different from outside backs. [e] = significantly different from middle forwards. Significance set at $p < 0.05$.

Figure 3.2 illustrates the practically significant differences that were identified between positional groups. Fullback was the only position to be deemed *likely* (>75% chance to be greater than the practical threshold) to be different from any other group. The probability that the increase in relative distance covered ranged from *likely* to *almost certainly* when compared to middle forwards, edge forwards and outside backs for moving averages 1 and 2 minutes in duration (ES = 0.8-1.2). When the moving average lasted 3 or more minutes in duration, the only practically significant (*likely* to *almost certainly*) difference observed was when fullbacks were compared to outside backs and middle forwards (ES = 1.1-1.4).

DISCUSSION

This study was the first to quantify the speed-based running demands of rugby league competition using a rolling average method of differing durations. The primary finding of this study was that rugby league match play involves periods of play that are considerably more intense than previously reported. Previous research has been limited to reporting on the speed-based intensities of rugby league using either the average across a whole match (Gabbett, 2013a; Gabbett, Jenkins, et al., 2012b; Twist et al., 2014), half a match (Austin & Kelly, 2014; Twist et al., 2014) 10-minute (Austin & Kelly, 2014) or five-minute (Kempton, Sirotic, & Coutts, 2015) blocks. Other studies have also described the demands of competition using the frequency of sprint efforts over a pre-determined threshold (Gabbett, Jenkins, et al., 2012b; Waldron, Twist, et al., 2011). Whilst such methods may be suitable for describing total match intensities or comparing periods within a game, they are unable to quantify demands over the short, most intense periods of play.

A recent study by Austin and Kelly (2014) reported that the maximum relative distance covered by professional rugby league forwards and backs for an entire match were 97 and 100 $m \cdot min^{-1}$, respectively. When matches were broken down further into 10-minute blocks of play, this value increased to 115 $m \cdot min^{-1}$ and 120 $m \cdot min^{-1}$ for these respective groups. Kempton et al. (2015) reported that players covered 540 m (95% CI = 529-550 m) during the peak 5-minute period of match play, a comparable intensity to that reported by Austin and Kelly (2014) for a 10-minute window. A similar trend was observed in the present study, where the maximum running demands of competition increased significantly as the duration of the moving average decreased. However, a major finding of the present study was that as the length of moving average decreased, the relative running intensities continued to increase, to as high as 156 ± 12 $m \cdot min^{-1}$ for the 1-minute moving average (Figure 3.1).

However, small differences in running intensities may not be useful for the prescription and monitoring of rugby league training. Therefore, these differences were assessed for practical significance, using a threshold of 10 $m \cdot min^{-1}$. This threshold was chosen because, from an applied perspective, it was considered unlikely that coaches would prescribe drills so specific that minute differences in relative distances would be required to be detected. Therefore, this threshold represented the smallest difference that would have any application in the prescription and monitoring of training. Subsequently, the analysis revealed that the moving averages of 6-10 minutes in length yielded quite similar intensities (Figure 3.1). Alternatively, the moving average method was sensitive enough to detect differences between the shorter rolling average windows of a more similar duration. Such information provides coaches with a valuable framework for the prescription of specific rugby league training drills, indicating that for training drills of

<6 minutes, a change in duration of just 1 minute should generate substantially different running intensities.

A secondary aim of this study was to develop a position-specific activity profile of rugby league competition. Significant differences were observed across positional groups and rolling averages. However, small differences between positions may not be of practical use in the field. For example, edge forwards covered a greater relative distance than middle forwards for the moving average of 4 minutes in duration (113 ± 8 vs 108 ± 12 $m \cdot min^{-1}$). However, such a small difference would not be substantial enough to warrant the prescription of different intensities, and this was supported by the magnitude-based analysis (Figure 3.2). It was established that the fullback position was the only position to exhibit a greater relative intensity than any other position, at any time point. For moving averages lasting 2 minutes and under, fullbacks covered a greater relative distance compared to outside backs, middle and edge forwards. For averages lasting 3 minutes and greater, fullbacks worked at a higher intensity than outside backs and middle forwards. The greater running demands of the fullback position could be attributed to a range of factors, such as the greater field coverage that is required of this position, or a greater involvement in contact situations amongst other positions (Gabbett, Jenkins, et al., 2012b). However, the quantification of contact situations was outside the scope of this study, and therefore this suggestion remains speculative.

Despite the differences observed for the fullback position, no other positions exhibited practically significant differences across any moving average duration. This is interesting, given the different absolute match-play requirements of each position (Austin & Kelly, 2014; Gabbett, Jenkins, et al., 2012b; Waldron, Twist, et al., 2011). Importantly, the interchange tactics of the team must be considered when interpreting these results. For example, in the present study, middle forwards and hookers were the most frequently interchanged, while fullbacks, halves, outside backs and edge forwards typically played the entire match. Gabbett et al. (2012b) recently reported that middle forwards are involved in more collisions per minute than any other position. Despite this fact, middle forwards still were observed to cover similar relative distances to other positions. The authors of this study grouped fullbacks, halves and hookers together, making comparisons between positions difficult. Nonetheless, the present study exhibited similar results, where no substantial difference in relative distance was observed between middle forwards and edge forwards, halves, hookers or outside backs. As the middle forward position is most frequently interchanged, it seems that they are able to sustain similar running intensities as most other positions for the time they are on the field. However, whilst only small differences exist between most positions, it must be noted that the present study reflects relative running demands, and the absolute running demands must also be considered when preparing athletes for competition.

A limitation of the present study was that only one NRL team was analysed. Due to the restrictions placed on the number of interchanges each team participating in a match can use, some positions are more frequently interchanged than others, such as middle forwards. As a result, the data presented for middle forwards reflects a large cohort of players (n = 13). In contrast, for positions that usually require the player to the entire match with no substitution (e.g. fullback), a much smaller number of players were used throughout the season. Therefore, it might be argued that the data presented in the present study for such positions are more reflective of the individual, rather than the position. However, the present study included samples from no fewer than four (n = 4) players for each position. Further, sharing such data between teams participating within the same competition is unlikely, and therefore this was unavoidable.

PRACTICAL APPLICATIONS

This study was the first to describe the running demands of rugby league competition using a rolling average method. The unique running profile of rugby league competition presented by the present study provides valuable information for the development and monitoring of specific training drills. Coaches are now able to prescribe training methodologies relative to an athlete's maximum match-play requirements. It is acknowledged that the results of this study reflect purely the running demands of competition, with no attempt of quantifying contacts and collisions made. Nonetheless, the most demanding running demands of match play have been captured, and as a result can now be replicated in field-based conditioning drills. Furthermore, to better replicate the reactive, multi-directional nature of rugby league, coaches may benefit from prescribing more specific methodologies, such as small-sided games (SSG). Through the manipulation of such factors as field dimensions, player numbers and verbal encouragement, the desired running intensity may be achieved. In addition, coaches may choose to incorporate a contact component into such a game, to more accurately replicate the collision-based nature of rugby league, whilst maintaining the required running demands.

The unique running requirements illustrated by the current study would suggest that for fullbacks to be placed under the same training stress relative to competition as other positions, they must cover a greater total distance per unit of time. In contrast, the findings of this study suggest that small differences observed between positions other than fullbacks may be too small to warrant manipulating training stimuli, and therefore these positions can be considered to have similar running requirements in such SSGs. However, it must be noted that the running requirements and intensities described by the current study are the maximum values attained across a match. These demands reflect the most intense block of running performed throughout the duration of a match. As a result, it is recommended that the running demands prescribed during training are part of an appropriately periodised conditioning program.

Whilst the collection and analysis of GPS data is widespread amongst team sports, practitioners are often limited to selecting from variables and analysis methods made available by the proprietors. The present study's utilisation of the high-performance MATLAB® software package is unique to the field of sports sciences. While the benefits of the running profile described by the present study are clear for use in training monitoring and prescription, such data may also be of use in competition. For example, such methods may be of use for developing a team or individual's specific interchange protocols, according to the observed running profile, or an individual's resistance to fatigue. In addition, these methods may assist with determining the effect of rule modifications, such as reducing the number of interchanges, or the recent introduction of an extra tackle from a 20 m restart. The development of appropriate customised functions within the software may provide coaches and practitioners with an unprecedented flexibility in GPS analytics.

ACKNOWLEDGEMENTS

No financial assistance was provided for the current project. There were no conflicts of interest.

Chapter 4

Factors that influence running intensity in interchange players within professional rugby league

Delaney, J. A., Thornton, H. R., Duthie, G. M., & Dascombe, B. J. (2016). Factors that influence running intensity in interchange players within professional rugby league. *Int J Sports Physiol Perform, 11*(8), 1047-1042. doi: 10.1123/ijspp.2015-0559.

ABSTRACT

Rugby league coaches adopt replacement strategies for their interchange players to maximise running intensity; however, it is important to understand the factors that may influence match performance. ***Purpose:*** To assess the independent factors affecting running intensity sustained by interchange players during professional rugby league. ***Methods:*** Global positioning system (GPS) data were collected from all interchanged players (starters and non-starters) within a professional rugby league squad across 20 matches of a National Rugby League (NRL) season. A multilevel, mixed-model approach was employed to establish the effect of various technical (attacking and defensive involvements), temporal (bout duration, time in possession etc.) and situational (season phase, recovery cycle etc.) factors on the relative distance covered and average metabolic power (P_{met}) during competition. Significant effects were standardised using correlation coefficients, and the likelihood of the effect was described using magnitude-based inferences. ***Results:*** Superior intermittent running ability resulted in *very likely* large increases in both relative distance and P_{met}. As the length of a bout increased, both measures of running intensity exhibited a small decrease. There were at least *likely* small increases in running intensity for matches played after short recovery cycles and against strong opposition. During a bout, the number of collision-based involvements increased running intensity, whilst time in possession and ball time-out-of-play decreased demands. ***Conclusions:*** These data demonstrate a complex interaction of individual and match-based factors that require consideration when developing interchange strategies, and the manipulation of training loads during shorter recovery periods and against stronger opponents may be beneficial.

INTRODUCTION

The quantification of competition movement demands in rugby league is now a common practice, primarily through the use of global positioning systems (GPS) (Kempton, Sirotic, & Coutts, 2014; Kempton, Sirotic, Rampinini, et al., 2015; McLellan et al., 2011). The analysis of match-play data has proved useful for differentiating positional demands (McLellan et al., 2011), monitoring workload (Kempton et al., 2014; Kempton, Sirotic, Rampinini, et al., 2015) and for developing recovery strategies (McLellan & Lovell, 2012). Moreover, recent research (Kempton et al., 2014) has demonstrated considerable match-to-match variability in physical performance measures such as high and very-high speed running, which highlights the need to investigate the factors that contribute to these changes in competition output. For example, the running demands of rugby league have been shown to be affected by both individual fitness capacities (Gabbett et al., 2013) and the quality of the opposition (Gabbett, 2013b). Whilst these findings are useful, it is important to note that these variables may not influence match performance in isolation, and it may be that controlling for the confounding effect of multiple variables simultaneously is the most appropriate method.

To account for the influence of multiple factors, Kempton and Coutts (2015) utilised a multilevel mixed-modelling approach to assess the independent effects of a variable whilst concurrently controlling for a range of other variables. It was found that the relative total ($m{\cdot}min^{-1}$) and high-speed running (HSR; $m{\cdot}min^{-1}$) distances were reduced as a result of short recovery cycles, playing both away from home and early in the season. In addition, running intensity was decreased through increased defensive loads, but remained unaffected by attacking involvements, and players exhibiting greater aerobic abilities were also able to sustain a greater running intensity throughout match play. Whilst these findings are useful for the development of specific preparation and recovery strategies, it is possible that for interchanged players, the time spent on the field may substantially influence the running intensity maintained throughout that bout.

Interchange strategies used in contemporary professional rugby league require backs to complete the entire match, whilst forwards often complete the match in two or more bouts (Gabbett, Jenkins, et al., 2012b). Previous research has demonstrated a decline in running intensity throughout an on-field bout amongst interchange professional rugby league players, potentially due to transient fatigue as a result of match play (Waldron et al., 2013). However, no study has yet investigated the impact of bout duration of the running intensity maintained, and such information could assist coaches in developing interchange plans.

In addition to the difference in match time between interchange and non-interchange players (Gabbett, Jenkins, et al., 2012b; Waldron et al., 2013), it is also important to address the differences in the physical requirements of these positions during match play. For example, hit-up forwards (props and second rowers) have been shown to be involved in more collisions, relative to playing time, than any other positional group (Gabbett, Jenkins, et al., 2012b). As a result of this increased contact load, it is important to control for attacking and defensive collisions when investigating the movement demands of these positions (Kempton & Coutts, 2015). This, combined with the spatial limitations imposed on rugby league players due to the presence of opposition players, would indicate that players in these positions may be unable to achieve the same total or high-speed relative distances as other players who are more laterally positioned (Kempton, Sirotic, Rampinini, et al., 2015). It therefore may be beneficial to also assess the acceleration-based running requirements when investigating the running demands of interchanged rugby league players. The metabolic power (P_{met}) method represents a theoretical model for quantifying team-sports movement demands, where the energetic cost of accelerated and decelerated running is accounted for (di Prampero et al., 2005; Osgnach et al., 2010). Specific to rugby league, Kempton et al. (2015) reported that hit-up forwards covered 76% more distance over a high-power threshold of 20 $W \cdot kg^{-1}$ when compared to an equivalent traditional high-speed threshold of 14.4 $km \cdot h^{-1}$, further demonstrating the importance of quantifying accelerated running for this position.

Overall, it can be seen that the competition requirements of interchange rugby league players are unique, and as a result they should be assessed independently of full-match players. Therefore, this study adapted the mixed model approach of Kempton and Coutts (2015) to assess the factors affecting the running intensity sustained by interchange rugby league players. Specifically, this study investigated the independent effects of bout duration, match location, recovery length, season phase, opposition strength and recent form, match outcome, time out of play, time in possession, tackles made and received, and individual player intermittent fitness on the running intensity achieved by these players. The findings of this study may assist coaches in formulating interchange strategies, which is particularly important given the recent decrease in number of available interchanges from ten to eight.

METHODS

Eighteen professional rugby league players (26.8 ± 5.3 yr, 102.2 ± 9.9 kg, 1.86 ± 0.05 m) from the same club were recruited for this study. This cohort included 14 middle forwards (props and locks) and four hookers, and was representative of all interchange players (starters and non-starters) throughout the season. Due to the coaching strategies of the team, no edge forwards were interchanged tactically (only substituted in the case of injury), and therefore these players were removed from analysis. Prior to the commencement of the study, all subjects were informed of the aims and requirements of the research, and informed consent was obtained. The Institutional Human Ethics Committee approved all experimental procedures.

Data were collected during 24 matches across the 2014 National Rugby League (NRL) competitive season (10 wins, 14 losses, final position 12th), to determine the effects of various contextual factors on the running performance of interchange players. Matches were played on outdoor grass surfaces between the hours of 14:00-20:00. Each match was classified according to season phase as early-season (mean match-day temperature ± SD, 25.1 ± 5.9º C), mid-season (18.2 ± 3.6º C) or late-season (19.3 ± 2.6º C) for matches 1-8, 9-16 and 17-24, respectively. Further, match location (home or away) and recovery cycle length (long, ≥7 days or short, 5-6 days) were used to describe match conditions. Opposition strength was categorised according to both final ladder position (strong, average or weak) and opposition recent form (number of wins in last 5 matches). Match result was recorded as won or lost, and points-differential in each game was taken as the score difference between the two sides at the end of each match. To account for collisions in both attack and defence, a commercial statistics supplier (Prozone, Sydney, Australia) provided the count of times each player was tackled (n) and the count of tackles effected by each player during each bout (n). In addition, time in possession and total time (minutes) in which the ball was out of play was recorded. Individual intermittent running ability was assessed via the maximum speed attained before exhaustion (vIFT) using the 30:15 Intermittent Fitness Test (IFT) (Buchheit, 2008), approximately 4 weeks prior to the start of the season.

Competition movement demands were recorded using GPS units at a raw sampling rate of 5 Hz, interpolated to 15 Hz (SPI HPU, GPSports, Canberra, Australia). Whilst the validity and reliability of these units for quantifying total distance covered during team sports has previously been described (Johnston et al., 2012), the inter-unit reliability for quantifying the acceleration-based movement demands of team sports has been challenged (Buchheit, Al Haddad, et al., 2014). To minimise such error, each player was fitted with the same unit for the entire season. Matches were completed in open stadiums, where the number of satellites and horizontal dilution of precision (HDOP) were 8.3 ± 1.4 and 1.1 ± 0.1, respectively. Each unit was fitted into a customised padded pouch in the player's jersey, positioned in the centre of the back slightly superior to the scapulae. The average duration spent on the field by each player was 48.6 ± 14.6 minutes, which was broken up into 2-4 bouts (each lasting 22.0 ± 8.2 minutes). The total number of observations was 289, and the average number of observations per player was 16.1 ± 13.3. Upon completion of each match, match files were downloaded using the appropriate proprietary software (Team AMS, GPSports, Canberra, Australia). Following this, data were trimmed to only include the time spent on the field and each bout was treated as a separate file. In the case that an interchange bout was broken up by the half-time break, the period was divided into two individual bouts, and analysed accordingly. The total distance covered during each bout was divided by bout duration to obtain the relative total distance ($m \cdot min^{-1}$).

In addition to relative distance, the P_{met} achieved throughout each interchange bout, calculated using the methods of Osgnach et al. (2010), was selected as the dependant variable in preference of the high-speed running (HSR) measure utilised by Kempton and Coutts (2015). High-speed running has been shown to underestimate the high-intensity activities of competition that are performed at low speeds, particularly for positions regularly interchanged such as hit-up forwards (Kempton, Sirotic, Rampinini, et al., 2015). As such, the P_{met} measure was included as a primary outcome measure. Whilst previous research has shown varying accuracy of this method for quantifying the energetic cost of team-sports movements (Buchheit et al., 2015; Buglione & di Prampero, 2013; Stevens et al., 2014), this measure has emerged as a stable measure of locomotor load (CV = 4.5%) (Rampinini et al., 2015), where acceleration and speed-based movements are accounted for. Considering the spatial restrictions placed on interchanged players due to the presence of opposition players (Kempton, Sirotic, Rampinini, et al., 2015), P_{met} was chosen as an appropriate reflection of external load during competition. It is important to note that this study made no attempt to quantify the energetic demands of tackling or kicking, as the P_{met} metric has been shown to be incapable of measuring the energetic demand of these activities (Highton et al., 2016), and therefore in the context of the present study the P_{met} variable represents only the running demands of competition.

Statistical Analysis

Multilevel linear mixed effect models were constructed, utilising a similar design to that of Kempton and Coutts (2015). Two separate models were constructed to examine the influence of various match-play and player characteristics on each of the dependent running measures including relative distance and P_{met} (Table 4.1). These 2-level models included both random and fixed effects (West, Welch, & Galecki, 2014) with units of analysis (individual bout) nested in clusters of units (individual player). Prior to analysis, the dependent variables, relative distance, and P_{met} values were log transformed, providing percentage effect of the mean (Hopkins et al., 2009).

In the model design, a 'step-up' approach was used where only a fixed intercept and the level 2 random factor (player) were included (West et al., 2014). Following this, each level 1 fixed effect was added and retained if statistical significance was demonstrated ($p < 0.05$) and improved the model information as determined by a likelihood ratio test. The order of entry of the fixed effects into the model was trialled a variety of different ways, and determined to have no effect on the final outcome of the model. The *t* statistics from the mixed models were converted to effect size correlations (ES) and associated 90% confidence intervals (90% CI) (Rosnow, Rosenthal, & Rubin, 2000). Effect size correlations (*r*) were interpreted as <0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; 0.9-0.99, almost perfect; 1.0, perfect. Furthermore, the likelihood of the observed effect was established using a progressive magnitude-based approach, where quantitative chances of the true effect were assessed qualitatively, as: <1%, *almost certainly not*; 1-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, possibly; 75-97.5%, *likely*; 97.5-99% *very likely*; >99%, *almost certainly* (Hopkins, 2007). All statistical analyses were conducted R statistical software (R.2.1, R foundation for Statistical Computing).

RESULTS

The percentage effect of various covariates on relative distance covered (Model 1) and P_{met} sustained (Model 2) for interchange players during match play are presented in Table 4.2. From the model output, the exponential intercept depicts the mean log transformed value for the outcome variable, whereas the coefficient intercept reflects the change associated with a one-unit change in this. For example, individual fitness level assessed using the IFT test possessed the greatest influence on the running demands achieved by interchange players, where a one-unit increase in the exponential intercept value is associated with a 1.4-unit increase in IFT score. This resulted in *very likely* large increases in both relative distance covered and P_{met} maintained throughout the bout. Tackling involvements occurring both in attack and defence resulted in at least *likely* small increases in running intensity. Small increases were also observed in both dependant measures for matches played against strong opposition (*likely* to *very likely)* and following a short recovery period (*very likely)*. There were *likely* and *possibly* small increases in P_{met} during the mid and late stages of the season, respectively, whilst relative distance covered remained unaffected during this period. There were at least *very likely* small decreases in both measures of running intensity as a result of increased bout duration. Similarly, this was evident when a greater time spent in possession and a higher quantity of ball-out-of-play time occurred. Neither measure of match result (win/loss or points differential) had a significant impact within either model.

Table. 4.1: List of individual, match-play and contextual covariates included in the models. The levels are representative of the hierarchical structure of the model, including a level 2 random factor (player) and level 1 dependent variables and the corresponding covariates.

	Level of Data	**Variable**	**Data**	**Classification**
Level 2	**Cluster of units (random factor)**	*Player*		
Level 1	**Unit of analysis**	*Individual bout*		
	Dependent Variables	Relative distance	Continuous	
		Power	Continuous	
	Covariates	IFT	Continuous*	
		Duration	Continuous*	Mins
		Location	Dummy	Home, away
		Turnaround	Dummy	Short, long
		Season phase	Dummy	Early, mid, late
		Opposition strength	Dummy	Strong, average, weak
		Result	Dummy	Won, lost
		Time out of play	Continuous*	Mins
		Tackles receieved	Continuous	Number
		Tackles made	Continuous	Number
		Time in possession	Continuous*	Mins
		Opposition form	Continuous	Number
		Points difference	Continuous	Number

IFT = Intermittent Fitness Test final speed; *Grand mean centered variable.

Table 4.2: Percentage effects of individual, match-play and contextual factors on log transformed relative distance and average metabolic power in interchange forwards of professional rugby league match play. Data are expressed as a percentage effect on the intercept coefficient, an effect size correlation (r) and the likelihood of effect (90% CI).

	Relative Distance ($m \cdot min^{-1}$)			**Metabolic Power ($W \cdot kg^{-1}$)**		
Fixed Effects	**Coefficient**	**Effect size (r)**	**Likelihood of Effect**	**Coefficient**	**Effect size (r)**	**Likelihood of Effect**
Intercept †	96.4; 95 to 98			91.5; 87.9 to 95.2		
IFT	1.4; 0.5 to 2.2	0.59; 0.18 to 0.82	*very likely* large ↑	3.3; 1.2 to 5.4	0.56; 0.16 to 0.8	*very likely* large ↑
Duration	-0.2; -0.2 to -0.1	0.28; 0.19 to 0.37	*most likely* small ↓	-0.3; -0.4 to -0.2	0.25; 0.15 to 0.34	*very likely* small ↓
Turnaround (short)	1.8; 1.1 to 2.8	0.22; 0.12 to 0.31	*very likely* small ↑	4.8; 2.7 to 6.8	0.23; 0.13 to 0.32	*very likely* small ↑
Season phase (late)	NS			3; 0.6 to 5.5	0.12; 0.02 to 0.22	*possibly* small ↑
Season phase (mid)	NS			3.2; 1.1 to 5.4	0.14; 0.04 to 0.24	*likely* small ↑
Opposition strength (strong)	1.6; 0.6 to 2.2	0.19; 0.09 to 0.28	*likely* small ↑	4.6; 2.6 to 6.6	0.22; 0.12 to 0.31	*very likely* small ↑
Time out of play	-0.2; -0.3 to -0.1	0.24; 0.14 to 0.33	*very likely* small ↓	-0.5; -0.7 to -0.3	0.21; 0.11 to 0.3	*very likely* small ↓
Tackles received	0.3; 0.1 to 0.4	0.19; 0.09 to 0.28	*likely* small ↑	0.6; 0.2 to 0.9	0.15; 0.05 to 0.25	*likely* small ↑
Tackled made	0.2; 0.1 to 0.3	0.29; 0.2 to 0.38	*most likely* small ↑	0.4; 0.3 to 0.6	0.24; 0.15 to 0.33	*very likely* small ↑
Time in possession	-0.4; -0.6 to -0.2	0.21; 0.12 to 0.31	*very likely* small ↓	-1; -1.5 to -0.6	0.23; 0.13 to 0.32	*very likely* small ↓
Opposition form	-0.4; -0.9 to -0.2	0.12; 0.02 to 0.22	*possibly* small ↓	-1.6; -2.5 to -0.8	0.18; 0.08 to 0.27	*likely* small ↓

CI = confidence interval; NS = not significant; † Exponential of intercept.

DISCUSSION

This study examined the influence of individual fitness and various match characteristics on interchange players' running intensity during professional rugby league match play, accounting for within-individual repeated observations. It was observed that individual intermittent fitness ability was the largest contributor to running intensity achieved throughout a bout amongst these players. Matches played following a short recovery period, against strong opponents, and involving more physical collisions all resulted in increased running demands. In contrast, longer bouts involving more time in possession and greater ball-out-of-play time, and against teams in good recent form all reduced the movement demands of interchanged players. Based on these findings, interchange strategies may be more appropriately structured and manipulated to account for such environmental and situational variants each match.

Intermittent running ability is critical to rugby league, and has been shown to differentiate match performance amongst professional players (Gabbett et al., 2013). As such, the IFT was chosen as an appropriate reflection of an individual's fitness ability, specific to the sport (Scott et al., 2015). The present study observed a large increase in both relative distance covered and P_{met} as a result of increased intermittent running ability. Our findings are very similar to those of Kempton and Coutts (2015), where large increases in running intensity were observed in players exhibiting greater aerobic fitness. Despite the difference in fitness tests utilised, the similarity in the magnitude of the effect suggests that this had little impact on the outcome. Therefore, these findings collectively demonstrate that irrespective of the interchange classification of the players in the present study, individual fitness capacities are imperative in achieving greater running intensities throughout rugby league competition, possibly due to an accelerated rate of energy restoration between high-intensity efforts (Tomlin & Wenger, 2001).

Modern interchange strategies permit middle forwards and hookers to complete intense bouts of activity before being replaced by a substitute player (Austin, Gabbett, & Jenkins, 2011c; Waldron et al., 2013). During these bouts, players are exposed to a higher frequency of physical collisions compared to their full-match counterparts (Gabbett, Jenkins, et al., 2012b). Kempton and Coutts (2015) recently suggested that the running intensity achieved throughout a match is decreased as a result of increased defensive collisions. However, these findings may have been confounded by the inclusion of both interchange and full-match players in the analysis. For example, whilst defensive involvements might induce poorer locomotive output in full-match players, the requirement of "middle" players to quickly retreat into the defensive line following a contact situation might lead to an increased running intensity compared to players who are less involved in collisions. This is supported by the findings of Austin et al. (2011c) who demonstrated that contact situations are normally preceded by a bout of high-intensity running. The findings of the present study suggest that interchange players who experience more contact situations exhibit a greater running intensity as a result. However, other factors must also be considered.

When considering the relationship between contextual factors and running output amongst interchange players, it is important to account for the varying duration of each bout required of this position. In the present study, the week-to-week interchange strategy of the team in question remained relatively constant, and the length of the bout required of the player resulted in a decrease in running intensity throughout that bout. This is in support of Waldron et al. (2013), who observed a decrease in both total and high-speed relative distance as an on-field bout progressed amongst professional rugby league players. Taken together, these findings are indicative of an accumulation of fatigue throughout an on-field bout, however it is important to note that this is not a result of the duration of the bout alone, and is rather an interaction of multiple factors. For example, the running demands and resultant fatigue of defending are far greater than time spent attacking (Gabbett et al., 2014), which explains the small decrease in running intensity as a result of time in possession observed in the present study. Further, during a match, regular stoppages occur for a number of reasons including video referrals for refereeing decisions, or time off for injury. The present study found small decreases in running performance occurred as a result of an increase in ball-out-of-play time. These stoppages allow players to recover from intense periods of play, therefore potentially prolonging the length of their interchange bout. As a result, coaches must take care when employing replacement strategies based on time on the field alone, and should make informed decisions incorporating all available contextual information to maximise team performance.

The findings of the present study show that during matches against strong opposition, interchange players cover a greater relative distance throughout each on-field bout. In contrast, Kempton and Coutts (2015) reported no change in relative distance covered as a result of opposition strength, but did observe small to moderate influences on HSR. The small increase in P_{met} may reflect the more appropriate measure of high-intensity running amongst this cohort, and therefore it could be suggested that matches completed against strong opposition result in a greater overall high-intensity running demand. In addition, the current study attempted to quantify recent form by accounting for the number of wins achieved in the last five games played, which resulted in slight decreases in both measures of running intensity. However, recording wins alone may not appropriately for the context of those wins in relation to the entire competition, or the strength of the opposition defeated. As such, future research may benefit from accurately quantifying recent form, accounting for these contextual factors. Recently, amongst semi-elite interchange rugby league players, Black and Gabbett (2014) observed an increase in running intensity towards the end of a match players competing in losing teams. Interestingly, the present study observed no effect of match outcome on the running intensity achieved by interchanged players, which may reflect the higher quality of players in the current cohort, or the lack of differentiation of where a bout occurred throughout the match for these players.

Another contextual factor that may be accounted in the planning of interchange strategies is the recovery period between consecutive matches. Whilst previous research (Kempton & Coutts, 2015) showed that shorter match recovery periods resulted in decrements in running intensity measures, the present study showed contrary evidence of this, identifying that reduced recovery periods (5-6 days) positively influenced both measures of running intensity. It is suggested that the successful attenuation of training loads during shorter recovery periods may have assisted in the dissipation of fatigue, permitting athletes to re-perform in a superior physiological state. It is possible that the dissimilarities in these findings may be attributable to discrepancies in training loads between the two clubs, particularly in the days prior to match-play. Whilst this is difficult to ascertain, future research may investigate this utilising data from multiple teams that adopt different training load strategies, determining the resultant effect on match performance, or examining physiological measures of fatigue such as salivary immune and endocrine indicators (Coad, Gray, Wehbe, & McCellan, 2015; McLean, Coutts, Kelly, McGuigan, & Cormack, 2010).

Interestingly, it was noted that mid to late season games had a positive effect on P_{met} of interchange players. These findings are in support of Kempton and Coutts (2015), where early season games negatively affected running intensity, indicating that games later in the season demonstrated greater running intensities. Possible reasons for this may be the heightened importance of achieving a higher ladder position to make finals toward the end of the season or environmental factors such as reduced thermal strain during the winter months. Further, these findings may be evidence of successful training load periodisation and enhanced recovery strategies adopted to attenuate cumulative fatigue throughout a congested match schedule. In contrast to the observed effect of season phase on running intensity, results of the present study showed no notable effect of match location (home or away) on either measure of running intensity. This is in contrast to the findings of Kempton and Coutts (2015) where matches played away from home negatively influenced the running intensities achieved. This discrepancy between findings may be a result of the inclusion of only interchanged players in the present study, where it is possible that the reduced playing duration of these players may diminish the effects of match location. As such, more scope for research exists to examine the effect of match location particularly when extended travel is required on the potential of this to affect match performance.

There are several limitations that must be considered when interpreting the findings of this study. Firstly, the study was able to recruit one team in isolation, and therefore the results may differ between teams due to differences in coaching strategy, or overall team performance. Secondly, only one measure of physical fitness was able to be taken prior to the start of the season, and it may be that fitness levels may deviate throughout the course of a season. Lastly, outside of the collision counts provided in the present study, no attempt was made to quantify the intensity or physical cost of the contact situation. Whilst this is undoubtedly an important element of match-play within interchange rugby league players, current technology is unable to detect the isometric contractions that form a large component of the "wrestle" situation. As a result, it was a focus of the current research to quantify the running demands of these players only, and therefore these results must be taken cautiously.

PRACTICAL APPLICATIONS

The findings of this study permit coaching staff to adopt evidence based replacement strategies that consider the multifaceted interplay of factors that potentially affect running performances, facilitating maximum team performance. During match play, athletes are inhibited in their ability to generate running intensity when the ball is out of play, and this should be considered before making replacement interchange decisions. In addition, the relative demands of attacking play seem to be less demanding than defensive play, and therefore may allow a player to prolong an on-field bout. The ability to maintain a high running intensity throughout an interchange bout may be attenuated by the development of intermittent fitness abilities, including exposure to regular collision events. Tailoring of recovery strategies as well as manipulating training loads during shorter recovery periods and when playing greater opposition strength may also help facilitate the increased running demands inflicted by these contextual factors. However, these findings are reflective of only one team, and therefore future multi-centre studies are recommended to confirm the results of the present study.

CONCLUSIONS

This study examined the independent effects of various match-related, contextual and individual characteristics on the running intensities of interchange players during professional rugby league match play. The statistical approach utilised provides a comprehensive understanding of the percentage effect of the various interacting factors, superior to that of commonly used statistical methods. Factors recognised to have had the greatest detrimental effect on the running intensity included longer bout durations, greater opposition strength, the longer the time the ball was out of play and time spent in attack. In contrast, factors positively influencing the running intensities included the tackling involvements (the number of tackles made by the player and the number of tackles made to the player) and a shorter match recovery period.

ACKNOWLEDGEMENTS

There were no conflicts of interest. No external sources of funding were provided for the completion for this study.

Chapter 5

Importance, reliability and usefulness of acceleration measures in team sports

Delaney, J. A., Thornton, H. R., Cummins, C. J., & Duthie, G. M. (2017). Importance, reliability and usefulness of acceleration measures in team sports. *J Strength Cond Res.* (Published Ahead of Print). doi: 10.1519/JSC.0000000000001849.

ABSTRACT

The ability to accelerate, decelerate and change direction efficiently is imperative to successful team-sports performance. Traditional intensity-based thresholds for acceleration and deceleration may be inappropriate for time-series data, and have been shown to exhibit poor reliability, suggesting other techniques may be preferable. This study assessed movement data from one professional rugby league team throughout two full seasons and one pre-season period. Using both 5 Hz and 10 Hz global positioning systems (GPS) units, a range of acceleration-based variables were evaluated for their inter-unit reliability, ability to discriminate between positions, and associations with perceived muscle soreness. The reliability of 5 Hz GPS for measuring acceleration and deceleration ranged from good to poor (CV = 3.7-27.1%), with the exception of high-intensity deceleration efforts (CV = 11.1-11.8%), the 10 Hz units exhibited moderate to good inter-unit reliability (CV = 1.2-6.9%). Reliability of average metrics (average acceleration/deceleration, average acceleration and average deceleration) ranged from good to moderate (CV = 1.2-6.5%). Substantial differences were detected between positions using time spent accelerating and decelerating for all magnitudes, but these differences were less clear when considering the count or distance above acceleration/deceleration thresholds. All average metrics detected substantial differences between positions. All measures were similarly related to perceived muscle soreness, with the exception of high-intensity acceleration and deceleration counts. This study has proposed that averaging the acceleration/deceleration demands over an activity may be a more appropriate method compared to threshold-based methods, due to a greater reliability between units, whilst not sacrificing ability to detect both within and between-subject changes.

INTRODUCTION

Global positioning systems (GPS) are commonly used in team sports to quantify the movement patterns of athletes during training and competition (Cummins et al., 2013). Team-sport athletes typically run at average intensities of 80-140 $m \cdot min^{-1}$ throughout a match (Cummins et al., 2013), equating to an average speed of 1.3-2.3 $m \cdot s^{-1}$, which by most reported standards would not be considered as high intensity. Therefore, the quantification of an athlete's ability to accelerate, decelerate and change direction quickly and efficiently may be more important for successful field-sport performance (Lockie et al., 2011). These actions are often undertaken at low speeds, and despite not reaching classification as high-speed running, are physically taxing and have important implications for developing training and recovery protocols (Osgnach et al., 2010; Young et al., 2012). For example, competition acceleration/deceleration profiles have been associated with indicators of muscle damage (creatine kinase; CK) (Young et al., 2012), decreases in neuromuscular performance (Nedelec et al., 2014) and increases in perceived muscle soreness (Nedelec et al., 2014) amongst team-sport athletes. Using a rolling average technique, Furlan et al. (2015) demonstrated a lack of agreement between the peak periods of rugby sevens competition using either relative distance or an acceleration-based metabolic power metric. Intuitively, this suggests that the most intense periods of match-play for speed and acceleration occur separately from each other, and therefore these metrics represent independent components of team-sport competition.

The ability of 10 Hz GPS units to accurately assess the acceleration-based requirements of team-sports activity has been validated against a laser device sampling at 2000 Hz (Akenhead et al., 2014). It was found that the GPS units possessed acceptable validity for quantifying instantaneous speed during acceleration (coefficient of variation, CV = 3.6-5.9%) (Varley, Fairweather, et al., 2012). However, during deceleration, the ability of these units to assess running speed accurately decreased, due to a greater magnitude of change in speed (CV = 11.3%). The authors concluded that although the ability of GPS to accurately assess the magnitude of an acceleration/deceleration effort is limited, these units possess the ability to accurately determine whether an acceleration or deceleration event has occurred.

During team-sports, it is common practice to assess the acceleration/deceleration demands of an activity using the distance, time spent or the number of efforts performed within discrete acceleration bands (Cummins et al., 2013). Large between-unit variations have been observed using GPS to assess the number of acceleration (CV = 10-43%) and deceleration (CV = 42-56%) efforts during a team-sport simulation protocol (Buchheit, Al Haddad, et al., 2014), which might be a result of the measurement technique employed. For example, using a 3 $m \cdot s^{-2}$ cut-off threshold, two separate units may measure the same acceleration effort as 3.01 $m \cdot s^{-2}$ and 2.99 $m \cdot s^{-2}$, respectively. In this case, the first unit would classify this effort as an acceleration, however the second unit would not, despite a non-substantial difference between the two. To account for such between-unit variability in a practical setting, each player is often assigned the same unit for the entire season, though this is not always the case. For example, if the number of players in the squad exceeds the number of GPS units available, this becomes logistically difficult (Buchheit, Al Haddad, et al., 2014). Furthermore, it is common practice for researchers to pool data for an entire positional group to describe the different demands of each position (Cummins et al., 2013), which may be inappropriate if large errors between GPS units exist. Therefore, it may be that other methods are preferable for quantifying the acceleration-based demands of team-sports activity.

In an attempt to overcome the poor reliability of common acceleration measures, a recent study proposed a novel average acceleration/deceleration metric (Ave Acc/Dec; $m \cdot s^{-2}$) (Chapter 6). This technique involved taking the absolute value of all acceleration/deceleration data, and averaging over the duration of the defined period (match, drill etc.). It may be that such a technique is more appropriate for analysing time-series data, where all acceleration and deceleration efforts are accounted for, regardless of the magnitude. This is important, as low-intensity acceleration/deceleration work undoubtedly carries some physiological and neuromuscular cost (Akenhead, Harley, & Tweddle, 2016), and therefore, warrants inclusion when monitoring these demands. This metric has been shown to be adequately able to detect positional differences in the peak acceleration/deceleration profile of rugby league (Chapter 6), however no study has yet quantified its reliability between GPS units. Furthermore, if this measure is to be chosen in place of commonly-used methods such as acceleration counts, it is important that practitioners are confident that it can be used for the same purpose (i.e. directing recovery protocols). Therefore, this study aimed to assess the reliability and usefulness of a range of acceleration metrics using GPS technology.

METHODS

Experimental Approach to the Problem

To assess the importance, reliability and usefulness of acceleration variables attained using GPS technology, this study was divided into three sections. 1) The importance of acceleration/deceleration during team sports was determined by establishing the association between the temporal occurrence of the most intense period of match play, for running speed and acceleration/deceleration, respectively (Chapter 6). It was hypothesised that the period of a match where acceleration/deceleration intensity was greatest, would occur separately to the peak period for running speed. 2) Secondly, the inter-unit reliability and interchangeability of acceleration-based metrics was obtained from 38 GPS units from two separate manufacturers (as detailed below), concurrently measuring the same team-sports simulation session. 3) Finally, the usefulness of each of these measures was determined by evaluating their ability to discriminate between positions during team sports competition, and their associations with perceived muscle soreness during a team-sport preparation program.

Subjects

Forty-eight full-time professional rugby league players (24 ± 5 yr; 1.86 ± 0.06 m 99.5 ± 8.9 kg) competing in the National Rugby League (NRL) participated in this study. Permission was granted from a professional rugby league club competing in the NRL to perform analyses on match and training monitoring data across the 2015-16 seasons and the preseason period that divided them. Institutional ethics approval for a retrospective analysis of training load and match data was attained prior to the commencement of this study (HRE16-142).

Procedures

Part 1

To determine the association between the temporal occurrences of the peak periods of both speed and acceleration/deceleration, 742 match files were analysed, where only files containing at least 35 consecutive minutes of on-field playing time were included.

Further, of the 48 matches recorded, six were removed from analysis due to poor satellite connectivity at three separate stadiums, leaving 672 individual files (14 ± 9 per player, range 1-38). Movement data was recorded using portable GPS units that possessed a raw sampling rate of 5 Hz (SPI HPU, GPSports, Canberra, Australia) fitted into a custom-made pouch in their playing jersey, located between the scapulae. Each player was assigned the same unit for the entirety of the collection period to minimise inter-unit variability (Buchheit, Al Haddad, et al., 2014). Throughout this study, all data was downloaded and analysed by the same member of the research team. Following each match, data were downloaded using the appropriate proprietary software (Team AMS v 2016.1., GPSports, Canberra, Australia), and further analysed using customised software (R, v R-3.1.3.). Specifically, this software calculated the distance covered per unit of time (speed; $m{\cdot}min^{-1}$), and a novel average acceleration/deceleration metric (Ave Acc/Dec; $m{\cdot}s^{-2}$) (Chapter 6). This technique involved taking the absolute value of all acceleration/deceleration data, and averaging over the duration of the defined period. Finally, a moving average approach was utilised to calculate both the magnitude and temporal location of the peak intensities of each variable, for a range of moving average durations (1 to 10 minutes). Importance of acceleration was assessed as the disassociation between the occurrence of the peak speed and Ave Acc/Dec intensities.

Part 2

To assess the inter-unit reliability of acceleration-based measures using GPS, this study adapted the methodology of Buchheit et al. (2014), where 38 GPS units (5 Hz SPI HPU units, GPSports, Canberra Australia, n = 19; 10 Hz Catapult S5 units, Catapult Innovations, Melbourne, Australia, n = 19) were securely attached to a sprint sled. Units were placed in a vertical position to allow equal exposure of the embedded antennae, with at least 2 cm separating units. The sled was then fixed to a harness, which was attached to one team-sport athlete. The subject performed a 40-minute team sport simulation, which involved periods of walking, jogging and running, at a range of speeds and accelerations. Upon completion of the session, files were downloaded and trimmed using proprietary software (Team AMS, GPSports, Canberra, Australia; Openfield, Catapult Innovations, Melbourne, Australia), and further analysed using customised software (R, v R-3.1.3.). A range of commonly used acceleration-based variables were calculated, including the number of efforts, distance covered and time spent over predefined intensity thresholds (1, 2 and 3 $m{\cdot}s^{-2}$ for low, moderate and high, respectively). In addition, Ave Acc/Dec was calculated as in Part 1, and further divided into acceleration (Ave Acc; $m{\cdot}s^{-2}$) and deceleration (Ave Dec; $m{\cdot}s^{-2}$). Interunit reliability was assessed as the agreement of acceleration-based measures between units.

Part 3a

To establish the usefulness of acceleration-based metrics, the same 672 match files from Part 1 were re-analysed using customised software (R, v R-3.1.3.). Subjects were classified as either fullbacks, outside backs (centres and wingers), halves (half-backs and five-eighths), hookers, edge forwards (second rowers) or middle forwards (props and locks). Using a 5-minute moving average, the peak 5-minute period was calculated for each of the acceleration/deceleration metrics outlined in Part 2, and the ability of each metric to discriminate between positions was assessed.

Part 3b

Training load data was collected across an entire preseason period, which lasted 16 weeks. During this phase, subjects typically completed four-to-five field-based sessions, four strength sessions, and two recovery/hydrotherapy sessions per week. Running loads were recorded using GPS units that possess a raw sampling rate of 5 Hz (SPI HPU, GPSports, Canberra, Australia), and downloaded and analysed using the same protocol as Parts 1 and 2. For the three average metrics (Ave Acc/Dec, Ave Acc and Ave Dec), each drill value was multiplied by duration to convert to a load measure. Next, a 7-day exponentially-weighted moving average (EWMA) (Hunter, 1986) was calculated for each metric, and converted to a Z-score. Perceived muscle soreness was assessed using a one-to-ten Likert scale for five major muscle groups (hamstrings, calves, quadriceps, groins and gluteal), which were then averaged and converted to a Z-score for comparisons with training load data.

Statistical Analyses

The association between the temporal occurrence of the peak periods of running speed and acceleration/deceleration was assessed using chi-squared test, where statistical significance was set at $p < 0.05$. For example, if the peak periods for speed and acceleration/deceleration (for each moving average duration) overlapped, a "Yes" value was recorded. Conversely, if these phases of play did not overlap, this instance was classified as a "No", indicating that the peak periods of each metric occur independently of each other. Inter-unit reliability was calculated using the coefficient of variation (CV; ±90% confidence intervals [90% CI]). Differences between manufacturers were described using a magnitude-based approach, where differences were considered real if the likelihood of the effect exceeded 75% (Hopkins et al., 2009).

To assess differences between the peak periods of competition by position, a linear mixed effects model was used, specifying individual athletes as a random effect, as to account for different within-subject standard deviations that were nested within individual match files. Positional groups were specified as a fixed effect, describing the relationship between that and of the dependent variables. Pairwise comparisons between positional groups were assessed using the Least Squares mean test, that were further assessed using a magnitude based inference network (Hopkins et al., 2009). Differences were described using standardised effect sizes (ES), categorised using the thresholds of; <0.2 trivial, 0.21-0.60 small, 0.61-1.20 moderate, 1.21-2.0 large and >2.0 very large (Hopkins et al., 2009). Quantitative chances of real differences in variables were assessed as: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possibly; 75-97.5%, likely; 97.5-99% very likely; >99%, almost certainly (Hopkins et al., 2009).

Associations between training load and perceived muscle soreness were also evaluated using linear mixed models, by converting the models' *t* statistics to ES correlations (*r*) and the associated 90% CI (Rosnow et al., 2000). Effect size correlations were interpreted as <0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; 0.9-0.99, almost perfect; 1.0, perfect (Hopkins et al., 2009). Descriptive statistics are presented as mean ± standard deviation (SD), while all other data are reported as ES ± 90% CI, unless otherwise stated. All statistical analyses were performed using R statistical software (R, v R-3.1.3.).

RESULTS

Figure 5.1 demonstrates a significant effect of moving average duration on the association between the peak periods of speed and acceleration/deceleration during professional rugby league competition (χ^2 = 943, df = 9, p < 0.001). Interunit reliability statistics for both 5 Hz and 10 Hz GPS are presented in Table 5.1. The CV% for 5 Hz GPS for measuring acceleration and deceleration ranged from 3.7% to 27.1%. With the exception of high-intensity deceleration efforts (CV = 11.1-11.8%), the interunit reliability (CV%) of 10 Hz units was <7.0%. Reliability of average metrics (Ave Acc/Dec, Ave Acc and Ave Dec) ranged from 1.2% to 6.5%. Units from the two manufactures were not comparable on any acceleration-based metric.

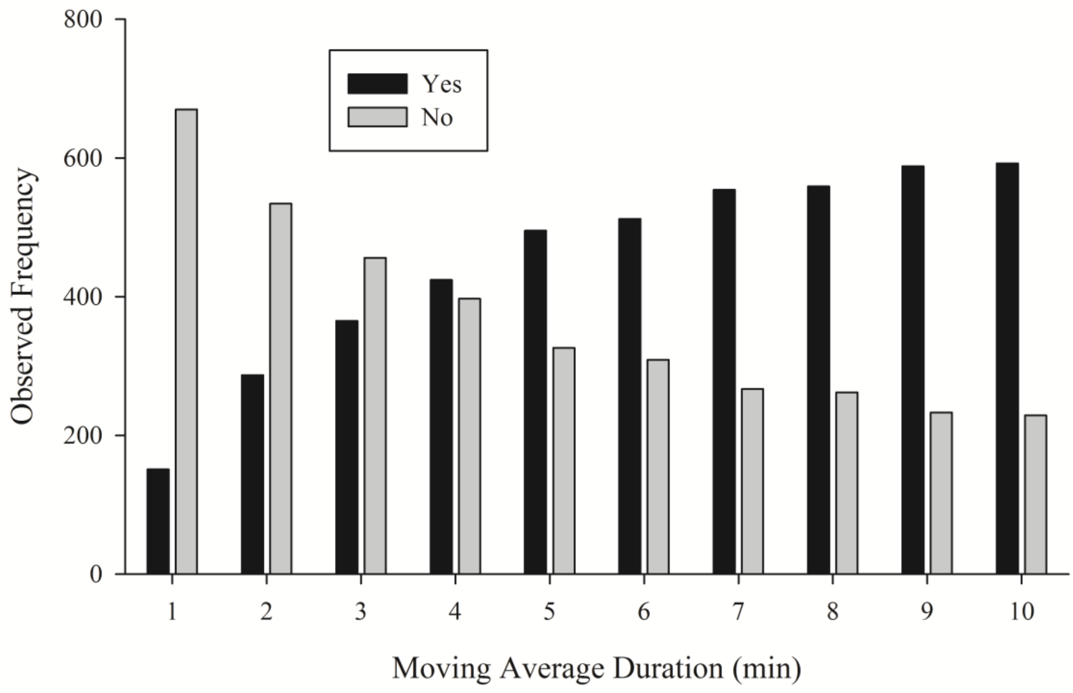

Figure 5.1: Temporal association between peak periods of acceleration/deceleration (m·s^{-2}) and relative distance (m·min^{-1}), represented as the observed frequency of overlapping periods.

Table 5.1: Inter-unit reliability and interchangeability of the global positioning systems (GPS) from two different manufacturers.

Variable	GPSports HPU (5 Hz)		Catapult S5 (10 Hz)		ES; 90% CI	Likelihood of the Difference
	Mean ± SD	CV%; 90% CI	Mean ± SD	CV%; 90% CI		
Average Acc/Dec ($m{\cdot}s^{-2}$)	0.72 ± 0.04	5.7%; 4.5-7.8%	0.56 ± 0.01	1.2%; 1.0 to 1.7%	1.18; 0.58 to 1.78	*likely* moderate
Average Acc ($m{\cdot}s^{-2}$)	1.16 ± 0.07	6.5%; 5.1 to 8.9%	0.83 ± 0.02	2.8%; 2.2 to 3.9%	1.57; 0.94 to 2.20	*likely* large
Average Dec ($m{\cdot}s^{-2}$)	-1.14 ± 0.06	4.9%; 3.8 to 6.8%	-0.61 ± 0.01	2.2%; 1.8 to 3.1%	3.40; 2.63 to 4.17	*most likely* very large
Low Acc (n)	60 ± 3	5.1%; 4.0 to 6.9%	112 ± 5	4.4%; 3.4 to 6%	1.79; 1.37 to 2.21	*very likely* large
Moderate Acc (n)	28 ± 1	3.7%; 2.9 to 5.0%	49 ± 3	5.3%; 4.2 to 7.3%	1.63; 1.20 to 2.05	*very likely* large
High Acc (n)	18 ± 2	13.2%; 10.5 to 18.1%	20 ± 1	5.9%; 4.7 to 8.2%	0.45; -0.06 to 0.95	*likely* small
Low Dec (n)	68 ± 3	4.6%; 3.7 to 6.3%	91 ± 3	3.3%; 2.6 to 4.5%	0.97; 0.51 to 1.42	*likely* moderate
Moderate Dec (n)	22 ± 1	4.8%; 3.8 to 6.6%	33 ± 2	5.2%; 4.1 to 7.2%	1.18; 0.74 to 1.63	*very likely* moderate
High Dec (n)	12 ± 1	6.5%; 5.2 to 8.9%	16 ± 1	4.8%; 3.8 to 6.6%	0.92; 0.46 to 1.38	*likely* moderate
Low Acc (s)	6.2 ± 0.3	5.5%; 4.4 to 7.5%	4.3 ± 0.1	2.1%; 1.7 to 3%	1.78; 1.13 to 2.42	*likely* large
Moderate Acc (s)	2.2 ± 0.3	13.4%; 10.7 to 18.4%	1.4 ± 0.1	3.9%; 3.1 to 5.4%	2.12; 1.39 to 2.84	*very likely* large
High Acc (s)	0.7 ± 0.2	24.3%; 19.3 to 33.3%	0.5 ± 0	5.6%; 4.4 to 7.8%	1.85; 1.01 to 2.68	*likely* large
Low Dec (s)	7.1 ± 0.5	7.0%; 5.6 to 9.6%	4.2 ± 0.1	1.6%; 1.3 to 2.2%	2.74; 2.01 to 3.47	*very likely* very large
Moderate Dec (s)	2.2 ± 0.3	14.8%; 11.8 to 20.3%	0.9 ± 0.1	6.4%; 5 to 8.8%	5.75; 4.65 to 6.84	*most likely* very large
High Dec (s)	0.6 ± 0.1	17.9%; 14.2 to 24.5%	0.2 ± 0	11.8%; 9.3 to 16.3%	5.76; 4.63 to 6.89	*most likely* very large
Low Acc (m)	849 ± 38	4.5%; 3.6 to 6.2%	590 ± 10	1.7%; 1.4 to 2.4%	1.75; 1.12 to 2.39	*likely* large
Moderate Acc (m)	354 ± 47	13.4%; 10.6 to 18.4%	226 ± 10	4.4%; 3.5 to 6.1%	2.22; 1.49 to 2.96	*very likely* large
High Acc (m)	132 ± 36	27.1%; 21.5 to 37.1%	79 ± 5	6.9%; 5.5 to 9.6%	2.59; 1.63 to 3.55	*likely* very large
Low Dec (m)	882 ± 65	7.4%; 5.9 to 10.1%	584 ± 11	1.8%; 1.4 to 2.5%	2.03; 1.36 to 2.7	*very likely* large
Moderate Dec (m)	316 ± 55	17.3%; 13.7 to 23.7%	125 ± 7	5.7%; 4.5 to 7.9%	5.94; 4.77 to 7.11	*most likely* very large
High Dec (m)	79 ± 18	23%; 18.3 to 31.6%	29 ± 3	11.1%; 8.8 to 15.4%	6.12; 4.82 to 7.42	*most likely* very large

ES = effect size; m = metres; Acc = acceleration; Dec = deceleration; CV = coefficient of variation; CI = confidence intervals; n = number; s = second; m = metre.

Table 5.2: Ability of various acceleration-based measures to detect positional differences in team sports using global positioning systems.

Variable	Edge Forwards	Fullbacks	Halves	Hookers	Middle Forwards	Outside Backs
Ave Acc/Dec ($m \cdot s^{-2}$)	0.89 ± 0.08	0.84 ± 0.06	0.92 ± 0.07[abef]	0.90 ± 0.09[abef]	0.84 ± 0.09	0.85 ± 0.08
Ave Acc ($m \cdot s^{-2}$)	0.44 ± 0.04	0.41 ± 0.03	0.45 ± 0.04[abef]	0.44 ± 0.04[abef]	0.40 ± 0.04	0.42 ± 0.04
Ave Dec ($m \cdot s^{-2}$)	0.46 ± 0.04	0.44 ± 0.03	0.48 ± 0.04[abef]	0.47 ± 0.05[abef]	0.44 ± 0.04	0.44 ± 0.04
Low Acc (n)	33.7 ± 4.0[f]	31.0 ± 4.8	37.6 ± 5.4[abef]	37.2 ± 5.5[abef]	31.6 ± 4.7	30.4 ± 6.4
Moderate Acc (n)	16.1 ± 2.5	15.6 ± 2.5	18 ± 3.2[abef]	16.7 ± 3.1[abef]	14.8 ± 2.7	15 ± 3.3
High Acc (n)	7.3 ± 1.7	7.6 ± 2.3	7.4 ± 2.2	7.0 ± 2.2	7.2 ± 2.2	7.0 ± 2.0
Low Dec (n)	32.9 ± 3.3[b]	30.1 ± 4.5	37.9 ± 4.5[abef]	35.6 ± 4.3[abef]	31.0 ± 4.1[b]	30.7 ± 5.5[b]
Moderate Dec (n)	12.6 ± 2.2[bf]	11.1 ± 2.1	11.5 ± 2.3	11.1 ± 2.1	11.2 ± 2.8	10.3 ± 2.5
High Dec (n)	4.4 ± 1.2e	4.3 ± 1.1	3.5 ± 1.3	3.1 ± 1.3	3.5 ± 1.4	3.9 ± 1.1
Low Acc (s)	47.8 ± 6	45.0 ± 4.6	50 ± 5.9[abef]	48.3 ± 6.3[abef]	44.0 ± 6.1	44.6 ± 5.9
Moderate Acc (s)	17.9 ± 2.9[b]	15.9 ± 1.7[f]	17.8 ± 2.4[bef]	18.4 ± 3.1[abef]	16.5 ± 2.7	15.9 ± 2.9
High Acc (s)	8.4 ± 1.6[b]	7.6 ± 1.3	7.8 ± 1.0	8.7 ± 1.3[abcef]	8.0 ± 1.5	7.6 ± 1.2
Low Dec (s)	51.1 ± 5.6	48.0 ± 4.7	54.8 ± 4.8[abe]	52.9 ± 6.7[abef]	48.3 ± 5.6	48.6 ± 5.3
Moderate Dec (s)	19.6 ± 2.5[a]	16.4 ± 3.1	19.4 ± 2.6[af]	18.9 ± 3.1[af]	17.8 ± 3[a]	16.9 ± 3[a]
High Dec (s)	7.9 ± 1.4[cdf]	6.2 ± 1.2	7.0 ± 1.5	7.2 ± 1.6[bcef]	6.6 ± 1.5[a]	6.2 ± 1.5[a]
Low Acc (m)	109.8 ± 51.3[e]	109.5 ± 13.2	106.8 ± 14.9[e]	103.4 ± 16.2[e]	93.8 ± 19.3	96.4 ± 16.1
Moderate Acc (m)	35.2 ± 8.4	35.6 ± 5.5	33.4 ± 5.1[e]	33.4 ± 7.6[e]	30.2 ± 6.6	31.8 ± 7.1
High Acc (m)	12.1 ± 4.3	11.1 ± 2.6	10.6 ± 2.4	10.8 ± 3.1	9.7 ± 3.1	10.8 ± 2.8
Low Dec (m)	123.3 ± 49.6	121.3 ± 11.1	124.3 ± 15.5	121.4 ± 19.1	108.7 ± 22.6	109.7 ± 17.1
Moderate Dec (m)	50.0 ± 9.1	45.5 ± 6.3	46.9 ± 7.4[ef]	45.7 ± 8.9[ef]	43.3 ± 9.2	42.8 ± 8.4
High Dec (m)	22.3 ± 4.3[cf]	20.2 ± 3.8	19.1 ± 4	19.3 ± 4.3	18.5 ± 4.4	18.7 ± 4.2

ES = effect size; m = metres; Acc = acceleration; Dec = deceleration; n = number; s = second; m = metre. [a] = greater than edge forwards, [b] = greater than fullbacks, [c] = greater than halves, [d] = greater than hookers, [e] = greater than middle forwards, [f] = greater than outside backs. All differences considered real if likelihood of effect exceeding 0.2 × between-subject SD was greater than 75%.

Ability of acceleration-based measures to discriminate positional demands can be found in Table 5.2. Differences were detected between positions using time spent accelerating and decelerating for all magnitudes, but these differences were less clear when considering the count or distance above acceleration/deceleration thresholds. The Ave Acc/Dec, Ave Acc and Ave Dec techniques all detected substantial differences between positions.

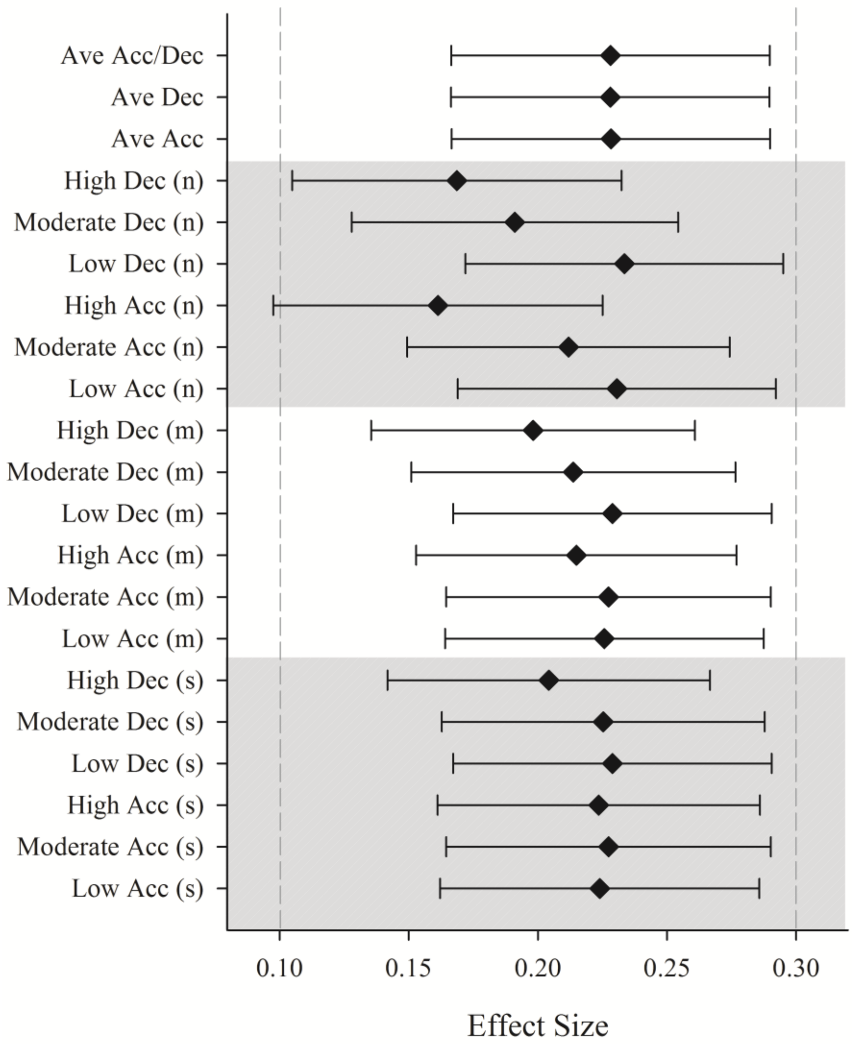

Figure 5.2: Association between acceleration and deceleration measures and perceived muscle soreness, presented as effect size ± 90% confidence interval.

Associations between acceleration/deceleration and perceived muscle soreness are illustrated in Figure 5.2. There were at least *likely* small positive relationships between perceived soreness and all acceleration and deceleration counts (ES [*r*] = 0.16-0.23), *very likely* small positive relationships with distance covered accelerating/decelerating (ES [*r*] = 0.20-0.23) and *most likely* small positive relationships with time spent accelerating and decelerating (ES [*r*] = 0.20-0.23). There were *most likely* small positive associations between muscle soreness and Ave Acc (ES [*r*] = 0.23, 90% CI = 0.17 to 0.29), Ave Dec (0.23, 0.17 to 0.29) and Ave Acc/Dec (0.23, 0.17 to 0.29).

DISCUSSION

The ability to accelerate, decelerate and change direction effectively is vital for team sports, commonly due to spatial constraints imposed by opposition players or field dimensions (Kempton, Sirotic, Rampinini, et al., 2015). Whilst GPS technology represents a method for quantifying these capacities during team-sports training and competition, due to the rapid nature of these movements, they are often difficult to capture effectively with these devices (Varley, Fairweather, et al., 2012). In agreement with the study hypothesis, the novel method of averaging acceleration and deceleration data over select temporal periods was determined to be a more robust technique for capturing the intensity of these movements during team-sports activity, and may be more appropriate when compared to using threshold-based methods. Furthermore, this increase in stability does not decrease the metrics ability to detect changes both within and between individuals, and therefore this measure presents as a preferable method for quantifying the acceleration/deceleration intensity of team-sports competition using GPS technology.

In support of our hypothesis, the present study observed that the peak periods of acceleration/deceleration often occurred separately to the peak periods of speed (Figure 1), particularly for moving average windows of shorter durations (<5 minutes). In the context of the cohort used within the present study (i.e., rugby league players), it may be that the acceleration/deceleration demands might be highest when defending the try-line, whilst the peak speed-based intensities might occur when a line break is made, resulting in a greater distance to be covered per unit of time. Although somewhat related, the correlation between acceleration and maximal sprinting speed (r = 0.56-0.87) (Harris, Cronin, Hopkins, & Hansen, 2008; Little & Williams, 2005; Vescovi & McGuigan, 2008) suggests that these are independent qualities (Buchheit, Samozino, et al., 2014). Moreover, it would seem that these events are equally as important to the match outcome, and therefore, should be prepared for appropriately. However, an interesting finding of the present study was that for moving averages of longer durations (>5 minute), the peaks in either speed or acceleration/deceleration more commonly occurred at the same time, suggesting that training drills of longer duration should be incorporative of both speed-based and accelerated/decelerated running.

When considering the reliability of GPS technology, the majority of literature has concentrated on the intra-unit reliability of the unit, or the repeatability of measures taken from the same device on repeat occasions (Scott et al., 2016). This is vital for the accuracy of within-individual comparisons, or for calculating accumulated training load over time. However, knowledge of the inter-unit reliability of these units is also important, for differentiating positional demands during training or matches, or for making comparisons with published literature and norms. The present study observed that across all acceleration and deceleration measures, there was a clear, inverse relationship between the magnitude of the change in speed, and the accuracy of the units.

This is a well-known limitation of GPS, which is a result of a limited sampling rate of these devices (Akenhead et al., 2014; Buchheit, Al Haddad, et al., 2014; Johnston, Watsford, et al., 2014). These findings are in line with others (Varley, Fairweather, et al., 2012), where an increase in sampling rate resulted in a greater stability of acceleration-based measures, and therefore, a minimum sampling rate of 10 Hz is recommended for comparing threshold-based acceleration measures between players and/or position groups. However, of all measures assessed within this study, the average metrics possessed the greatest inter-unit reliability, particularly with 10 Hz devices. This is not surprising, as small differences between units can be magnified using intensity bands, as two non-substantially different efforts could quite easily be classified into different zones (Buchheit et al., 2015). Although none of the acceleration-based measures reported within this study were comparable between manufacturers, the stability of several of these within the same manufacturer allows coaches and practitioners to compare the acceleration-based demands of athletes within the same session, or relate to published literature.

Whilst knowledge of the reliability of a measure is important, an increase in stability may come at the cost of a decrease in usefulness. If a particular metric is not able to detect subtle differences between sessions, players or positions, the reliability of the measure becomes redundant. Within the present study, the usefulness of each acceleration-based metric in a team-sport setting was assessed in two ways. Firstly, the ability of each measure to discriminate between the peak intensities of competition for different positions was examined. Across all methods, there seemed to be an increase in the acceleration/deceleration profile for hookers and halves when compared to all other positions, though this difference was clearer for some methods compared to others. This is in agreement with other research, where inter-positional differences in acceleration and deceleration profiles have been reported (Akenhead et al., 2016; Taskin, 2008) (Chapter 6). Though the present study cannot attest to the validity or accuracy of these metrics in such a chaotic environment, it would seem that the average acceleration/deceleration metrics proposed by this study are equally able to detect positional differences as threshold-based methods.

Lastly, this study evaluated the association between accumulated acceleration-based training loads and self-reported perceived muscle soreness. The present study observed that most acceleration and deceleration measures were similarly related to perceived muscle soreness (ES = ~0.20-0.25), with the exception of high-intensity acceleration and deceleration counts and distances. Both time spent above each intensity threshold and acceleration/deceleration averaged over the duration of each drill exhibited small but consistent relationships with perceived muscle soreness. Objective markers of muscle damage (CK) have been linked to high-intensity decelerations (Young et al., 2012), possibly due to the high eccentric force production involved during deceleration. The concentration of CK and the time course of muscle function recovery following sport-specific repeated sprint efforts has been examined (Howatson & Milak, 2009). Specifically, CK and muscle function, as measured by maximal isometric voluntary contractions, were impaired 24 hr post-exercise when compared to pre-exercise, and perceived muscle soreness was elevated 24 hr following the protocol (Howatson & Milak, 2009). Taken together, it would seem that monitoring the time spent accelerating/decelerating, or the density of accelerated and/or decelerated running (i.e. Ave Acc, Ave Dec and Ave Acc/Dec) will provide coaches with the useful information as to the training status of their athletes for sessions on upcoming days.

Given that the peak match intensities of various team sports have been quantified (Chapters 3, 6, 7 and 11), coaches may utilise these data to optimally periodise a training program that reflects the typical microcycle of their athletes, such as a "multiple peaking" model commonly required of team sports athletes (Pyne, Mujika, & Reilly, 2009). It has been established that compared to constant speed running, acceleration and deceleration at low speed can elicit a substantially different physical and mechanical stress (Buchheit, Samozino, et al., 2014; Osgnach et al., 2010). For example, high-speed running relies heavily on stretch-shortening cycle activity, lower-limb stiffness and hip extensor activity to generate greater vertical force production (Dorn, Schache, & Pandy, 2012). In contrast, acceleration is generally considered a result of concentric force development, impulse and hip and knee extensor activity (Harris et al., 2008; Little & Williams, 2005; Vescovi & McGuigan, 2008). As such, performance staff may be interested in the tactical periodization of training drills with these capacities in mind, in collaboration with an appropriate resistance training program, allowing a specificity of both the technical and physical aspects of competition.

The present study has presented a comprehensive overview of the use of acceleration-based metrics using GPS technology within team sports. Despite the clear importance of acceleration to success in team-sports activity, there remains no consensus to the most appropriate method of quantifying these demands using GPS technology. It is suggested by the current authors that when addressing time-series data, it is inappropriate to classify actions by their intensity, using predefined thresholds. The present study has presented a simple method for the accurate quantification of acceleration and deceleration in a team sport setting, where all changes in speed are included, regardless of their magnitude. Overall this method seems to be equally if not more reliable than threshold-based methods for assessing these demands, and this increased stability did not seem to be detrimental to the usefulness of the metric. Therefore, averaging the acceleration and/or deceleration profile of an activity seems to be a more appropriate method for the measurement of these demands during team-sports competition and training when compared to traditional threshold-based measures.

PRACTICAL APPLICATIONS

- Classification of acceleration/deceleration into intensity bands is inappropriate for time-series data, and is primarily poorly reliable, and averaging the demands over select periods is a more stable, equally as useful and therefore more appropriate method.
- Coaches may measure acceleration and deceleration independently from each other, or combine as an indication of overall acceleration/deceleration, or multiply by the duration of the drill, reflective of the load imposed through acceleration and deceleration.
- Monitoring the density of these demands during specific training methodologies relative to peak match intensity will assist coaches in ensuring that athletes are prepared to compete at the level required during competition, and furthermore will provide useful information regarding the efficacy of certain training drills for developing acceleration/deceleration capacity.
- It is recommended that practitioners establish the smallest worthwhile change (SWC) within their own specific cohort, to determine whether each of the variables assessed in the present study are practically useful for detecting within-individual changes in their environment (i.e. CV% < SWC).

Chapter 6

Acceleration-based running intensities of professional rugby league match-play.

Delaney, J. A., Duthie, G. M., Thornton, H. R., Scott, T. J., Gay, D., & Dascombe, B. J. (2016). Acceleration-based running intensities of professional rugby league match play. *Int J Sports Physiol Perform*. *11*(6), 802-809. doi: 10.1123/ijspp.2015-0424.

ABSTRACT

Rugby league involves frequent periods of high-intensity running including acceleration and deceleration efforts, often occurring at low speeds. ***Purpose*:** To quantify the energetic cost of running and acceleration efforts during rugby league competition to aid in prescription and monitoring of training. ***Methods*:** Global Positioning System (GPS) data were collected from 37 professional rugby league players across two seasons. Peak values for relative distance, average acceleration/deceleration and metabolic power (P_{met}) were calculated for ten different moving average durations (1 to 10 minutes), for each position. A mixed-effects model was used to assess the effect of position for each duration, and individual comparisons were made using a magnitude-based inference network. ***Results*:** There were *almost certainly* large differences in relative distance and P_{met} between the 10-minute window and all moving averages <5 minutes in duration (ES = 1.21-1.88). Fullbacks, halves and hookers covered greater relative distances than outside backs, edge forwards and middle forwards for moving averages that lasted between 2 and 10 minutes. Acceleration/deceleration demands were greatest in hookers and halves compared to fullbacks, middle forwards and outside backs. P_{met} was greatest in hookers, halves and fullbacks compared to middle forwards and outside backs. ***Conclusions*:** Competition running intensities varied by both position and moving average duration. Hookers exhibited the greatest P_{met} of all positions, due to high involvement in both attack and defence. Fullbacks also reached high P_{met}, possibly due to a greater absolute volume of running. This study provides coaches with match data that can be used for the prescription and monitoring of specific training drills.

INTRODUCTION

The importance of Global Positioning Systems (GPS) for quantifying rugby league competition demands has been thoroughly documented (Kempton et al., 2014; McLellan et al., 2011). Recently, the most intense periods of match play have been described, using a moving average method (Chapter 5). Briefly, this method applied a moving average to match position-time data to determine the peak relative distance achieved during competition amongst professional rugby league players, for a range of moving average durations. It was observed that as the length of the moving average was reduced, the maximal relative running intensity increased significantly. Such data demonstrated running intensities as high as 156 ± 12 $m \cdot min^{-1}$ for a 1-minute window. These values present substantially greater physical demands than previously reported by the relative distances for rugby league match-play, which typically range between 80-100 $m \cdot min^{-1}$ (Johnston, Gabbett, et al., 2014). Whilst such data regarding the running intensities of rugby league are useful, it could be suggested that they are limited in their ability to account for the varying match demands of different positions. Gabbett et al. (2012b) reported that collisions (i.e. hit-ups and tackles) are more frequent in hit-up forwards than any other position. Subsequently, the ability of forwards to cover large relative distances may become impaired, due to the constant presence of opposition players (Waldron, Twist, et al., 2011). These positions are regularly required to accelerate, decelerate and change direction, for which the physical demands are typically not accounted for by traditional speed-based methods (di Prampero et al., 2005).

Previously, di Prampero et al. (2005) presented a theoretical model that quantified the energetic cost of accelerations and decelerations. This model considers the energetic cost of accelerated running on flat terrain to be equivalent to the known physiological cost of uphill running at a constant pace (di Prampero et al., 2015). Using the acceleration of a player at any time point, an instantaneous energy cost can be estimated. This cost can be summated to provide an estimation of overall energy expenditure throughout the activity, or multiplied by speed, as an indication of metabolic power (P_{met}; $W \cdot kg^{-1}$) (di Prampero et al., 2015). Recently, this model has been applied to team sports such as soccer (Osgnach et al., 2010), Australian football (AF) (Coutts et al., 2015), rugby sevens (Furlan et al., 2015) and rugby league (Kempton, Sirotic, Rampinini, et al., 2015). For example, amongst professional soccer players, Osgnach et al. (2010) estimated the distance players would have covered at a constant pace, using the total energy expenditure throughout the match (equivalent distance, EqD). It was found that players EqD exceeded actual distance by around 20%. Using a similar analysis amongst AF players, Coutts et al. (2015) reported a difference of just 10-11%, indicating a greater percentage of constant running amongst these athletes. However, when considering rugby league players, Kempton et al. (2015) reported higher differences of 27-29%, suggesting a greater proportion of accelerated running contributed to energy expenditure compared to soccer and AF players.

As previously stated, the running demands of certain positions in rugby league are limited due to the presence of opposition players and, as a result, may increase the reliance on acceleration abilities. Fullbacks have been shown to exhibit a greater running intensity than any other position, due to the open-style running requirements of this position (Chapter 5). In contrast, Kempton et al. (2015) compared distance covered over a high-power running (HPR) threshold of 20 $W \cdot kg^{-1}$ with distance covered over a traditional high-speed running (HSR) threshold of 14.4 $km \cdot h^{-1}$. The difference between these two values was strongly influenced by position, with hit-up forwards covering 76% more distance at HPR compared to HSR, whilst the difference for outside backs (wingers and centres) was just 37%. These data outline a significant oversight by previous match-play analysis techniques, where high-intensity activities performed at low velocities were unaccounted for. However, the HPR and HSR data reported by these authors are representative of absolute match values, and have limited application in the prescription and monitoring of training. Therefore, the aim of this study was to describe the acceleration-based duration-specific running demands of rugby league match-play, for the development of precise training methodologies. The overloading of these demands through an appropriately periodised program may result in increases in relevant physical capacities, and in turn, match performance.

METHODS

Design

GPS data were collected during the 2013 and 2014 National Rugby League (NRL) competitive seasons, to establish the duration and position-specific, acceleration-based running demands of rugby league. Prior to the commencement of the study, all subjects were informed of the aims and requirements of the research, and informed consent was obtained. The Institutional Human Ethics Committee approved all experimental procedures.

Subjects

Thirty-seven professional rugby league players (27.0 ± 5.1 yr, 98.5 ± 8.8 kg, 1.84 ± 0.05 m) from the same club volunteered for this study. Data was collected throughout 43 matches of the 2013 (12 wins, 10 losses, 1 draw, final position 7th) and 2014 NRL seasons (9 wins, 11 losses, final position 12th). It must be noted that some minor rule changes were introduced at the beginning of the 2014 season, aimed to increase the amount of time the ball was active in play (e.g. total game time once stoppages are removed). However, data obtained from a commercial statistics provided (Prozone, Sydney, Australia) revealed that ball-in-play time, for matches involving the team in question, between seasons was similar between the 2013 and 2014 season (mean ± SD; 52.7 ± 5.0 and 53.0 ± 3.9 minutes, respectively), and therefore this was deemed to have little effect.

A typical training week consisted of 2-3 field sessions, 1-2 resistance sessions and 1-2 recovery-based sessions. Each match was 80 minutes in duration that was separated into two 40-minute halves. Players were classified by playing position as follows: fullbacks (n = 39), outside backs (n = 153), halves (half-back and five-eighth; n = 81), middle forwards (props and locks; n = 200), edge forwards (second rowers; n = 81) and hookers (n = 58). The mean (± SD) number of observations per player was 17 ± 13.

Methodology

The match running demands of players were recorded using a portable GPS unit at a raw sampling rate of 5 Hz (SPI HPU, GPSports, Canberra, Australia). These units were worn in a customised padded pouch in the player's jersey and positioned in the centre of the upper back area, slightly superior to the scapulae. The number of satellites and horizontal dilution of precision (HDOP) during match play were 8.3 ± 1.4 and 1.1 ± 0.1, respectively. Whilst the validity and reliability of GPS for measures of total distance have been established (Johnston, Watsford, et al., 2014; Rampinini et al., 2015), the inter-unit reliability of GPS for assessing accelerations during team-sport movements has been questioned (Buchheit, Al Haddad, et al., 2014). To account for this issue, each player wore the same unit for the entire study. Lastly, whilst the validity of the calculations of di Prampero et al. (2005) for estimating the energetic requirements of team-sports movements has varied between studies (Buchheit et al., 2015; Buglione & di Prampero, 2013; Stevens et al., 2014), mean P_{met} has recently been presented as a stable marker of locomotor load, where acceleration and speed-based running are accounted for (coefficient of variation [CV] = 4.5%) (Rampinini et al., 2015). As a result, this measure was selected as the most appropriate measure for quantifying the chaotic nature of rugby league match-play.

Upon completion of each match, GPS data were extracted using the appropriate proprietary software (Team AMS, Canberra, Australia). A total of 612 individual match files were obtained. Each file was trimmed to include only match time (excluding extra-time periods) and within-match stoppages (i.e. decision referred to video referee), and the average total match duration was 86 ± 13, 84 ± 12, 52 ± 14, 81 ± 15, 47 ± 15 and 87 ± 9 minutes for fullbacks, halves, hookers, edge forwards, middle forwards and outside backs, respectively. If a player's match time was less than 10 minutes, the file was removed from analysis. Velocity-time curves were linearly interpolated to 15 Hz, and a fourth-order Butterworth filter applied with a 1 Hz cut-off frequency. Following this, each file was further analysed using customised MATLAB® software (Version 8.4.0.150421, MathWorks Inc, MA, USA). This method allowed the computation of a number of output variables for each player, including relative distance ($m \cdot min^{-1}$), average acceleration/deceleration (Ave Acc/Dec; $m \cdot s^{-2}$) and metabolic power (P_{met}; $W \cdot kg^{-1}$) (Osgnach et al., 2010). For this study, relative distance was representative of the traditional model, where accelerated running is ignored. For the Ave Acc/Dec measure, all values (accelerations and decelerations) were made to be positive, and this variable provided an indication of the total acceleration requirements of the athlete, irrespective of speed. Finally, P_{met} was calculated by integrating the instantaneous speed and acceleration, using the energetic calculations detailed previously (di Prampero et al., 2005; Osgnach et al., 2010).

The customised MATLAB® software was then used for the computation of a moving average over each output variable, using ten different durations (1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 minutes), and the maximum value for each duration was recorded. For example, for a 1-minute rolling average, the software identified the 900 consecutive data points (i.e. 15 samples per second for 60 seconds) where the subject exhibited the highest values. For a 2-minute rolling average, 1800 samples were used, etc. As a result, for each match, maximum values for each of the three output variables (relative distance, Ave Acc/Dec, P_{met}) were calculated for each of the 10 moving average durations. Data was then collated by playing position, and averaged across all observations for that positional group, for between-position comparisons.

Statistical Analyses

Data distribution was assessed for normality using the Shapiro-Wilk test. If a dataset violated the assumption of normality, the data was log-transformed to reduce the non-uniformity of error. A multilevel linear mixed-effects model was constructed to determine differences in the individual responses in running intensity between positions (n = 6) for each moving average duration (n = 10). Individuals were included as a random effect in the model, to correct for pseudoreplication. When significant main effects were observered, data were entered into a customised spreadsheet (Microsoft Excel; Microsoft, Redmond, USA), where pairwise comparisons between groups were made using a magnitude-based inference network (Hopkins, 2007). This method assessed the probability that differences were greater than the smallest worthwhile difference (SWD), calculated as 0.2 × the between-subject SD. Further, to examine the effect of moving average duration on running intensities, a magnitude-based approach was used to compare moving averages 1-9 to the 10-minute moving average, for each outcome variable. Quantitative chances of real differences in variables were assessed qualitatively as: <1%, *almost certainly not*; 1-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, possibly; 75-97.5%, *likely*; 97.5-99% *very likely*; >99%, *almost certainly* (Hopkins, 2007). A difference was considered substantial when the likelihood that the true value was greater than the SWD exceeded 75%. Where necessary, statistical analyses were performed using R statistical software (R 3.1.0, R foundation for Statistical Computing), and significance was set at $p < 0.05$.

RESULTS

The mixed-model analysis revealed significant main effects duration for each outcome variable. Figure 6.1 illustrates the increasing running demands of competition as a function of moving average duration. Comparisons with the 10-minute moving average revealed *almost certainly* large increases in relative distance covered and P_{met} for moving averages 1 to 4 minutes in duration, and *almost certainly* large increases in Ave Acc/Dec for moving averages 1 to 2 minutes in duration (Table 6.1). All windows shorter than 8 minutes were *almost certainly* greater for both Ave Acc/Dec and P_{met} respectively. For relative distance covered, all windows except for the 9-minute window were *almost certainly* higher when compared to the 10-minute moving average.

A significant effect of position was observed for all moving average durations for both relative distance and $P_{met.}$ For the Ave Acc/Dec measure, the model revealed significant effects for moving averages of 2 to 10 minutes in duration, but no differences between position for the 1-minute window. Maximum relative distances for each moving average duration are displayed in Table 6.2. There were *likely* small to moderate increases in relative distance covered for hookers and halves compared to edge forwards, outside backs and middle forwards across all moving averages. Fullbacks exhibited *almost certainly* large increases in relative distance compared to outside backs for moving averages of 5 to 10 minutes in duration.

Table 6.3 illustrates positional differences in Ave Acc/Dec across moving averages 2 to 10 minutes in duration. Edge forwards exhibited at least *likely* small increase in Ave Acc/Dec compared to fullbacks, outside backs and middle forwards for moving averages between 2 and 4 minutes in duration. For moving averages greater than this, the difference was *likely* to be moderate. Halves and hookers presented at least *likely* moderate increases compared to outside backs and middle forwards for all moving averages at least 2 minutes in duration.

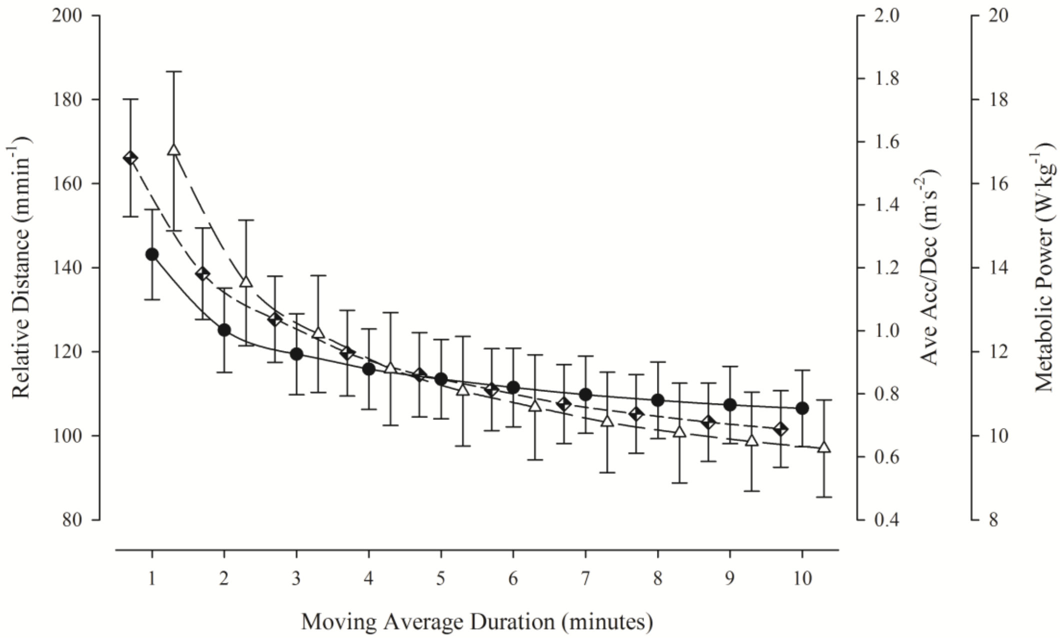

Figure 6.1: Maximum running intensities of rugby league match-play by rolling average duration. Data are presented as mean ± SD for each outcome variable.

Fullbacks and hookers maintained a greater P_{met} compared to edge forwards, outside backs and middle forwards across all moving average durations, and the magnitude of these differences were at least *likely* to be moderate (Table 6.4). Halves were also able to attain a greater P_{met} than outside backs and middle forwards for moving averages 2 to 10 minutes in duration, but exhibited poorer values compared to fullbacks for the 1-minute window.

Table 6.1: Magnitude of increase in running intensities compared to 10-minute moving average. Differences are presented as mean ±90% confidence limits (90% CL).

Moving Average Length (minutes)	Relative Distance ($m \cdot min^{-1}$)		Ave Acc/Dec ($m \cdot s^{-2}$)		Metabolic Power ($W \cdot kg^{-1}$)	
	Mean; ±90% CL	**Effect size, likelihood of effect**	**Mean; ±90% CL**	**Effect size, likelihood of effect**	**Mean; ±90% CL**	**Effect size, likelihood of effect**
1	64; ±5	1.88, *Almost certainly* large ↑	0.49; ±0.04	1.76, *Almost certainly* large ↑	7.1; ±0.5	1.83, *Almost certainly* large ↑
2	37; ±3	1.76, *Almost certainly* large ↑	0.25; ±0.02	1.39, *Almost certainly* large ↑	3.9; ±0.3	1.65, *Almost certainly* large ↑
3	26; ±2	1.61, *Almost certainly* large ↑	0.17; ±0.01	1.13, *Almost certainly* moderate ↑	2.7; ±0.2	1.46, *Almost certainly* large ↑
4	18; ±1	1.36, *Almost certainly* large ↑	0.12; ±0.01	0.90, *Almost certainly* moderate ↑	1.9; ±0.1	1.21, *Almost certainly* large ↑
5	13; ±1	1.12, *Almost certainly* moderate ↑	0.09; ±0.01	0.70, *Almost certainly* moderate ↑	1.4; ±0.1	0.97, *Almost certainly* moderate ↑
6	9; ±1	0.89, *Almost certainly* moderate ↑	0.07; ±0.01	0.52, *Almost certainly* small ↑	1.0; ±0.1	0.75, *Almost certainly* moderate ↑
7	6; ±1	0.61, *Almost certainly* moderate ↑	0.04; ±0.01	0.35, *Almost certainly* small ↑	0.6; ±0.1	0.51, *Almost certainly* small ↑
8	4; ±1	0.38, *Almost certainly* small ↑	0.03; ±0.01	0.21, *Possibly* small ↑	0.4; ±0.1	0.31, *Very likely* small ↑
9	2; ±1	0.17, *Possibly* trivial ↑	0.01; ±0.01	0.09, *Very unlikely* trivial ↑	0.2; ±0.1	0.14, *Unlikely* trivial ↑

Table 6.2: Peak relative distances ($m \cdot min^{-1}$) of professional rugby league players by position for each moving average duration (± SD).

Moving Average (minutes)	Fullback	Halves	Hooker	Edge Forwards	Outside Backs	Middle Forwards	Effect Size > 0.60
1	179 ± 15[bcdef]	168 ± 12[ef]	172 ± 14[def]	165 ± 11	164 ± 14	163 ± 14	FB > HA, EF, OB & MF
2	148 ± 13[bdef]	142 ± 9[def]	146 ± 11[bdef]	137 ± 9	137 ± 10	135 ± 10	FB & HK > EF & OB; FB, HA & HK > MF
3	134 ± 11[bdef]	131 ± 8[def]	136 ± 11[bdef]	127 ± 9	125 ± 9	125 ± 10	FB & HK > EF & MF; FB, HA & HK > OB
4	127 ± 10[def]	124 ± 10[def]	127 ± 11[def]	119 ± 9	117 ± 9	117 ± 10	FB & HK > EF, FB; HA & HK > OB & MF
5	122 ± 9[def]	120 ± 9[def]	122 ± 11[def]	114 ± 8	112 ± 8	111 ± 10	FB, HA & HK > EF, OB & MF
6	119 ± 9[def]	116 ± 8[def]	118 ± 11[def]	111 ± 8[ef]	107 ± 8	108 ± 9	FB, HA & HK > EF, OB & MF
7	116 ± 10[def]	113 ± 8[def]	114 ± 11[def]	108 ± 8[ef]	104 ± 8	104 ± 9	FB, HA & HK > EF, OB & MF
8	114 ± 9[bdef]	110 ± 8[def]	111 ± 11[def]	106 ± 8[ef]	102 ± 7	102 ± 9	FB > EF; FB, HA & HK > OB & MF
9	111 ± 8[bdef]	108 ± 8[def]	110 ± 11[def]	104 ± 8[ef]	100 ± 7	100 ± 9	FB > EF; FB, HA & HK > OB & MF
10	109 ± 8[def]	107 ± 8[def]	108 ± 11[def]	102 ± 7[ef]	99 ± 7	98 ± 11	FB & HK > EF; FB, HA & HK > OB & MF

FB = Fullback, HA = Halves; HK = Hooker, EF = Edge Forwards; OB = Outside Backs; MF = Middle Forwards, [a] = greater than FB; [b] = greater than HA; [c] = greater than HK; [d] = greater than EF; [e] = greater than OB; [f] = greater than MF. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 x between-subject SD).

Table 6.3: Peak Ave Acc/Dec ($m{\cdot}s^{-2}$) of professional rugby league players by position for each moving average duration (± SD).

Moving Average (minutes)	Fullback	Halves	Hooker	Edge Forwards	Outside Backs	Middle Forwards	Effect Size > 0.60
1	1.22 ± 0.16	1.26 ± 0.14	1.28 ± 0.13	1.27 ± 0.1	1.23 ± 0.16	1.23 ± 0.14	N/A
2	0.98 ± 0.14	1.05 ± 0.13[aef]	1.06 ± 0.14[aef]	1.04 ± 0.11[aef]	0.96 ± 0.12	0.99 ± 0.13	HA & HK > OB
3	0.89 ± 0.12	0.98 ± 0.12[aef]	0.99 ± 0.14[aef]	0.95 ± 0.11[aef]	0.88 ± 0.12	0.91 ± 0.13	HA & HK > FB & OB
4	0.85 ± 0.12	0.93 ± 0.13[aef]	0.94 ± 0.14[aef]	0.90 ± 0.11[aef]	0.84 ± 0.12	0.86 ± 0.12	HA & HK > FB & OB
5	0.83 ± 0.12	0.90 ± 0.13[aef]	0.91 ± 0.14[aef]	0.88 ± 0.11[aef]	0.8 ± 0.11	0.83 ± 0.12	HK > FB; HA, HK & EF > OB
6	0.80 ± 0.11	0.87 ± 0.13[aef]	0.88 ± 0.13[aef]	0.85 ± 0.1[aef]	0.78 ± 0.11	0.80 ± 0.13	HA, HK & EF > OB
7	0.79 ± 0.11	0.85 ± 0.12[aef]	0.85 ± 0.13[aef]	0.83 ± 0.1[aef]	0.76 ± 0.11	0.78 ± 0.13	HA, HK & EF > OB
8	0.77 ± 0.11	0.83 ± 0.12[aef]	0.83 ± 0.13[aef]	0.81 ± 0.1[aef]	0.74 ± 0.11	0.76 ± 0.12	HA, HK & EF > OB
9	0.75 ± 0.11	0.82 ± 0.12[aef]	0.82 ± 0.13[aef]	0.8 ± 0.1[aef]	0.73 ± 0.11	0.74 ± 0.13	HA, HK & EF > OB
10	0.75 ± 0.11	0.81 ± 0.12[aef]	0.81 ± 0.13[aef]	0.78 ± 0.1[aef]	0.72 ± 0.11	0.73 ± 0.13	HA, HK & EF > OB

FB = Fullback, HA = Halves; HK = Hooker, EF = Edge Forwards; OB = Outside Backs; MF = Middle Forwards, [a] = greater than FB; [b] = greater than HA; [c] = greater than HK; [d] = greater than EF; [e] = greater than OB; [f] = greater than MF. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 x between-subject SD).

Table 6.4: Peak average metabolic power ($W \cdot kg^{-1}$) of professional rugby league players by position for each moving average duration (± SD).

Moving Average (minutes)	Fullback	Halves	Hooker	Edge Forwards	Outside Backs	Middle Forwards	Effect Size > 0.60
1	18.1 ± 1.9^{bcdef}	17.0 ± 1.9^{f}	17.4 ± 1.8^{def}	16.7 ± 1.5	16.6 ± 1.9	16.4 ± 1.9	FB > EF, OB & MF
2	14.6 ± 1.5^{bdef}	14.1 ± 1.6^{ef}	14.4 ± 1.6^{def}	13.6 ± 1.2	13.4 ± 1.4	13.3 ± 1.4	FB > EF; FB & HK > OB & MF
3	13.0 ± 1.2^{def}	12.8 ± 1.3^{ef}	13.3 ± 1.6^{def}	12.5 ± 1.2	12.1 ± 1.3	12.1 ± 1.3	FB & HK > OB & MF
4	12.2 ± 1.2^{def}	12.1 ± 1.4^{def}	12.4 ± 1.5^{def}	11.6 ± 1.2	11.3 ± 1.2	11.3 ± 1.3	FB, HA & HK > OB & MF
5	11.7 ± 1^{def}	11.6 ± 1.3^{def}	11.8 ± 1.5^{def}	11.1 ± 1.1^{ef}	10.7 ± 1.1	10.7 ± 1.3	FB, HA & HK > OB & MF
6	11.4 ± 1^{def}	11.2 ± 1.3^{def}	11.4 ± 1.4^{def}	10.8 ± 1.0^{ef}	10.3 ± 1.0	10.4 ± 1.2	FB, HA & HK > OB & MF
7	11.0 ± 1^{def}	10.9 ± 1.2^{def}	11.0 ± 1.4^{def}	10.5 ± 1.0^{ef}	9.9 ± 1.0	10.0 ± 1.2	FB, HA & HK > OB & MF
8	10.7 ± 1^{def}	10.6 ± 1.2^{ef}	10.8 ± 1.3^{def}	10.2 ± 1.0^{ef}	9.7 ± 1.0	9.8 ± 1.2	FB, HA & HK > OB & MF
9	10.5 ± 1^{def}	10.4 ± 1.2^{ef}	10.6 ± 1.4^{def}	10.0 ± 1.0^{ef}	9.5 ± 1.0	9.6 ± 1.1	FB, HA & HK > OB & MF
10	10.3 ± 1^{def}	10.2 ± 1.2^{def}	10.4 ± 1.4^{def}	9.8 ± 0.9^{ef}	9.3 ± 0.9	9.4 ± 1.1	FB, HA & HK > OB & MF

FB = Fullback, HA = Halves; HK = Hooker, EF = Edge Forwards; OB = Outside Backs; MF = Middle Forwards, ^{a} = greater than FB; ^{b} = greater than HA; ^{c} = greater than HK; ^{d} = greater than EF; ^{e} = greater than OB; ^{f} = greater than MF. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 x between-subject SD).

DISCUSSION

The present study investigated the acceleration-based running requirements of professional rugby league competition, concurrently with traditional velocity-based methods, using a novel rolling average method. Whilst the duration-specific running demands of rugby league have been investigated previously (Chapter 5), the present study was able to describe the elevated accelerated/decelerated running demands of halves and hookers, and the greater P_{met} values achieved by halves, hookers and fullbacks when compared to other positional groups. In addition, the peak acceleration-based running intensities achieved during match-play increased substantially as the length of the moving average applied decreased. The interactions of peak running intensity and moving average durations observed in this study provide additional benefit for coaches and practitioners when attempting to replicate position-specific competition movement demands using specific training methodologies.

Recently, Furlan et al. (2015) utilised a 2-minute moving average, to determine the peak periods of rugby sevens performance. The authors observed that relative distance underestimated the intensity of the identified peak period when compared to the $P_{met,}$ calculated using the methods of Gray (2011), which suggests the incorporation of acceleration-based methods are necessary when quantifying team-sport movement demands. The findings of this study are in support of this notion, where the inclusion of acceleration-based indices assist in differentiating the varying positional requirements of rugby league. In the present study, Ave Acc/Dec was calculated as the rate of change in speed, regardless of the direction of change. This may be considered a limitation, as the energetic cost of acceleration has been suggested to be far greater than that of deceleration (Osgnach et al., 2010). However, this variable was intended to represent the overall acceleration and deceleration load imposed on the athlete, rather than an estimate of energy consumption. Recent research has demonstrated that GPS possess poor inter-unit reliability for both acceleration counts >3 $m \cdot s^{-2}$ and >4 $m \cdot s^{-2}$ (CV = 31%

and 43%, respectively), and deceleration counts <-3 m·s^{-2} and <-4 m·s^{-2} (CV = 42% and 56%, respectively) (Buchheit, Al Haddad, et al., 2014). However, in the present study, each player was assigned the same unit for each match, and this coupled with the 'smoothing' effect of the moving average method, may have provided a more stable measure for differentiating demands between positions and durations.

This study observed higher Ave Acc/Dec amongst halves and hookers, compared to outside backs and middle forwards, for moving averages 2 to 10 minutes in duration. These findings are similar to whole match acceleration and decelerations counts (acceleration and deceleration efforts exceeding >2.78 m·s^{-2} and <-2.78 m·s^{-2}, respectively) observed by Kempton et al. (2015), where adjustables (halves, hookers and fullbacks) were substantially different from all other positions. Taken together, these differences would suggest that for positions where acceleration and deceleration requirements are high, athletes may benefit from training methodologies that mimic these demands. For improvements in performance to occur, these qualities should be progressively overloaded through an appropriately periodised program. This could be facilitated through the incorporation of strength and power training, due to the well-established links with acceleration (Lockie et al., 2011) and change-of-direction (Delaney et al., 2015) performance. Specifically, to improve field sport acceleration, training should be targeted towards improving the rate of force production (Lockie et al., 2011), through explosive power movements such as plyometrics or resisted sprint training (Lockie, Murphy, Schultz, Knight, & Janse de Jonge, 2012).

The present study is the first to analyse the duration-specific metabolic demands of rugby league competition. In theory, the metabolic power method integrates the energetic demands of accelerated running with traditional velocity-based methods (di Prampero et al., 2005). In the present study, the peak metabolic demands of match-play were substantially higher in hookers compared to outside backs, edge forwards and middle forwards across all moving average durations. Previously, the hooker position has been grouped with fullbacks and halves due to somewhat similar competition requirements, in that they are responsible for providing structure and organisation in both attack and defence. However, modern defensive strategies require the hooker to be located in the centre of the field, exposing them to a similar number of absolute collisions compared to hit-up forwards (40 ± 13 vs. 44 ± 13 per game) (Gabbett, 2015b), in addition to them attending most rucks in attack to distribute the ball to other players. As a result of this, it is common for teams to utilise a second hooker on the interchange bench, in order to maintain the intensity around the ruck throughout a match. This was evident in the present study, where although the average match time was similar between hookers (52 ± 14 minutes) and middle forwards (47 ± 15 minutes), hookers exhibited a considerably higher P_{met} response compared to other positions. However, it must be noted that the findings of the present study are reflective of the interchange strategy of the team in question, and this may differ between clubs. Future research may benefit from examining the factors which may limit players from maintaining running intensities throughout a match, which may inform individual interchange and conditioning strategies.

In contrast to the hooker position, halves and fullbacks are commonly required to complete the entire match. The similarly elevated P_{met} values observed for halves would indicate these positions reach similar peak running intensities to hookers, and although they are not regularly interchanged, they are not exposed to the same collision loads of interchanged players (Gabbett, 2015b), allowing them to recover from high-intensity periods of match-play more adequately. However, an interesting finding of the present study was the elevated P_{met} response observed in the fullback position. In defence, for the majority of gameplay fullbacks are positioned behind the defensive line and are not required to move forward and retreat over 10 m, nor are they required to be involved in regular physical collisions, as is necessary for most other positions. As a result, the acceleration and deceleration demands of this position are substantially lower than that of halves and hookers (Table 6.3). However, the lower acceleration and deceleration demands did not translate to a lower P_{met} of this position, with fullbacks exhibiting similar P_{met} values to halves and hookers. These findings illustrate the strength of the P_{met} method for integrating the varying match-play requirements of each position, however the findings of the present study question the grouping of halves, hookers and fullbacks when describing competition running requirements. This positional grouping method may affect the prescription of specific training based on competition demands, as the way an athlete achieves high-intensity running must be addressed – whether that be the open-style running for fullbacks, or the acceleration-based running of halves and hookers.

If athletes are to be adequately prepared for the most intense periods of competition, training prescription should account for the acceleration-based running requirements common to rugby league. The novel methodology of the present study may attenuate this implication, in comparison to that of previous research, where the metabolic power method was used to describe the mean P_{met} sustained in range of team sports, such as rugby sevens (~10 $W \cdot kg^{-1}$) (Furlan et al., 2015), soccer (~8 $W \cdot kg^{-1}$) (Osgnach et al., 2010), rugby league (~9 $W \cdot kg^{-1}$) (Kempton, Sirotic, Rampinini, et al., 2015) and AFL (~10 $W \cdot kg^{-1}$) (Coutts et al., 2015). However, these values represent whole-match averages, and fail to account for the peaks in running intensity imposed on players throughout a match. Furlan et al. (2015) observed that peak P_{met} for a 2-minute moving average was significantly greater than the average of the entire period. In the present study, large increases in P_{met} were observed between the 10-minute moving average and all moving averages <5 minutes in duration (ES = 1.21-1.83). This phenomenon may be due to athletes adopting pacing strategies, where energy is distributed across the period to allow for completion of the entire match (Black & Gabbett, 2014), or possibly the stochastic nature of team sports such as rugby league. Regardless of the mechanism behind these differences, it would be beneficial to condition athletes for these peaks in intensity observed throughout a match. However, it is important to note that these findings are reflective of the tactical strategies of one team only, and future research may benefit from investigating these running demands across a number of clubs concurrently.

Despite the theoretical advantages associated with the integration of velocity and acceleration when quantifying team-sport movement demands, the metabolic power method (di Prampero et al., 2005) is not without limitation. For example, this method assumes the biomechanics, frequency of movement of the limbs, and environmental conditions to be similar between uphill running on a treadmill at constant speed and accelerated running on flat terrain (di Prampero et al., 2005; Osgnach et al., 2010). Recently, the validity of this method in team sports has been questioned, due to the inability to account for the metabolic cost of sport-specific activities such as dribbling and turning (Buchheit et al., 2015), or in rugby league, tackling and wrestling (Kempton, Sirotic, Rampinini, et al., 2015). In addition, this method is unable to account for differences in body size or running economy (Buchheit et al., 2015), which may potential influence the metabolic cost of running. However, whilst the “metabolic” nature of this measure can be questioned, this variable still reflects a relatively stable measure which collaborates accelerated and decelerated running with traditional velocity-based techniques (Rampinini et al., 2015). Future research may benefit from validating this energetic model in rugby-league specific conditions, potentially accounting for positional differences in body size and running economy.

PRACTICAL APPLICATIONS

The results of the present study show that the peak running requirements of rugby league competition differ according to position, and increase as the duration of the moving average decreases. Using the framework provided by the current study, coaches may differentiate the training prescribed to each positional group. More specifically, if the aim of training is to replicate and overload competition demands, specific small-sided games (SSG) could be used. For example, fullbacks may benefit from open-style games such as offside touch, played on large field dimensions, as these games have been shown to generate high velocity-based running intensities (Gabbett, Abernethy, & Jenkins, 2012). In contrast, the acceleration-based demands could be achieved through small, tight games, with a greater importance placed on support plays (Gabbett, Jenkins, & Abernethy, 2010). Lastly, the findings of the current study suggest that the P_{met} measure may be useful as a global measure of external training load, due to the interaction of both acceleration and velocity-based running.

CONCLUSIONS

The present study has provided a holistic overview of the peak metabolic demands of rugby league competition. The main outcomes demonstrated that although the metabolic power calculations incorporate both acceleration- and velocity-based movements, the method in which athletes achieve metabolic power differs by position. The findings of this study allow coaches to prescribe and monitor specific training drills according to duration- and position-specific competition requirements, and appropriately overload athletes to achieve increases in match performance. The findings of the present study also question the use of a combined “adjustables” positional group when describing competition movement demands.

ACKNOWLEDGEMENTS

No financial assistance was provided for the current project. There were no conflicts of interest.

Chapter 7

Peak running intensity of international rugby: Implications for training prescription

Delaney, J. A., Thornton, H. R., Pryor, J. F., Stewart, A. M., Dascombe, B. J., & Duthie, G. M. (2016). Duration specific running intensities of international Rugby competition: Implications for training prescription. *Int J Sports Physiol Perform.* (Published Ahead of Print). doi: 10.1123/ijspp.2016-0469.

ABSTRACT

Purpose: To quantify the duration and position-specific peak running intensities of international rugby union, for the prescription and monitoring of specific training methodologies. **Methods:** Global positioning systems (GPS) were used to assess the activity profile of 67 elite-level rugby union players from two separate nations, across 33 international matches. A moving average approach was used to identify the peak relative distance (m·min^{-1}), average acceleration/deceleration (Ave Acc/Dec; m·s^{-2}) and average metabolic power (Pmet) for a range of durations (1 to 10 minutes). Differences between positions and durations were described using a magnitude-based network. **Results:** Peak running intensity increased as the length of the moving average decreased. There were likely small to moderate increases in relative distance and Ave Acc/Dec for outside backs, half-backs and loose forwards compared to the tight 5 group across all moving average durations (effect size; ES = 0.27-1.00). Metabolic power demands were at least likely greater for outside backs and half-backs when compared to the tight 5 (ES = 0.86-0.99). Half-backs demonstrated the greatest relative distance and Pmet outputs, but were similar to outside backs and loose forwards in Ave Acc/Dec demands. **Conclusions:** The present study has presented a framework to describe the peak running intensities achieved during international rugby competition by position, which are considerably higher than previously reported whole-period averages. These data provide further knowledge of the peak activity profiles of international rugby competition, and this information can be used to assist coaches and practitioners in adequately preparing athletes for the most demanding periods of play.

INTRODUCTION

Rugby union is a high intensity, intermittent, collision-based team sport, involving frequent bouts of high-speed running (HSR) interspersed with regular acceleration and deceleration efforts (Duthie, Pyne, & Hooper, 2003). The movement demands during competition and training have been quantified using global positioning systems (GPS), where players have been shown to cover 4000-7500 m, depending on position (Cunniffe et al., 2009; Jones, West, Crewther, Cook, & Kilduff, 2015; Lindsay, Draper, Lewis, Gieseg, & Gill, 2015). Such differences have been attributed to the increased total impact requirements of forwards (0.56 ± 0.23 impacts per minute) when compared to backs (0.36 ± 0.17 impacts per minute), or an inability to generate running output due to physiological restrictions (Lindsay et al., 2015). In addition, it has been recently proposed that the ability to perform repeated high-intensity efforts (RHIE) within a match may be important to the outcome (Austin, Gabbett, & Jenkins, 2011b; Roberts et al., 2008). Such a capacity has been shown to be particularly important for loose forwards, as these players perform a greater number of RHIE (three or more high acceleration [>2.79 $m \cdot s^{-2}$], HSR [>5 $m \cdot s^{-1}$] or contact efforts with <21 s recovery) (Gabbett, Jenkins, et al., 2012b) throughout a match compared to both half-backs and outside backs (Jones et al., 2015). Taken together, these data indicate that it is important to differentiate the match-play requirements of individual positions when developing a training program.

When prescribing and monitoring specific training drills, information regarding the movement intensity of competition may assist in contextualising training demands. As such, whole-match volumes have been reported relative to time spent on the field for comparisons with training intensities (Higham, Pyne, Anson, Hopkins, & Eddy, 2016). However, due to the stochastic nature of many team sports including the rugby codes, fluctuations in running intensity throughout the match are expected (Waldron & Highton, 2014), and it may be that whole-match averages are unable to detect the subtle fluctuations in running intensity that occur throughout competition (Furlan et al., 2015; Jones et al., 2015; Lacome, Piscione, Hager, & Carling, 2016; Roberts et al., 2008). For example, professional rugby union players have been shown to cover the greatest relative distance during the first 10-minute period of each half of play, possibly indicating a state of transient fatigue during the latter stages of the match (Jones et al., 2015; Roberts et al., 2008). Whilst these data provide insight into the temporal changes in the activity profile of rugby union, these findings are based on data collected from predefined 10-minute periods of play. It may be that the most intense phase of play does not fall completely within one of these periods, and therefore the peak running intensities of competition may be underestimated (Varley, Elias, et al., 2012).

A rolling average approach has been proposed as the most appropriate method for quantifying peaks in running intensity during team-sport activity (Varley, Elias, et al., 2012). For example, during professional soccer competition, pre-defined 5-minute blocks were shown to underestimate the true peak in intensity by up to 25% when compared to a 5-minute moving average method (Varley, Elias, et al., 2012). A similar analysis was performed throughout international rugby sevens competition, where the peak 2-minute period (identified using a moving average method) was almost certainly higher than both the preceding (effect size; ES = 2.25) and ensuing 2-minute period (ES = 2.92) (Furlan et al., 2015). Moreover, peak running intensity has been shown to be substantially influenced by the length of the moving average window amongst professional rugby league players (Chapter 5). Taken together, it can be seen that whole-match averages are not reflective of the most intense periods of competition, and training prescription based on these demands may be underpreparing athletes for the rigors of competition.

During international rugby union competition, forwards spend 33 ± 6% of the exercise periods within a match involved in "static" activities (scrums, rucks and mauls), compared to just 8 ± 3% amongst the back-line players (Lacome et al., 2014). This affords backs greater time to regenerate energy stores between high-intensity running efforts (Lacome et al., 2014; Tomlin & Wenger, 2001), allowing a greater running intensity to be achieved compared to forwards (Jones et al., 2015). In contrast, the greater mean acceleration values reported amongst forwards compared to backs (2.46 ± 0.92 vs 2.36 ± 0.93 $m \cdot s^{-2}$) may be a reflection of the greater dependence on acceleration abilities amongst this position (Lacome et al., 2014). Furthermore, temporal decreases in acceleration and deceleration output have been described during professional rugby competition, suggesting that this quality may also be sensitive to fatigue and/or the tactical strategies of the team in question (Jones et al., 2015; Tee, Lambert, & Coopoo, 2016), and therefore exposure to such activity during training may delay the onset of fatigue during competition.

The metabolic power (P_{met}) method (Osgnach et al., 2010) represents a theoretical model for quantifying the physiological cost of team-sports activity, accounting for both HSR and acceleration and deceleration efforts performed at low speed. Whilst the ability of this metric to accurately assess movements such as kicking, jumping and tackling has been questioned (Buchheit et al., 2015), this metric averaged over the duration of an activity presents as a stable measure of external load, where acceleration and speed-based demands are accounted for (coefficient of variation, CV <5%) (Highton et al., 2016; Rampinini et al., 2015). This is particularly important for team sports exhibiting heterogeneous positional activity profiles such as rugby union (Jones et al., 2015; Lindsay et al., 2015). Furthermore, temporal fluctuations in P_{met} have been identified, further justifying its use in quantifying the demands of rugby competition (Furlan et al., 2015).

In a team-sport setting, coaches are faced with the challenge of providing an environment in which technical, competitive and physical traits can be nurtured optimally (Charlesworth, 1994). Small-sided games (SSG) present as an effective methodology for stimulating athletes to perform in a game-specific environment, where both physiological and tactical abilities can be developed concurrently (Gamble, 2004). However, coaches have typically been restricted to prescribing and monitoring these drills relative to whole-match intensities, which may have resulted in the under-preparation of their athletes for the peak intensities they will be exposed to during match play. Therefore, the primary purpose of the present study was to describe the duration-specific peak running intensities achieved by elite rugby union players during competition. Secondly, the study aimed to differentiate the peak demands of different positional groups, to assist coaches in the accurate prescription and monitoring of specific training methodologies.

METHODS

An observational design was employed to determine the duration and position-specific activity profiles of elite-level rugby union players. Data were collected from 67 different players from two nations (27.3 ± 3.1 yr, 1.87 ± 0.08 m, and 104.7 ± 13.0 kg), for a total of 570 individual match observations (8 ± 8 matches per player, range 1-28). Due to the limited number of matches per competition, the dataset consisted of matches played across several competitions that were all Test matches (n = 33). Match characteristics included the world ranking of both the team investigated and the opposing team at the time the match was played. Further, players were grouped according to position (n = 4), as tight 5 (196 match files; prop, n = 84; hooker, n = 31; lock, n = 81), loose forwards (102 match files; flanker, n = 76; Number 8, n = 26), half-backs (86 match files; scrum half, n = 45; fly half, n = 41) and outside backs (186 match files; centre, n = 84; wing, n = 71; fullback, n = 31). Informed consent and institutional ethics approval were obtained prior to the commencement of the study.

During matches, each player's individual movements were assessed using a portable GPS unit (SPI HPU, GPSports, Canberra, Australia) fitted into a custom-made pouch in their playing jersey, located between the scapulae. Each player was assigned the same unit for the entirety of the collection period to minimise inter-unit variability (Buchheit, Al Haddad, et al., 2014). Following each match, data were downloaded using the appropriate proprietary software (Team AMS v 2016.1., GPSports, Canberra, Australia). Specifically, this software provided 5 Hz speed data ($m \cdot s^{-1}$) interpolated to 15 Hz, which was then further analysed using customised software (R, v R-3.1.3.). Using the speed data provided, relative distance was calculated as distance covered per unit of time (relative distance; $m \cdot min^{-1}$). In addition, the instantaneous acceleration/deceleration of the participant was calculated as the rate of change in speed, and the absolute of this value was derived as an indication of the total acceleration/deceleration requirement of the activity (Ave Acc/Dec). Instantaneous metabolic power (P_{met}; $W \cdot kg^{-1}$) was calculated using methods detailed previously (Osgnach et al., 2010) to account for acceleration/deceleration and speed-based movements collaboratively. Finally, the software allowed for the calculation of a moving average over each output variable, using ten different durations (1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 minutes). For example, for a 1-minute moving average, the software identified the 900 consecutive data points (i.e. 15 samples per second for 60 seconds) where the subject exhibited the greatest relative distance. For a 2-minute rolling average, 1800 successive samples were used, and so on (Chapter 6). Finally, the maximum value attained during the match for each duration was recorded for between-group comparisons (i.e., 10 moving average durations for each of the three variables).

Statistical Analysis

Multiple linear mixed models were constructed to examine differences in running intensity between position (n = 4) and moving average duration (n = 10). Athletes' positional group was included as a fixed effect, whilst the strength of both the team studied and the opposition (quantified as current world ranking) were controlled for by being included as covariates due to their known influence on running performance in team sport (Chapter 4) (Kempton & Coutts, 2015). The random effects included the individual athlete that was nested within a match file identifier. This within-subject random effect structure was determined as being the most appropriate method as it improved the model information criteria, decided by a likelihood ratio test (West et al., 2014). If a main effect was not evident for the team ranking or opposition ranking, it was removed. The Least Squares means provided pairwise positional group comparisons from the final model. Effect sizes and their associated 90% CI (Rosnow et al., 2000) for the positional group comparisons were determined, with thresholds interpreted as: < 0.20, trivial; 0.20-0.60, small; 0.60-1.2, moderate; 1.20-2.0, large; and >2.0, very large (Hopkins, 2007). Furthermore, the likelihood of the observed effect was established using a progressive magnitude- based approach, where quantitative chances of the true effect were assessed qualitatively (Hopkins, 2007), and differences were considered substantial when the likelihood that the true value was greater than the smallest worthwhile difference (SWD; 0.2 × the between subject SD) exceeded 75%. All statistical analyses were conducted using the R statistical software (R.3.1, R foundation for Statistical Computing).

RESULTS

Figure 7.1 illustrates an increase in running intensity as the duration of the moving average decreases, for each of the three outcome variables (relative distance, Ave Acc/Dec and P_{met}). Compared to the 10-minute moving average, running intensity was at least *likely* greater for windows less than 8 minutes in duration for relative distance (ES = 0.23-2.96), and windows less than 7 minutes in duration for both Ave Acc/Dec and P_{met} (ES = 0.22-1.75 and 0.29-2.69, respectively).

Results of the mixed-model analysis revealed main effects for positional groups for relative distance, Ave Acc/Dec and P_{met} for all moving average durations (Figure 7.2). Table 7.1 demonstrates at least *likely* small to moderate increases in relative distance for the outside backs, half-backs and loose forwards when compared to the tight 5 positional group across all moving average durations (ES = 0.46-1.00). Half-backs exhibited a *likely* small increase in relative distance compared to outside backs and loose forwards across moving averages 1-8 minutes in duration (ES = 0.27-0.41). Tight 5 players were at least *likely* to exhibit lower Ave Acc/Dec compared to loose forwards (ES = 0.46-0.57), outside backs (ES = 0.60-0.65) and half-backs (ES = 0.65-0.74) across all moving average durations. There was at least *likely* to be a moderate increase in P_{met} for the outside backs and half-backs when compared to the tight 5 group across all moving average durations (ES = 0.86-0.95 and 0.88-0.99 for outside backs and half-backs, respectively). There were no substantial differences between outside backs and loose forwards across any moving average duration for any variable assessed.

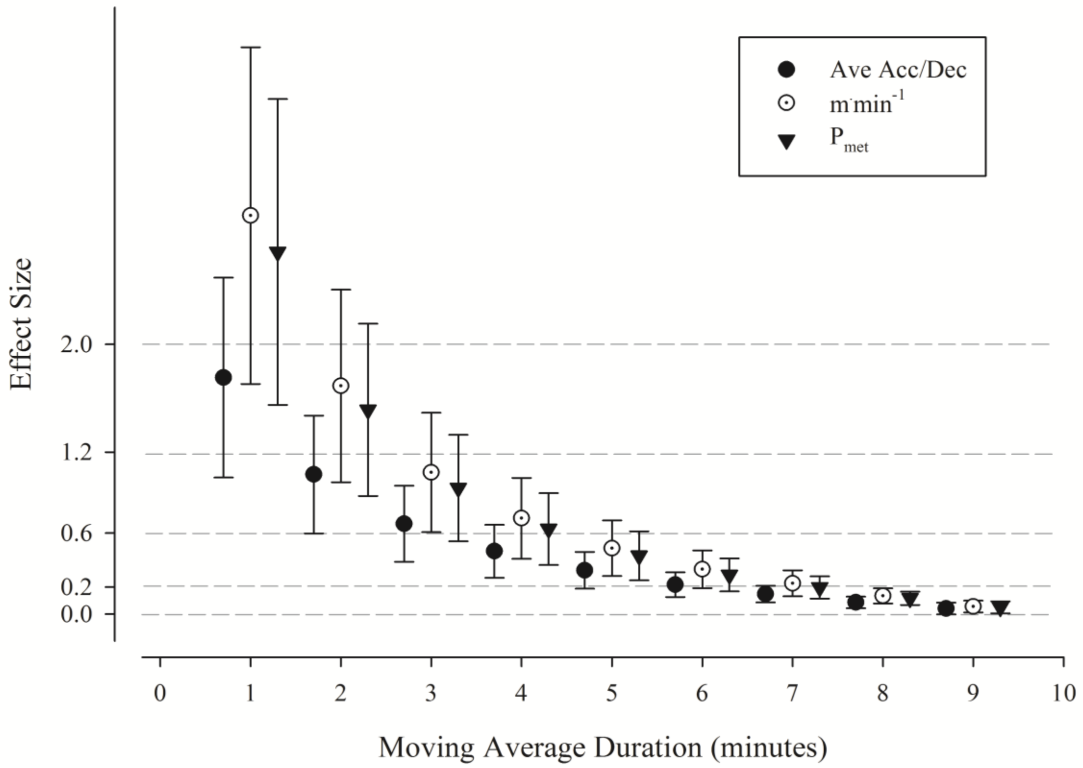

Figure 7.1: Magnitude of difference in running intensity between moving average durations. Data are presented as standardised effect ± 90% confidence limits.

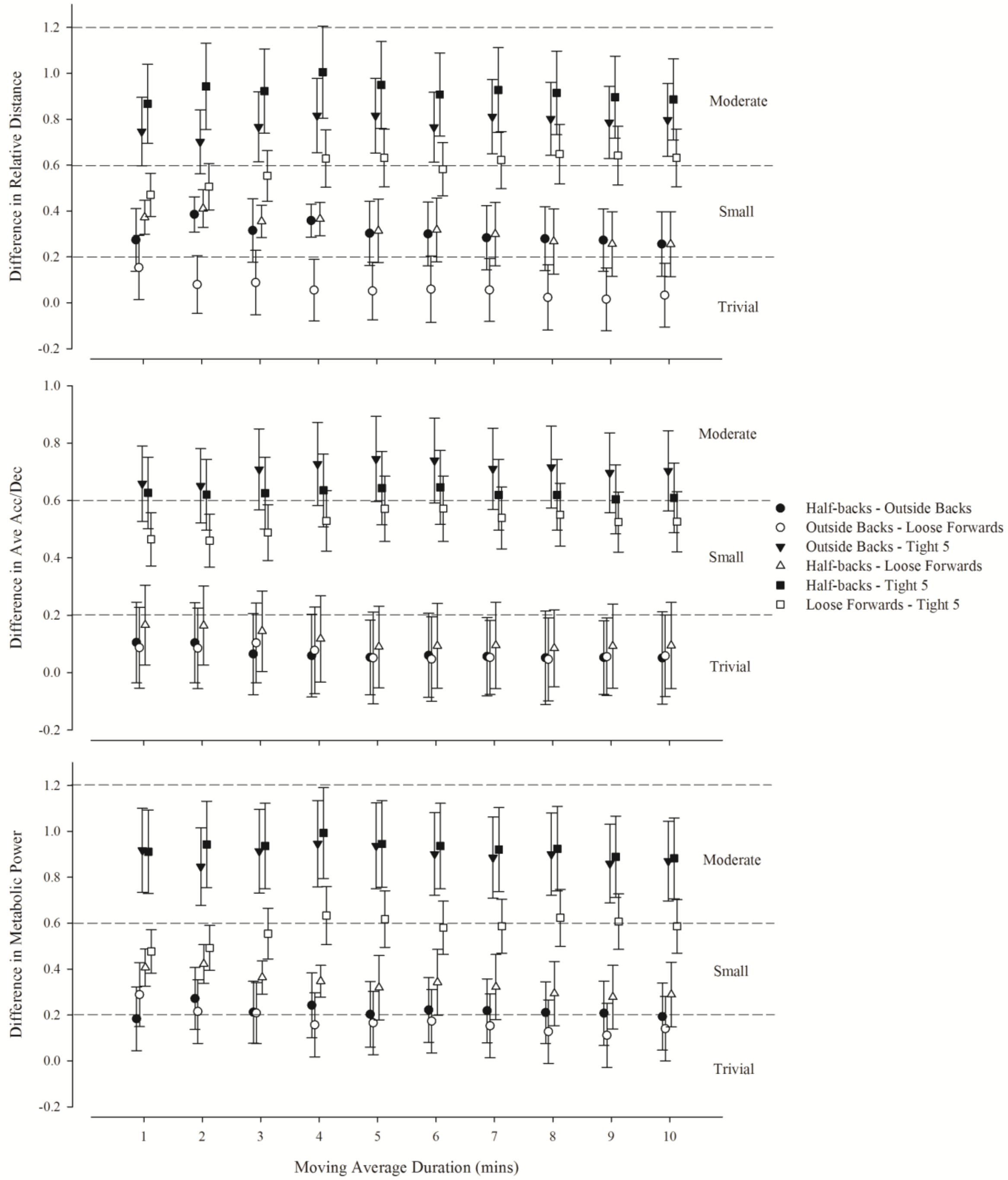

Figure 7.2: Magnitude of difference in running intensity between positional groups. Data are presented as standardised effect ± 90% confidence limits.

Table 7.1: Peak running intensities of international rugby players (mean ± SD).

Relative Distance ($m \cdot min^{-1}$)	Outside Backs	Half-backs	Loose Forwards	Tight 5	Effect Size > 0.60
1†	175 ± 22^{d}	184 ± 28^{acd}	169 ± 23^{d}	154 ± 21	OB & HB > T5
2$^{\dagger *}$	137 ± 16^{d}	147 ± 21^{acd}	135 ± 16^{d}	122 ± 17	OB & HB > T5
3*	119 ± 13^{d}	126 ± 18^{acd}	117 ± 14^{d}	105 ± 15	OB & HB > T5
4*	109 ± 12^{d}	117 ± 16^{acd}	108 ± 13^{d}	96 ± 13	OB, HB & LF > T5
5	103 ± 10^{d}	108 ± 15^{acd}	102 ± 11^{d}	91 ± 12	OB, HB & LF > T5
6*	98 ± 10^{d}	103 ± 14^{acd}	97 ± 11^{d}	88 ± 12	OB & HB > T5
7$^{\dagger *}$	95 ± 10^{d}	100 ± 13^{acd}	94 ± 11^{d}	85 ± 11	OB, HB & LF > T5
8$^{\dagger *}$	93 ± 9^{d}	97 ± 12^{acd}	92 ± 11^{d}	82 ± 11	OB, HB & LF > T5
9†	90 ± 9^{d}	95 ± 12^{d}	90 ± 11^{d}	81 ± 11	OB, HB & LF > T5
10*	89 ± 9^{d}	93 ± 12^{d}	88 ± 11^{d}	79 ± 11	OB, HB & LF > T5

Ave Acc/Dec = average acceleration/deceleration, P_{met} = metabolic power, OB = outside backs, HB = half-backs, LF = loose forwards, T5 = tight 5, ^{a} = greater than outside backs, ^{b} = greater than half-backs, ^{c} = greater than loose forwards, ^{d} = greater than tight 5, * = main effect of opposition ranking, † = main effect for team ranking. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 x between-subject SD).

Table 7.1 (cont.): Peak running intensities of international rugby players (mean ± SD).

Ave Acc/Dec ($m{\cdot}s^{-2}$)	**Outside Backs**	**Half-backs**	**Loose Forwards**	**Tight 5**	**Effect Size > 0.60**
1*	0.99 ± 0.14^{d}	1.01 ± 0.18^{d}	0.97 ± 0.15^{d}	0.87 ± 0.16	OB & HB > T5
2	0.81 ± 0.12^{d}	0.83 ± 0.16^{d}	0.78 ± 0.14^{d}	0.69 ± 0.15	OB & HB > T5
3	0.72 ± 0.12^{d}	0.73 ± 0.14^{d}	0.7 ± 0.13^{d}	0.61 ± 0.14	OB & HB > T5
4	0.67 ± 0.11^{d}	0.68 ± 0.13^{d}	0.65 ± 0.12^{d}	0.56 ± 0.13	OB & HB > T5
5	0.63 ± 0.10^{d}	0.64 ± 0.12^{d}	0.62 ± 0.12^{d}	0.53 ± 0.12	OB & HB > T5
6	0.60 ± 0.10^{d}	0.61 ± 0.12^{d}	0.60 ± 0.11^{d}	0.51 ± 0.12	OB & HB > T5
7*	0.58 ± 0.10^{d}	0.59 ± 0.12^{d}	0.58 ± 0.11^{d}	0.49 ± 0.12	OB & HB > T5
8*	0.57 ± 0.1^{d}	0.58 ± 0.11^{d}	0.56 ± 0.11^{d}	0.48 ± 0.11	OB & HB > T5
9*	0.56 ± 0.10^{d}	0.57 ± 0.11^{d}	0.55 ± 0.11^{d}	0.47 ± 0.11	OB & HB > T5
10*	0.55 ± 0.10^{d}	0.55 ± 0.11^{d}	0.54 ± 0.11^{d}	0.46 ± 0.10	OB & HB > T5

Ave Acc/Dec = average acceleration/deceleration, P_{met} = metabolic power, OB = outside backs, HB = half-backs, LF = loose forwards, T5 = tight 5, ^{a} = greater than outside backs, ^{b} = greater than half-backs, ^{c} = greater than loose forwards, ^{d} = greater than tight 5, * = main effect of opposition ranking, † = main effect for team ranking. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 x between-subject SD).

Table 7.1 (cont.): Peak running intensities of international rugby players (mean ± SD).

P_{met} ($W \cdot kg^{-1}$)	Outside Backs	Half-backs	Loose Forwards	Tight 5	Effect Size > 0.60
1	16.6 ± 2.3^{d}	17.3 ± 3.0^{cd}	15.6 ± 2.3^{d}	14.0 ± 2.2	OB & HB > T5
2	12.8 ± 1.8^{d}	13.6 ± 2.3^{acd}	12.2 ± 1.7^{d}	10.9 ± 1.8	OB & HB > T5
3	11.1 ± 1.5^{d}	11.6 ± 1.9^{cd}	10.6 ± 1.5^{d}	9.3 ± 1.5	OB & HB > T5
4^{*}	10.1 ± 1.3^{d}	10.6 ± 1.7^{cd}	9.8 ± 1.3^{d}	8.5 ± 1.4	OB & HB > T5
5	9.4 ± 1.1^{d}	9.8 ± 1.6^{cd}	9.1 ± 1.2^{d}	8.0 ± 1.2	OB, HB & LF > T5
6	9.0 ± 1.1^{d}	9.4 ± 1.5^{cd}	8.7 ± 1.2^{d}	7.7 ± 1.2	OB, HB & LF > T5
7	8.7 ± 1.1^{d}	9.1 ± 1.4^{cd}	8.4 ± 1.2^{d}	7.4 ± 1.2	OB & HB > T5
8	8.4 ± 1.0^{d}	8.8 ± 1.3^{cd}	8.2 ± 1.2^{d}	7.2 ± 1.1	OB, HB & LF > T5
9	8.2 ± 1.0^{d}	8.5 ± 1.3^{cd}	8.0 ± 1.2^{d}	7.1 ± 1.1	OB, HB & LF > T5
10	8.1 ± 1.0^{d}	8.4 ± 1.2^{cd}	7.8 ± 1.2^{d}	6.9 ± 1.1	OB & HB > T5

Ave Acc/Dec = average acceleration/deceleration, P_{met} = metabolic power, OB = outside backs, HB = half-backs, LF = loose forwards, T5 = tight 5, [a] = greater than outside backs, [b] = greater than half-backs, [c] = greater than loose forwards, [d] = greater than tight 5, [*] = main effect of opposition ranking, [†] = main effect for team ranking. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 x between-subject SD).

DISCUSSION

The purpose of this study was to describe the peak running intensities achieved during international rugby competition, using a moving average approach. The primary finding of this study was that the peak intensities achieved during competition are considerably higher than previously reported whole-period averages. By dividing the match into discrete, 10-minute periods, several authors have reported that running intensity peaked at ~75-85 m·min^{-1} during the first period of the first half of professional rugby competition (Jones et al., 2015; Roberts et al., 2008). Whilst these values are somewhat comparable to the 10-minute moving average duration used in the present study (~80-90 m·min^{-1}), the current study observed substantial increases from these values as the length of the moving average decreased, up to as high as 184 m·min^{-1} for half-backs for a 1-minute window (ES = 0.05-2.96). Using pre-defined 5-minute blocks, peak values of 113 ± 11 and 104 ± 10 m·min^{-1} have been reported for backs and forwards, respectively (Lacome et al., 2016). Whilst these values are slightly higher than those reported in the present study for a 5-minute moving average (~90-110 m·min^{-1}, depending on position), differences in the measurement system used (i.e. GPS vs video coding), level of competition and positional grouping used may have influenced the results. Nonetheless, the findings of the present study provide coaches with data that may be used for direct comparisons between training and match intensities for drills <10 minutes in duration.

Rugby union players are often restricted in reaching high speed during competition due to the presence of opposition players in a relatively confined environment, and therefore acceleration/deceleration qualities are important to success (Duthie et al., 2003). The peak relative distances covered throughout match-play (~150-180 m·min^{-1}, depending on position) equate to an average speed of approximately 2.5-3 m·s^{-1}, which is substantially lower that the reported maximal aerobic speed exhibited by rugby union players (4.2 ± 0.4 m·s^{-1} and 4.9 ± 0.1 m·s^{-1} for forwards and outside backs respectively) (Swaby, Jones, & Comfort, 2016).

Therefore, it can be seen that these players' distances are not limited as a result of their aerobic capacities alone, and therefore the contribution of other demands must be considered.

Traditionally, acceleration and deceleration during team-sport competition is quantified using counts in pre-determined bands or zones, and this method has been shown to be sensitive to temporal changes throughout professional competition, peaking within the first 10-minute period of each half (Jones et al., 2015). However, this method has been reported to exhibit poor inter-unit reliability using GPS technology (CV% = 31-56%), and therefore cannot be recommended (Buchheit, Al Haddad, et al., 2014). In preference, the present study assessed acceleration/deceleration by calculating the rate of change in speed, regardless of the direction of the change (i.e. absolute), across all measured data points. This metric (Ave Acc/Dec) represents the overall acceleration/deceleration load on the athlete, and has been shown to detect positional and temporal changes during professional rugby league (Chapter 6). Similar to the increases in relative distance for shorter duration windows, this study observed substantial increases in Ave Acc/Dec demands as the length of the moving average decreased (ES = 0.04-1.75). Within team-sport competition, the ability to accelerate effectively is vital for success during pivotal moments, such as beating an opponent to the ball (Silvestre, West, Maresh, & Kraemer, 2006) The duration-specific acceleration profile presented in the present study permits coaches to accurately monitor the demands of training drills up to and including 10 minutes in duration. Importantly, exposing athletes to these intensities during training will allow them to be adequately prepared for when they arise within competition.

Despite the known limitations of the P_{met} method for estimating energy cost during team-sports activity (Buchheit et al., 2015; Highton et al., 2016), combining both HSR and acceleration/deceleration efforts performed at low speed into one marker of external load may be useful for monitoring training intensities during drills such as SSG (Gaudino, Alberti, & Iaia, 2014). Using a 2-minute moving average method, peak P_{met} during rugby sevens match play has been shown to be substantially higher than the whole match average (13 vs 9.5 W·kg^{-1}) (Furlan et al., 2015). Whilst the method used to calculate P_{met} differed slightly, the results are similar to the 2-minute average used in the present study, where P_{met} values of ~11-13.5 W·kg^{-1} were observed, depending on position. In addition, the present study is the first to describe the peak demands of rugby competition using the P_{met} method for a range of durations, providing coaches with the ability to monitor the intensity of training drills relative to the most demanding phases of match play.

A secondary aim of the current study was to identify differences in peak running intensities that may exist between positions. During match play, backs use possession to gain territory and/or score points, whilst forwards are typically responsible for possession contests such as scrums, lineouts, rucks and tackles (Quarrie, Hopkins, Anthony, & Gill, 2013). Compared to back-line players, forwards have been reported to participate in more static exercise bouts (89 ± 21 vs 24 ± 10), at a greater average duration (5.2 ± 0.8 vs 3.6 ± 0.8 s) during professional competition (Roberts et al., 2008). As such, it is no surprise that the movement profiles of each position differ, with backs typically covering greater relative distance than forwards throughout a match (84.7 ± 10.4 vs 77.3 ± 20.5 m·min^{-1}) (Quarrie et al., 2013). The findings of the present study are in support of this notion, where outside backs and half-backs exhibited a greater relative distance compared to the tight 5 group, across all moving average durations assessed. However, the present study observed that loose forwards also covered greater relative distance than the tight 5 across all moving average durations, suggesting that these positions should not be combined when prescribing training intensities based on the peak activity profiles of competition. However, the present study did not attempt to quantify these static collision-based events, which forms approximately 30% of all exercise periods for forwards (Lacome et al., 2014), representing a substantial proportional of the game. As such, it is important that future analyses attempt to include these contact components of competition to provide a more holistic assessment of the physiological demands of elite competition, which in turn may allow for a greater specificity of training.

Due to the requirement of forwards to be regularly involved in collision-based activities such as rucks and mauls (Quarrie et al., 2013), their ability to generate high speeds is limited, and therefore acceleration abilities may be more important. Interestingly, despite a larger mean acceleration value in forwards than backs (2.46 ± 0.92 vs 2.36 ± 0.93 $m \cdot s^{-2}$), the duration of these efforts has been shown to be greater for backs compared to forwards (0.85 ± 0.06 vs 0.76 ± 0.03 s) (Lacome et al., 2014). Therefore, it may be that backs perform less frequent acceleration bouts, but are able to sustain these efforts for a longer period. However, the authors only classified acceleration efforts greater than 1 $m \cdot s^{-2}$, and made no attempt to quantify deceleration. In contrast, the Ave Acc/Dec metric utilised in the present study encompasses all acceleration and deceleration efforts, regardless of the magnitude. Whilst it is conceded that this method loses the ability to differentiate the differing physiological cost of acceleration and deceleration (Osgnach et al., 2010), this measure adequately accounts for all acceleration/deceleration efforts, and therefore may be a more appropriate measure for assessing the overall acceleration-based requirements of an activity. Using this metric, the present study was able to determine that the tight 5 positional group consistently exhibited the lowest overall Ave Acc/Dec demands of any position, whilst outside backs, half-backs and loose forwards demonstrated similar results. As a result, coaches and practitioners may group these positions together when prescribing training targets and thresholds based on peak competition demands.

Throughout the literature, clear positional differences have been shown in regards to the HSR and acceleration requirements of rugby competition (Lacome et al., 2014; Quarrie et al., 2013; Roberts et al., 2008), and it is therefore important to replicate these demands within training. During rugby-specific drills that reflect the technical and tactical demands of competition, it would seem beneficial to monitor the physical profile of such activities using a metric that accounts for both acceleration/deceleration and speed-based running, such as P_{met} (Gaudino et al., 2014). Within the present study, there were clear, moderate increases in P_{met} achieved amongst outside backs and half-backs when compared to the tight 5 positional group across all moving average durations, due to a both an elevated acceleration-based requirement, but also a higher distance-based running demand. Whilst this metric is useful as an isolated depiction of overall running intensity, it must be noted that expressing the entire locomotor load of an activity using a single number may mask the mechanical origins of the load. Nonetheless, the P_{met} measure remains a stable, attractive measure for monitoring the demands of specific training methodologies, such as SSG (Gaudino et al., 2014; Rampinini et al., 2015).

PRACTICAL APPLICATIONS

This study is the first to describe the duration-specific activity profiles of elite rugby union competition, using a moving average approach. This method provides rugby union coaches with a true indication of the peak demands of competition, for a range of durations, which may be applied in the prescription and monitoring of specific training methodologies such as SSG. Importantly, coaches may manipulate such factors as player numbers and field dimensions to illicit and overload the desired training response relative to the peak demands of competition, whilst also developing technical and tactical abilities (Gaudino et al., 2014; Vaz, Gonçalves, Figueira, & Garcia, 2016). However, the prescription of training drills based on these data must only form a part of an athlete's preparation, as there is still a need to develop an individual's capacity to perform high-intensity running above these intensities, both as an injury prevention tool, but also so that the match requirements become less demanding relative to an athlete's gross capability.

It is important to consider that demands described in the current study represent only the running requirements of competition, and do not account for the large proportion of rugby union match-play where players are involved in non-locomotor activity such as jumping, pushing, pulling and wrestling (Austin et al., 2011a). Furthermore, no attempt was made to quantify what occurred prior to, within, or following these peak periods of play. The moving average method may be useful for expanding on recent research (Lacome et al., 2016), where temporal decreases in both physical and technical outputs were observed following the peak 5-minute period of play, identified using pre-defined 5-minute blocks. Further, knowledge of the skill-based contributions (i.e. attacking or defending) that may occur during peaks in physical activity could be useful when developing specific training drills aimed to replicate the demands of competition.

Chapter 8

Duration-specific running intensities of Australian Football match play

Delaney, J. A., Thornton, H.R., Burgess, D. J., Dascombe, B. J., & Duthie, G. M. (2017). Duration-specific running intensities of Australian Football match play. *J Sci Med Sport.* (Published Ahead of Print). doi: 10.1016/j.jsams.2016.11.009.

ABSTRACT

Objectives: To establish the position and duration-specific running demands of Australian Football (AF) competition for the prescription and monitoring of specific training drills. **Design:** An observational time-motion analysis was performed on 40 professional AF players during 30 games throughout the 2014-15 competitive seasons. **Methods:** Player movements were collected and peak values were calculated for moving averages of between 1 and 10 minutes in duration for relative distance ($m \cdot min^{-1}$), high-speed running relative distance (HS $m \cdot min^{-1}$), average acceleration/deceleration (Ave Acc/Dec; $m \cdot s^2$) and metabolic power (P_{met}). A mixed-model analysis was used to detect positional differences, and differences were described using a magnitude-based network. **Results:** Relative distance was *likely* greater for midfielders (MID), and mobile forwards (MF) compared to tall backs (TB) across all moving average durations assessed, with MF peaking at 223 ± 35 $m \cdot min^{-1}$ for a 1-minute window. High-speed relative distance was at least *likely* to be greater for MF compared to all other positions, across all moving average durations (ES = 0.27-0.94). Acceleration/deceleration demands were similar across positions. **Conclusions:** The present study demonstrated that the peak running intensities of AF are well above previously reported peak intensities when considering the distance-based running requirements of match-play. Whilst the acceleration-based metric was unable to detect large differences between positions, it is important to note their contribution to the overall competition demands. This study presents a useful framework for the prescription and monitoring of drills specific to AF competition requirements.

INTRODUCTION

Australian Football (AF) is an intermittent team sport where both high velocity running and high intensity accelerations/decelerations are important (Coutts et al., 2015). Global Positioning System (GPS) units are permitted to be worn during competition and are used by all teams competing within the Australian Football League (AFL) (Coutts et al., 2010), resulting in extensive research quantifying the physical demands (Black et al., 2015; Coutts et al., 2010; Montgomery & Wisbey, 2014) and energetic costs of match play (Coutts et al., 2015). Of particular interest is the assessment of the peak periods of activity during competition, as previously demonstrated in rugby league (Chapter 3). Amongst AF players, it has been shown that less experienced players elicit a greater reduction in physical and technical performance following the most intense periods of the game compared to their more experienced counterparts (Black et al., 2015). Knowledge of the peak physical demands of elite match-play allows coaches to prepare players for the most demanding requirements of competition. This is highly relevant in the prescription of game based training methodologies, for example small sided games (SSG) or conditioning games, that are aimed at mimicking the physical and tactical demands of competition (Farrow, Pyne, & Gabbett, 2008). The intensity of such training can then be referenced against these peak periods of activity to ensure the players are adequately prepared for the rigours of competition.

Previous research has attempted to identify the peak periods of match play using time and/or distances within specific speed bands (Coutts et al., 2015; Coutts et al., 2010; Montgomery & Wisbey, 2014), or volume of work performed within a discrete time frame (e.g., 3-minute block) (Black et al., 2015). There is an inconsistency between studies regarding the classification of speed zones, and therefore comparisons between studies are often difficult. Further, the use of pre-defined time periods has been shown to substantially underestimate the peak running demands of soccer competition by 20 to 25% compared to when using a moving

5-minute average technique (Varley, Elias, et al., 2012). This error occurs as a result of the peak period not falling completely within the discrete time frame used, and such discrepancies in results could lead to coaches underpreparing athletes for the most intense periods of team-sport competition (Varley, Elias, et al., 2012). Therefore, it would seem that a moving average method may be a more appropriate for outlining the most demanding periods of match play.

Throughout a match, AF players typically cover distances of ~13 km at average intensities of up to 128 $m \cdot min^{-1}$, depending on position (Coutts et al., 2015). Furthermore, these players cover substantially more distance at high speed (>5.5 $m \cdot s^{-1}$) per minute of match play compared to both rugby league and soccer players (Varley et al., 2014). However, given the fluctuating nature of team-sport running demands (Furlan et al., 2015), whole-match averages do not reflect the intensities reached at pivotal moments throughout the match (Gabbett et al., 2014). Recent research has established the most intense periods of rugby league competition using a moving average technique across a range of durations (1 to 10 minutes) (Chapters 3 and 6). These studies demonstrated a substantial increase in running intensity as the length of the moving average decreased, indicative of a fluctuating running profile of professional rugby league players. Given the considerable running demands imposed on professional AF players (Black et al., 2015; Coutts et al., 2010; Montgomery & Wisbey, 2014), it would seem beneficial to replicate these methods amongst such a cohort, to ascertain the peak running intensities these athletes are exposed to throughout match play.

Within team sports, particularly the collision-dominant sports, players are often not afforded the opportunity to reach maximal speed due to spatial constraints imposed by field dimensions or opposing players (Kempton, Sirotic, Rampinini, et al., 2015). Therefore, the ability to generate speed over a short distance or duration is vital for successful field sport performance (Lockie et al., 2011). Despite the uncertainty surrounding the reliability of GPS for assessing acceleration/deceleration demands (Buchheit, Al Haddad, et al., 2014), the evaluation of these efforts is common in team sports such as AF (Aughey, 2011; Coutts et al., 2015). Furthermore, the metabolic power (P_{met}; $W \cdot kg^{-1}$) metric has recently emerged as a useful tool in quantifying the movement demands of team sports, accounting for both high-speed running, and acceleration and deceleration that often occurs at low speeds (di Prampero et al., 2005; Osgnach et al., 2010). Whilst the validity of this measure for quantifying the true physiological cost of team-sports activity has been recently challenged (Brown et al., 2016; Buchheit et al., 2015; Highton et al., 2016), this measure exhibits considerable stability (Rampinini et al., 2015), and therefore may provide further insight into the external running demands of team sports, regardless of the metabolic cost of the activity. Indeed, when considering whole-match values, this measure has been utilised to differentiate positions during AF match play (Coutts et al., 2015). It may be the case that such differences are magnified when considering the peak demands of competition, and therefore a moving average method analysis to detect peak intensities beyond whole-match averages is warranted. The purpose of this investigation was to establish the duration-specific peak running intensities of elite AF competition to be used in the prescription and monitoring of an appropriately periodised program.

METHODS

An observational design was used to establish position-specific distance and acceleration-based movement indicators for professional AF players. Data were collected from 40 professional AF players (24 ± 3 yr, 87.9 ± 5.4 kg, 1.91 ± 0.04 m) playing for the same club during 30 matches across the 2014 and 2015 AFL competitions (16 wins, 14 losses). Between matches, a typical training week generally consisted of 3 field sessions, 3 resistance sessions and 3 recovery-based sessions. The total number of match observations was 623, and the mean

(± SD) number of observations per player was 16 ± 10 (range 1-29). Players were classified into positions as midfielders (MID), mobile backs (MB), mobile forwards (MF), rucks (RKS), tall backs (TB) and tall forwards (TF), and the total observations per positional group were 235, 128, 94, 37, 71 and 58, respectively. Informed consent and institutional ethics approval were obtained prior to the commencement of the study (HREC no: H-2013-0283).

The movement demands of competition were assessed using a portable GPS unit, sampling at 10 Hz (Catapult S5, Catapult Innovations, Melbourne, Australia). The unit was worn in a custom-made pouch fitted into the player's jersey, positioned on the upper back, slightly superior to the scapulae. To minimise inter-unit error (Buchheit, Al Haddad, et al., 2014), each player was assigned the same unit for the entire season. The validity and reliability of these units has been previously reported (Johnston, Watsford, et al., 2014; Rampinini et al., 2015). Upon completion of each match, data were downloaded using the necessary proprietary software (Openfield v.1.12.0, Catapult Innovations, Melbourne, Australia). This software provided instantaneous speed data ($m \cdot s^{-1}$), which was then re-imported into customised software (R; v R-3.1.3) for further analysis. Firstly, this software calculated the distance covered by each athlete, per unit of time (relative distance; $m \cdot min^{-1}$), and distance covered at high-speed (relative distance >5.5 $m \cdot s^{-1}$; HS $m \cdot min^{-1}$). The instantaneous acceleration/deceleration of the participant was calculated using the rate of change in speed, and all values were made to be positive, providing an indication of the absolute acceleration/deceleration requirements (Ave Acc/Dec). This whole-period average was chosen in preference to a traditional count method, where efforts that do not reach the desired threshold remain unquantified despite incurring some degree of physical cost. Whilst a limitation of this method may be that the ability to differentiate between acceleration and deceleration using this metric, this method allows for the incorporation of all data points, regardless of the magnitude. Next, P_{met} was derived using a series of calculations, the details of which have been reported previously (di Prampero et al., 2005; Osgnach et al., 2010). Finally, the software applied a moving average over each output variable (relative distance, HS relative distance, Ave Acc/Dec and P_{met}), using ten different durations (1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 minutes), and the maximum value for each duration was recorded (10 durations for each of the four variables) (Chapter 6). Data was then collated and averaged for each playing position, for between-position comparisons.

Assumptions of normality were confirmed prior to statistical analyses using the Shapiro-Wilk test. Linear mixed-effects models were constructed to establish differences in individual running performance between position (n = 6) and moving average duration (n = 10). To account for error associated with repeated measures from the same athlete, individuals were included as a random effect in the model, allowing different within-individual standard deviations. The effect of positional group on running intensities of each duration was determined by including a fixed effect in the model. Additionally, the interaction of the teams ranking and opposition ranking were accounted for in the model also by fixed effects, which were retained if statistical significance (p <0.05) was reached and improved the model criteria. If these were not achieved, the interaction was removed from the model. For pairwise comparisons between positions and moving average durations, the *post-hoc* Least Squares mean test was used. A magnitude-based inference network (Hopkins, 2007) was used to identify differences between position groups that were greatest worthwhile difference (SWD), calculated as 0.20 × the between-subject standard deviation. Standardised differences were classified according to Hopkins (Hopkins et al., 2009) as small (>0.2), moderate (>0.6), large (>1.2) and very large (>2). Differences were considered real if the likelihood of the observed effect exceeded 75% (Hopkins, 2007). Descriptive statistics are presented as mean ± SD, while all other data are reported as mean and 90% confidence limits (CL), unless otherwise stated.

Where necessary, statistical analyses were performed using R statistical software (R 3.1.0, R foundation for Statistical Computing).

RESULTS

The results of this analysis revealed main effects of positional group in each running intensity measure for all durations (1 to 10 minutes). The effect of the team's final ranking was significant for all acceleration durations except the 1-minute window, for all P_{met} durations and all HS durations. The final season ranking of the opposition (opposition strength) had no effect on any measure of running intensity, for any of the moving averages assessed. Figure 8.1 illustrates differences in each outcome measure relative to the 10-minute moving average. As the length of the moving average decreased, running intensity increased substantially across all outcome measures (relative distance, HS relative distance, Ave Acc/Dec and P_{met}). Compared to the 10-minute moving average, running intensity was not substantially lower for periods lasting 6 minutes and longer for HS relative distance, 7 minutes and longer for Ave Acc/Dec and relative distance, and 8 minutes and longer for P_{met}.

Descriptive statistics for peak running intensities achieved throughout competition are shown in Table 8.1, where small differences are annotated within the table, and differences of at least moderate magnitude are reported explicitly. Relative distance was *likely* to be lower for the TB group when compared to the MB (moving average duration 1-8 minutes), the TF (2 to 10 minutes), the MID (all durations) and the MF (all durations) groups. Acceleration demands were *likely* greater for the MB compared to the TF for windows more than 4 minutes in duration (ES = 0.26-0.39), and compared to MID for windows more than 6 minutes in duration (ES = 0.28-0.39). High-speed relative distance was at least *likely* to be greater for MF compared to all other positions, across all moving average durations (ES = 0.27-0.94). The P_{met} requirements of competition were *likely* to *most likely* greater than all other positions for the 1-minute window (ES = 0.27-0.62), but these differences diminished as the length of the moving average window increased.

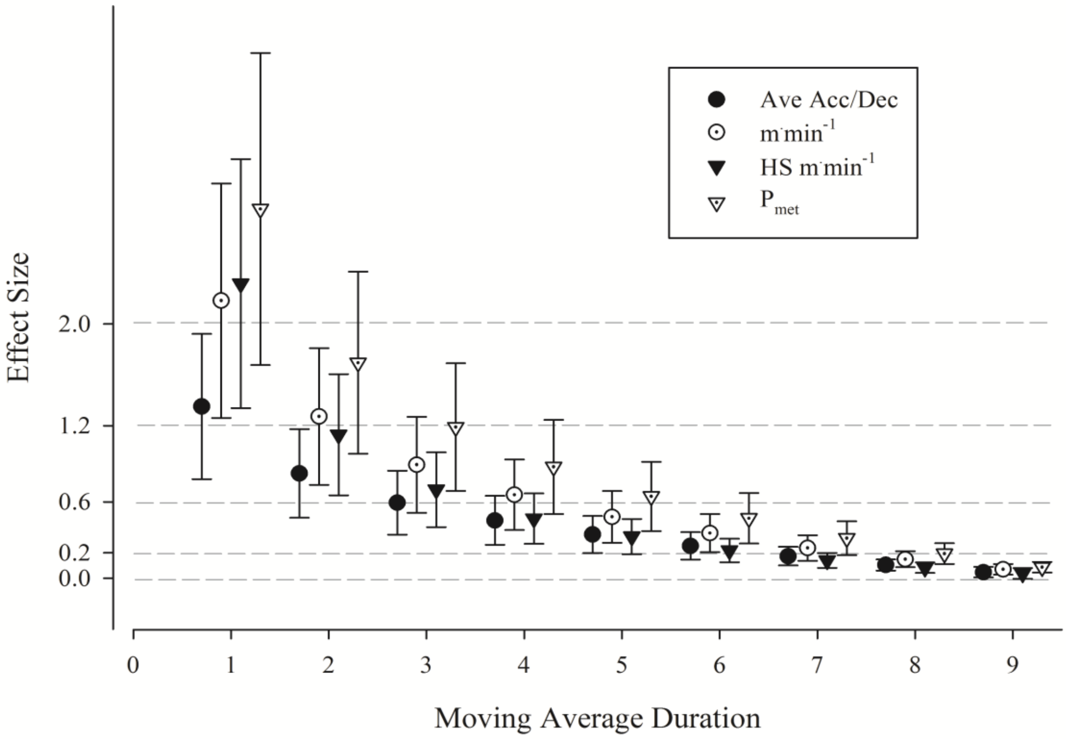

Figure 8.1: Maximum running intensity achieved during Australian football competition by moving average duration. Data are presented relative to the 10-minute move average (effect size; ±90% confidence limits).

Table 8.1a: Peak relative distances ($m \cdot min^{-1}$) of professional Australian Football players by position for each moving average duration (± SD).

	Midfielders	Mobile Backs	Mobile Forwards	Rucks	Tall Backs	Tall Forwards	Effect Size > 0.60
1	215 ± 21[e]	210 ± 22[e]	223 ± 35[bdef]	203 ± 15	199 ± 19	209 ± 17	N/A
2	184 ± 19[e]	181 ± 19[e]	187 ± 21[e]	178 ± 12	169 ± 14	180 ± 15[e]	N/A
3	171 ± 19[e]	168 ± 18[e]	173 ± 19[e]	166 ± 11	158 ± 15	168 ± 14[e]	N/A
4	164 ± 18[e]	160 ± 16[e]	165 ± 17[e]	159 ± 11	150 ± 14	160 ± 13[e]	N/A
5	158 ± 18[e]	153 ± 16[e]	159 ± 16[e]	153 ± 11	145 ± 14	155 ± 12[e]	N/A
6	153 ± 18[e]	149 ± 16[e]	154 ± 17[e]	150 ± 10	141 ± 14	152 ± 12[e]	N/A
7	149 ± 19[e]	145 ± 16[e]	150 ± 17[e]	146 ± 11	138 ± 14	148 ± 13[e]	N/A
8	146 ± 19[e]	142 ± 16[e]	147 ± 17[e]	143 ± 11	135 ± 14	146 ± 13[e]	N/A
9	143 ± 19[e]	140 ± 17	144 ± 17[e]	141 ± 11	133 ± 14	143 ± 13[e]	N/A
10	141 ± 18[e]	137 ± 17	142 ± 17[e]	138 ± 11	131 ± 14	141 ± 13[e]	N/A

MID = midfielders; MobB = mobile backs; MobF = mobile forwards; RKS = rucks; TB = tall backs; TF = tall forwards. [a] = greater than MID; [b] = greater than MobB; [c] = greater than MF; [d] = greater than RKS; [e] = greater than TB; [f] = greater than TF. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 × between-subject SD).

Table 8.1b: Peak high-speed (>5.5 m·s^{-1}) relative distances (HSR m·min^{-1}) of professional Australian Football players by position for each moving average duration (± SD).

	Midfielders	Mobile Backs	Mobile Forwards	Rucks	Tall Backs	Tall Forwards	Effect Size > 0.60
1	95 ± 30de	94 ± 29de	110 ± 45^{abde}	70 ± 20	76 ± 23	95 ± 24de	MobF > RKS & TB
2	58 ± 19de	58 ± 17de	71 ± 38^{abdef}	40 ± 11	47 ± 15	58 ± 14^{d}	MobF > RKS & TB
3	45 ± 15de	46 ± 14de	55 ± 25^{abdef}	29 ± 10	35 ± 10	45 ± 11de	MobF > RKS & TB
4	39 ± 14de	38 ± 11de	47 ± 20^{abdef}	23 ± 8	28 ± 9	37 ± 9de	MobF > RKS & TB
5	34 ± 12de	34 ± 10de	41 ± 16^{abdef}	20 ± 7	25 ± 8	33 ± 8de	MobF > RKS & TB; MID > RKS
6	31 ± 11de	31 ± 9de	37 ± 15^{abdef}	17 ± 5	23 ± 7	30 ± 7de	MobF > RKS & TB; MID & MobB > RKS
7	29 ± 10de	29 ± 8de	35 ± 13^{abdef}	15 ± 5	21 ± 6^{d}	27 ± 6de	MobF > RKS & TB; MID & MobB > RKS
8	27 ± 10de	27 ± 8de	33 ± 13^{abdef}	14 ± 4	19 ± 6	25 ± 5de	MobF > RKS & TB; MID & MobB > RKS
9	25 ± 9de	26 ± 7de	31 ± 11^{abdef}	13 ± 4	18 ± 6	24 ± 5de	MobF > RKS & TB; MID & MobB > RKS
10	24 ± 9de	24 ± 7de	30 ± 11^{abdef}	13 ± 4	17 ± 6	23 ± 5de	MobF > RKS & TB; MID & MobB > RKS

MID = midfielders; MobB = mobile backs; MobF = mobile forwards; RKS = rucks; TB = tall backs; TF = tall forwards. ^{a} = greater than MID; ^{b} = greater than MobB; ^{c} = greater than MF; ^{d} = greater than RKS; ^{e} = greater than TB; ^{f} = greater than TF. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 × between-subject SD).

Table 8.1c: Peak Ave Acc/Dec ($m \cdot s^{-2}$) of professional Australian Football players by position for each moving average duration (± SD).

	Midfielders	Mobile Backs	Mobile Forwards	Rucks	Tall Backs	Tall Forwards	Effect Size > 0.60
1	1.02 ± 0.15	1.05 ± 0.17[d]	1.02 ± 0.18	0.94 ± 0.06	1.01 ± 0.17	0.99 ± 0.16	N/A
2	0.89 ± 0.13	0.92 ± 0.16[df]	0.90 ± 0.18	0.84 ± 0.05	0.89 ± 0.17	0.87 ± 0.14	N/A
3	0.84 ± 0.11	0.87 ± 0.13	0.85 ± 0.16	0.80 ± 0.04	0.84 ± 0.15	0.82 ± 0.14	N/A
4	0.81 ± 0.11	0.83 ± 0.14	0.81 ± 0.15	0.77 ± 0.05	0.81 ± 0.15	0.78 ± 0.14	N/A
5	0.78 ± 0.10	0.81 ± 0.13[f]	0.78 ± 0.13	0.75 ± 0.05	0.78 ± 0.15	0.76 ± 0.12	N/A
6	0.76 ± 0.09	0.78 ± 0.09[f]	0.76 ± 0.11	0.74 ± 0.05	0.76 ± 0.12	0.74 ± 0.09	N/A
7	0.74 ± 0.08	0.76 ± 0.07[af]	0.74 ± 0.09	0.73 ± 0.05	0.74 ± 0.1	0.72 ± 0.07	N/A
8	0.72 ± 0.07	0.74 ± 0.06[acf]	0.72 ± 0.08	0.72 ± 0.05	0.73 ± 0.08	0.71 ± 0.06	N/A
9	0.71 ± 0.07	0.73 ± 0.05[acf]	0.71 ± 0.07	0.72 ± 0.05	0.71 ± 0.08	0.70 ± 0.06	N/A
10	0.69 ± 0.07	0.72 ± 0.05[af]	0.70 ± 0.07	0.71 ± 0.05	0.70 ± 0.07	0.69 ± 0.06	N/A

MID = midfielders; MobB = mobile backs; MobF = mobile forwards; RKS = rucks; TB = tall backs; TF = tall forwards. [a] = greater than MID; [b] = greater than MobB; [c] = greater than MF; [d] = greater than RKS; [e] = greater than TB; [f] = greater than TF. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 × between-subject SD).

Table 8.1d: Peak average metabolic power ($W \cdot kg^{-1}$) of professional Australian Football players by position for each moving average duration (± SD).

	Midfielders	Mobile Backs	Mobile Forwards	Rucks	Tall Backs	Tall Forwards	Effect Size > 0.60
1	19.9 ± 1.7[def]	19.7 ± 1.8[de]	20.8 ± 3.6[abdef]	17.8 ± 1.3	18.7 ± 1.5	18.9 ± 1.4	MobF > RKS
2	16.9 ± 1.4[de]	16.8 ± 1.5[de]	17.3 ± 2.1[def]	15.7 ± 1.1	15.7 ± 1.0	16.3 ± 1.5	MobF > TB
3	15.7 ± 1.4	15.5 ± 1.4	16.0 ± 1.7	14.7 ± 1.0	14.5 ± 1.0	15.2 ± 1.3	N/A
4	14.9 ± 1.3[de]	14.7 ± 1.2[e]	15.1 ± 1.5[def]	14.1 ± 1.0	13.8 ± 1.0	14.4 ± 1.3[e]	MID & MobF > TB
5	14.3 ± 1.3[de]	14.1 ± 1.2[e]	14.6 ± 1.3[def]	13.6 ± 0.9	13.3 ± 0.9	13.9 ± 1.2[e]	MobF > TB
6	13.9 ± 1.3[e]	13.7 ± 1.1[e]	14.1 ± 1.2[de]	13.3 ± 0.9	12.9 ± 0.8	13.6 ± 1.1[e]	MobF > TB
7	13.5 ± 1.3[e]	13.3 ± 1.1[e]	13.6 ± 1.2[de]	13.0 ± 1.0	12.6 ± 0.8	13.3 ± 1.0[e]	N/A
8	13.2 ± 1.4[e]	13.0 ± 1.1[e]	13.3 ± 1.3[e]	12.7 ± 1.0	12.2 ± 0.8	13.0 ± 0.9[e]	N/A
9	12.9 ± 1.3[e]	12.7 ± 1.2[e]	13.1 ± 1.3[e]	12.5 ± 1.0	12 ± 0.9	12.8 ± 0.9[e]	N/A
10	12.7 ± 1.3[e]	12.5 ± 1.2[e]	12.8 ± 1.3[e]	12.3 ± 1.0	11.8 ± 1.0	12.7 ± 0.9[e]	N/A

MID = midfielders; MobB = mobile backs; MobF = mobile forwards; RKS = rucks; TB = tall backs; TF = tall forwards. [a] = greater than MID; [b] = greater than MobB; [c] = greater than MF; [d] = greater than RKS; [e] = greater than TB; [f] = greater than TF. All observed differences are >75% likelihood of being greater than the SWD (calculated as 0.2 × between-subject SD).

DISCUSSION

The aim of the present study was to identify the most demanding running periods of AF competition for the prescription and monitoring of training. Previous research has described the movement demands of AF competition using discrete, pre-determined blocks of play (Aughey, 2010; Coutts et al., 2010). Whilst these data provide valuable information about the running intensity achieved at different stages of the match, they fail to identify the true maximum values attained throughout competition. Using a moving average approach, this study was able to establish the most demanding periods of competition, for a range of moving average durations. Whilst no attempt was made to quantify the energetic demands of tackling or kicking (Highton et al., 2016) within this study, the present findings may assist coaches in adequately preparing athletes for the most demanding running intensities they will be exposed to during match play.

A major finding of the present study was the differences in peak running profiles exhibited by different positions. For example, TB exhibited consistently lower relative distances compared to all other positions besides RKS, suggesting a lower overall running requirement for this group. These differences were accentuated for high-speed running, particularly when compared to the MF position. Such results are in line with recently reported whole-match averages, where the TB and TF groups exhibited the lowest values, whilst running intensity was highest for the MF position (di Prampero et al., 2005). This is unsurprising as TB typically remain in the defensive half of the field, even when the ball progresses forward, whereas most other positions are required follow the movement of the ball and/or opponent. For the P_{met} metric, the differences observed closely reflected those observed for the distance-based measures, which would suggest a larger contribution of high-speed running than accelerated or decelerated running to the P_{met} demands of competition. When averaged across a match, this metric has been shown to be greatest amongst MF (~11 $W \cdot kg^{-1}$) compared to all other positions (~9.2 to 10.3 $W \cdot kg^{-1}$) (Coutts et al., 2015). The present study is in agreement with these results, where P_{met} was the greatest of any positional group. In contrast to these differences, the acceleration demands of competition were similar across positions, with only small inconsistent differences evident for the MB position compared to a range of other positions. It may be that these differences are representative of the fluctuating requirements of the MB position. Typically, MB are required to react to an opponent's movements, in addition to initiating offensive play, and therefore the acceleration/deceleration requirements of this position may be higher. As such, when prescribing sport specific drills aimed at replicating the acceleration-based demands of competition, coaches do not need to differentiate between positions, as the acceleration and deceleration demands of competition are similar across positional groups.

During professional AF competition, fluctuations in running intensity have been reported in some (Coutts et al., 2010; Mooney et al., 2013) but not all (Aughey, 2010) studies. For example, one study reported that the relative distance covered during AF competition did not differ substantially from the first rotation period (~130 $m \cdot min^{-1}$) to any of the subsequent rotation periods, suggesting a similar overall intensity was sustained across the match (Aughey, 2010). In opposition to these findings, several authors have demonstrated a decline in running performance from the first quarter to the following periods during AF competition (Coutts et al., 2010; Mooney et al., 2013). However, when investigating within-match fluctuations in running intensities, it is important to note the increased variability of typical running performance measures for time periods of shorter durations, largely due to a decreased number of observation points (Kempton et al., 2014). The present study reported differences between time epochs accounting for such variability, demonstrating substantial increases in running intensity as the length of the moving average window decreased. These data are particularly important for the prescription of specific training drills, where subtle deviations in drill duration (i.e. 1 minute) may illicit a considerably different response. Whilst such within-match fluctuations in running intensity have been attributed to a range of factors including fatigue, pacing and game situation (Waldron & Highton, 2014), the present study made no attempt to quantify such determinants. Alternatively, it was an aim of this study to accurately describe the true peaks in running intensity observed during match-play, allowing coaches to prescribe training with the most demanding periods of competition in mind.

An interesting observation of the present study was that the relatively similar peak acceleration/deceleration profiles between AF positions, with only the MB group exhibiting an elevated response. This differs from a recent study (Coutts et al., 2015), where the TB group was the only position that was consistently lower than other positions. However, the inconsistency between studies could simply reflective of the team assessed, as each study was only able to quantify match demands from a singular club. Alternatively, these differences could be a result of the count method used to detect acceleration/deceleration efforts, which has been shown to exhibit questionable reliability using GPS technology (Buchheit, Al Haddad, et al., 2014). Furthermore, such analyses are not inclusive of all acceleration/deceleration efforts, and subsequently the overall acceleration demand of the period might not be accurately represented. To account for this issue, the present study utilised a time series analysis (moving average method) where all data points are included in the calculation of the final value. Pilot data collected from our laboratory have revealed this technique to exhibit similar if not greater stability (CV = 7.2%) when compared to the number of efforts over predefined thresholds (CV = 5.7-13.7%). As such, this metric was deemed to be adequately reliable for the quantification of the acceleration-based movement demands of AF. Further, by including all the acceleration data in the analysis, this method accounts for even moderate changes in speed (i.e. acceleration). For example, it may be that regular low to moderate (0 to 2 $m \cdot s^{-2}$) acceleration efforts over a 2-minute period may induce greater fatigue than several irregular, higher intensity (>2 $m \cdot s^{-2}$) accelerations performed over the same time frame. In both cases, the relative distance ($m \cdot min^{-1}$) covered by the athlete may be low, and therefore a metric which encapsulates the acceleration demands of the such periods is necessary, as these movements may provide a different neuromuscular stimulus compared to higher speed, constant running, though this remains speculative. Nonetheless, it would be important that drills in training mimic these demands to induce the preferred neuromuscular adaptations in the athletes, and the Ave Acc/Dec metric represents an appropriate method to do so.

In addition to the differences established between positions, this study also quantified the effect of the duration of the moving average on the running intensity achieved. It was observed that for durations lasting longer than ~5 to 7 minutes (depending on the variable chosen), peak match running intensity seemed to plateau. These data are in agreement with a recent study, where shorter on-field rotations (~5 minutes) were shown to exhibit higher average running demands, whereas running intensity did not change substantially for periods 11 minutes and longer (Montgomery & Wisbey, 2014). Whilst knowledge of the average demands of on-field bouts is useful for planning interchange tactics and protocols, it is vital that the peak intensities achieved during competition are utilised when prescribing and monitoring training. To adequately prepare athletes for the most intense periods of place, training drills should reflect the duration-specific running intensity of competition, provided they are done so in an appropriately periodised manner. In a team-sport setting, coaches are faced with the challenged of providing an environment in which technical, competitive and physical traits can be nurtured optimally (Charlesworth, 1994). Small-sided games present as an ideal training methodology where athletes are stimulated to perform in a game-specific environment, whilst concurrently developing both physiological and technical abilities. Whilst SSG are a time-efficient method of combing physical and tactical training effectively, the correct periodisation of these drills is paramount. By monitoring drills relative to peak match intensities, coaches are able to ensure athletes are prepared for the rigors of competition. As a result of regular exposure to these demands, athletes will become more resilient, and when faced with challenging situations within competition, the athletes will be prepared.

As is evident throughout this study and others (Coutts et al., 2015; Coutts et al., 2010), the running demands of AF competition are high. Traditionally, AF players exhibit considerable levels of aerobic fitness (Bellenger et al., 2015), and as a result a primary focus of AF training is to develop the maximal aerobic ability of the athletes. Despite the lower acceleration demands observed in the present study compared to other sports (Chapter 6), there is still a need to include these movements in training as opposed to constant velocity training. For example, this study observed the maximal relative distance covered in a 1-minute period to be ~200-200 $m \cdot min^{-1}$, depending on position. This equates to an average running velocity of 4.0 $m \cdot s^{-1}$, which is below the reported 4.5 $m \cdot s^{-1}$ maximal aerobic speed (MAS) of AF players (Bellenger et al., 2015). Therefore, it may be that the added physical cost of the acceleration/deceleration efforts during competition is the limiting factor, and as a result conditioning drills should be designed to mimic both the distance and acceleration-based demands of competition, so that the physiological adaptations achieved are specific to the requirements of competition.

PRACTICAL APPLICATIONS

The findings of this study demonstrate a clear framework for the prescription and monitoring of skill-based training drills, which should be used to replicate the specific demands of AF competition. It is evident that the peak running intensities of AF competition are high, and therefore athletes must be adequately prepared for exposure to such loads. However, for optimal adaptations to occur, it is pertinent that the running intensities reported in the present study are utilised in a manner that coincides with an appropriately periodised program.

- Coaches may prescribe and monitor skill-based training drills to replicate the specific demands of competition.
- If a player cannot achieve the required running demands of competition in a sports-specific environment, they may benefit from undertaking isolated training practices to increase their overall running capacity before they are able to compete at the required level in competition.
- Once an increase has been observed via traditional conditioning methods, there will be a greater likelihood that a player can express high-intensity running efforts in a sports-specific environment.
- Using this framework, training prescription can be simplified and generalised for positional groups with similar competition demands and requirements.

ACKNOWLEDGEMENTS

The authors thank the Port Adelaide Football Club for their assistance with this project. There has been no financial assistance associated with this study.

Chapter 9

Modelling the decrement in running intensity within professional soccer players

Delaney, J. A., Thornton, H.R., Rowell, A. E., Dascombe, B. J., Aughey, R. J., & Duthie, G. M. (2017). Modelling the decrement in running intensity within professional soccer players. *Sci Med Football.* (Accepted for Publication).

ABSTRACT

Knowledge of the most intense periods of competitive soccer may assist in the development of specific training methodologies. Match activity profiles were obtained from 24 players across 40 professional matches. Player movements were collected and peak values were calculated for moving averages 1 to 10 minutes in duration for relative distance ($m \cdot min^{-1}$), high-speed relative distance (HS $m \cdot min^{-1}$), average acceleration/deceleration (Ave Acc/Dec; $m \cdot s^2$) and metabolic power (P_{met}). To quantify the decrease in running intensity for longer moving average durations, each measure was evaluated relative to the moving average duration, as a power law relationship, and differences between positions were described using a magnitude-based network. Peak relative distance and P_{met} were at least likely lowest for central defenders (effect size [ES] = 0.79-1.84), whilst acceleration/deceleration intensity was highest for wide defenders (ES = 0.67-1.42). Differences in the rate of decline in running intensity between positions were considered trivial to small, indicating a similar rate of decline in running intensity across positions. Using power law, the peak running intensities of professional soccer can now be predicted as a function of time, providing coaches with a useful tool for the prescription and monitoring of specific training drills.

INTRODUCTION

Soccer is characterised by brief bouts of high-intensity running interspersed with longer periods of low-intensity activity (Rampinini et al., 2007). Typically, a competitive match involves players covering between 10 000 and 12 000 m, depending on position (Mohr et al., 2003; Rampinini et al., 2007). There is a need for well-developed acceleration capacity (Varley & Aughey, 2013), as this is vital for pivotal moments of a match such as competing for the ball with an opposition player, or creating/stopping goal scoring opportunities (Reilly, Bangsbo, & Franks, 2000). During professional match-play, wide defenders (WD) have been shown to complete more maximal accelerations (>2.78 $m \cdot s^{-2}$) compared to all other positions. Depending upon team formation, the WD position has a dual role of maintaining their defensive structure but also providing support as a wide passing option when setting up for goal scoring opportunities (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009), explaining the elevated acceleration response amongst this positional group. Whilst data such as these may be useful for quantifying player movement during competition, whole match values may not be sensitive enough to detect the most intense period of a match. As a result, they provide inadequate information for the prescription of training relative to the acute within-match requirements of professional soccer.

The chaotic nature of the running intensity of team sports is well-known, whereby changes in athletes' physical output throughout a match can be attributed to a multitude of factors, including fatigue (Bendiksen et al., 2012), pacing (Edwards & Noakes, 2009) and match situation (Carling & Dupont, 2011). The within-match fluctuations in running intensity has been assessed by separating matches into discrete blocks lasting five to 15-minutes in duration (Barrett et al., 2015; Bradley & Noakes, 2013; Mohr et al., 2005). Running intensity declined following both the initial period of the match (Barrett et al., 2015), as well as immediately succeeding the most demanding block of play (Bradley & Noakes, 2013). These data outline the need to prepare athletes for the most demanding periods of play, which are commonly associated with point scoring or match deciding situations (Reilly et al., 2000). However, pre-defined segments of time may not be sensitive to small fluctuations in running intensity if the variation occurs across the designated time segment (Di Salvo et al., 2009). In comparison, possession changes, goal attempts, and defending against attacking plays occur randomly within a match, and therefore a moving average method has been proposed as the appropriate method for detecting the most demanding periods of play (Chapters 3 and 6).

In an attempt to quantify the peak running intensities of competition, a moving average technique has been applied to a number of locomotor measures, across a range of team sports (Chapter 6) (Furlan et al., 2015). A substantial decline in running intensity has been observed in rugby league players as the duration of moving average increased from 1 to 10 minutes (Chapter 6). This decline in the peak running intensity as duration increased provides preliminary quantification of the rate of decline in activity in high level team-sport athletes. Further to this, the interaction between running time and distance has been assessed amongst individual sports, where it was proposed that an apparently non-linear relationship can be accurately evaluated using log or power analyses (Katz & Katz, 1999). Whilst team sports represent an environment where external factors may have a greater influence on the running requirements of the activity such as strength of the opposition and match location (Kempton & Coutts, 2015; Paul, Bradley, & Nassis, 2015), it may be that a power law relationship still exists between running intensity and duration. Therefore, mathematical modelling of the relationship between peak running intensity achieved and the moving average duration may reveal novel information regarding both the peak running capacity athletes during competition (i.e. the greatest running intensity an athlete might reach within a match), as well as the rate of decline in intensity as a function of time. Such data may assist coaches in predicting the required running intensity of specific training drills relative to peak match activity profiles, or detecting deficiencies within individuals. Therefore, this study aimed to: 1) quantify the peak running intensities generated by professional soccer players during competition, and 2) establish the rate at which this peak running intensity declines as a function of time.

METHODS

An observational design was used to evaluate the rate of decline in running intensity as the moving average duration increased, amongst professional soccer players. Data were collected from 24 elite-level players (24.4 ± 5.4 yr, 1.79 ± 0.06 m, 75.2 ± 5.8 kg) playing for the same team in the Australian A-League competition. Players were assessed during 40 games for a total of 434 individual match observations (18 ± 10 matches per players, range 1-34), which was representative of the entire playing cohort. Match files were classified according to position, as central midfield (CM; n = 49), central defender (CD; n = 78), striker (STR; n = 33); wide defender (WD; n = 83), wide midfield (WM; = 103); and winger (WNG; n = 88). The team in question typically utilised a 4-3-3 formation (2 CD and 2 WD; 1 CM and 2 WM; 1 STR and 2 WNG). Informed consent and institutional ethics approval was attained prior to the commencement of the study (HREC no: H-2013-0283).

Activity Profile

During matches, players' movements were recorded with a portable GPS unit (CatapultSports™ OptimEye S5; 10 Hz), placed between the shoulder blades in a custom-made vest worn underneath their playing jersey. Upon completion of each match, data were downloaded using the same version of the appropriate proprietary software (CatapultSports™ Openfield software; version 1.11.1), where a raw speed ($m \cdot s^{-1}$) trace for the entire match (inclusive of stoppage time) was exported and further analysed using customised software (R, v R-3.1.3.), which removed data points where speed exceeded 10 $m \cdot s^{-1}$, or acceleration/deceleration exceeded 6 $m \cdot s^{-2}$ (Weston, Siegler, Bahnert, McBrien, & Lovell, 2015). These instances were replaced with zero values, and given the nature of the peak intensity analysis utilised in the present study (details below), this was deemed to have little effect on the values observed for each match file. The number of available satellites and horizontal dilution of precision during the testing period were 10.6 ± 1.7 and 0.86 ± 0.28, respectively.

Four measures of running intensity were chosen, based on current trends in player monitoring within high-level soccer, which were identified as total distance, high-speed distance (>5.5 $m \cdot s^{-1}$), acceleration variables, and metabolic power (Akenhead & Nassis, 2016). Specifically, relative distance ($m \cdot min^{-1}$) was calculated as total distance covered per unit of time, along with relative distance covered above a predefined high-speed threshold (>5.5 $m \cdot s^{-1}$; HS $m \cdot min^{-1}$) (Akenhead & Nassis, 2016). Further to this, the change-of-direction requirement of the activity was assessed using a novel average acceleration/deceleration (AveAcc; $m \cdot s^{-2}$), which has recently been proposed (Chapter 6). This technique involved taking the absolute value of all acceleration/deceleration data, and averaging over the duration of the defined period. Whilst it is acknowledged that the amalgamation of both acceleration and deceleration data into one measure may mask the mechanism behind the load (i.e. energetically demanding acceleration efforts vs. eccentrically damaging decelerations (Osgnach et al., 2010; Young et al., 2012), this metric was considered indicative of the combined acceleration and deceleration intensity of the activity. Metabolic power (P_{met}) was calculated using methods detailed previously (di Prampero et al., 2015; Osgnach et al., 2010), as a representation of the combined external demands of the activity, inclusive of both acceleration and deceleration, and speed-based movements. A moving average technique was then applied to each of the output variables, using ten different durations (i.e. 1 to 10 minutes), and the peak value achieved throughout each match for each variable was recorded.

Unfortunately, due to the recent release of the model of GPS unit used in the present investigation, validity and reliability data are limited to one study, where it was reported that maximal speed during straight-line sprinting trials was comparable with the criterion radar gun (r = 0.95, 90% confidence interval [90% CI] 0.93 to 0.97; standard error of the estimate [SEE] = 1.87, 1.65 to 2.18 $m \cdot s^{-1}$) (Roe et al., 2016). In addition, pilot data from our laboratory has revealed that compared to previously validated 5 Hz devices (Scott et al., 2016), these 10 Hz units possessed stronger inter-unit reliability for all measures used within this study (CV = 0.9 to 1.0% vs. 0.5 to 5.7%). Though this does not confirm the validity of these units, these units were deemed acceptable for discriminating positional demands during competition.

Running Intensity Modelling

To quantify the decrease in running intensity for longer moving average durations, each of the four peak output measures were evaluated relative to the moving average duration, as a power law relationship (Katz & Katz, 1999; Katz & Katz, 1994). A power law curve describes non-linear but clearly dependent relationships between two variables (*x* and *y*) can be given by the equation:

$$y = cx^n$$

where *n* and *c* are constants. A plot of log (*x*) against log (*y*) results in a straight line with slope *n*, and intercept of c^e (Katz & Katz, 1994). Linear regression revealed the values for *n* and *c* for each variable within each match file. The exponential of *c* was calculated, and therefore a predictive equation of running intensity (*i*) as a function of time (*t*) was achieved, using the formula:

$$i = ct^n$$

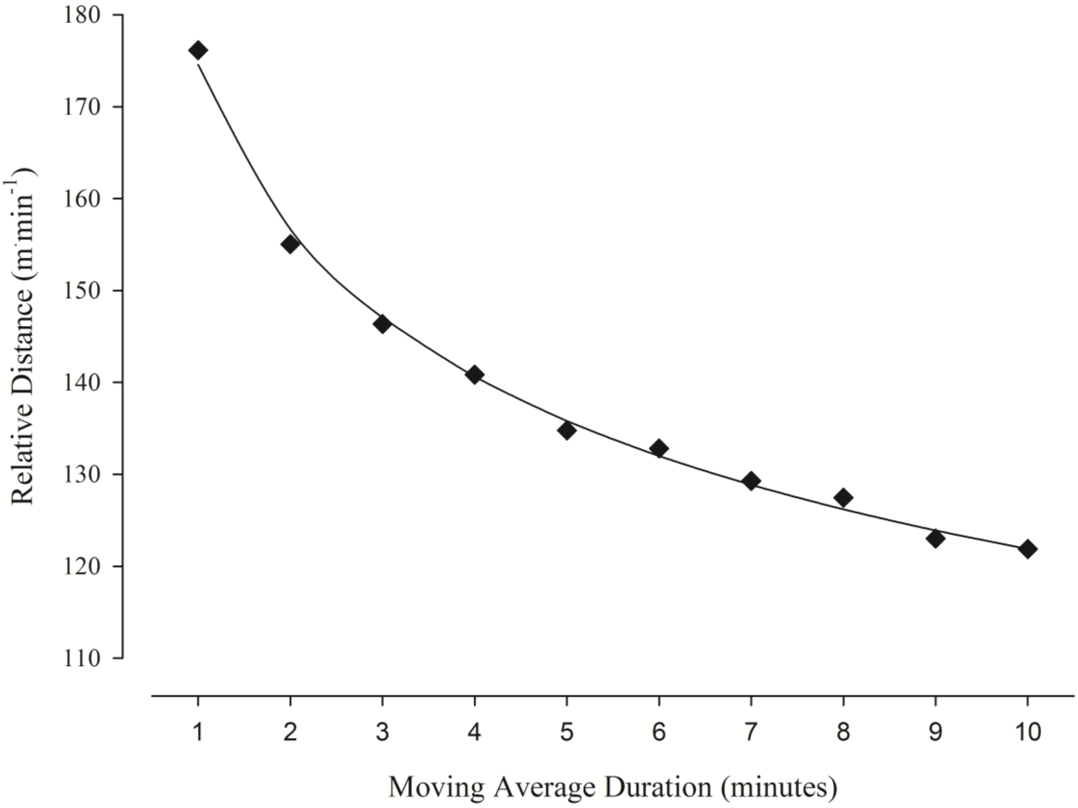

Figure 9.1: Example of power law analysis. Raw relative distance (*y*-axis; $m{\cdot}min^{-1}$) is plotted for each moving average duration. Curve represents predicted values as a function of time (*x*-axis).

As such, running intensity was deemed to be proportionately related to the duration of the moving average window (i.e. time). An example of this method can be found in Figure 9.1, where the raw relative distance achieved is plotted as a function of time (symbols), and the predicted values from the log transformed data are represented by the curve. The close relationship between the predicted and actual data demonstrates the "fit" of the model, and provides support for the use of this method. Data was then collated by playing position and averaged, to provide a position-specific framework of the decline in running intensity as the moving average increased.

Statistical Analysis

Goodness of fit for the log-transformed data was assessed using Pearson's correlation coefficient (r), and was rated as; <0.1 trivial; <0.3 small; <0.5 moderate; <0.7 large; <0.9 very large and >0.9 almost perfect (Hopkins et al., 2009). Pairwise comparisons between positional groups were investigated using linear mixed models, as these models appropriately handle repeated measures data. Random effects (individual athletes) were specified to allow for different within-subject standard deviations by the use of random intercepts, and fixed effects (positional groups) were included to describe the relationship with the dependent variables. The Least Squares mean test provided positional comparisons from the final models, that were further assessed using a magnitude-based inference network (Hopkins, 2007). Standardised differences between positional groups were assessed using effect sizes (ES), classified according to Hopkins et al. (2009) as; <0.20 trivial; <0.60 small; <1.20 moderate; <2.0 large and >2.01 very large. Differences were considered real if they were at least *likely* (i.e. >75% chance) of being greater than the smallest worthwhile difference (SWD), calculated as 0.2 × the between-subject standard deviation (SD). Descriptive statistics are reported as mean ± SD, and while all other data are reported as mean ±90% confidence limits (CL), unless otherwise stated. Statistical analyses were performed in a customised spreadsheet (Microsoft Excel, Redmond, USA) (Hopkins, 2007) and R Studio Statistical software (V 0.99.446).

RESULTS

All log-transformed output variables exhibited almost perfect relationships with log-transformed moving average duration (r = 0.97 ± 0.00 to 0.98 ± 0.00). Figure 9.2 illustrates the raw peak running intensities achieved by professional soccer players during competition by position, as a function of moving average duration. Results of the running intensity modelling analysis can be found in Table 9.1. The relative distance and P_{met} intercepts were at least *likely* lower for the CD group compared to all other positions (ES = 0.79-1.84). Ave Acc/Dec intercept was highest for the WD group, compared to all other positions (ES = 0.67-1.42). There was a *likely* small increase in the HS relative distance intercept for the STR and WD positions when compared to the WNG group (ES = 0.35-0.43), and *very likely* moderate increases compared to all other positions (ES = 0.63-1.10). Substantial differences between positions for the slope of each calculated variable were considered small (ES = 0.32-0.55).

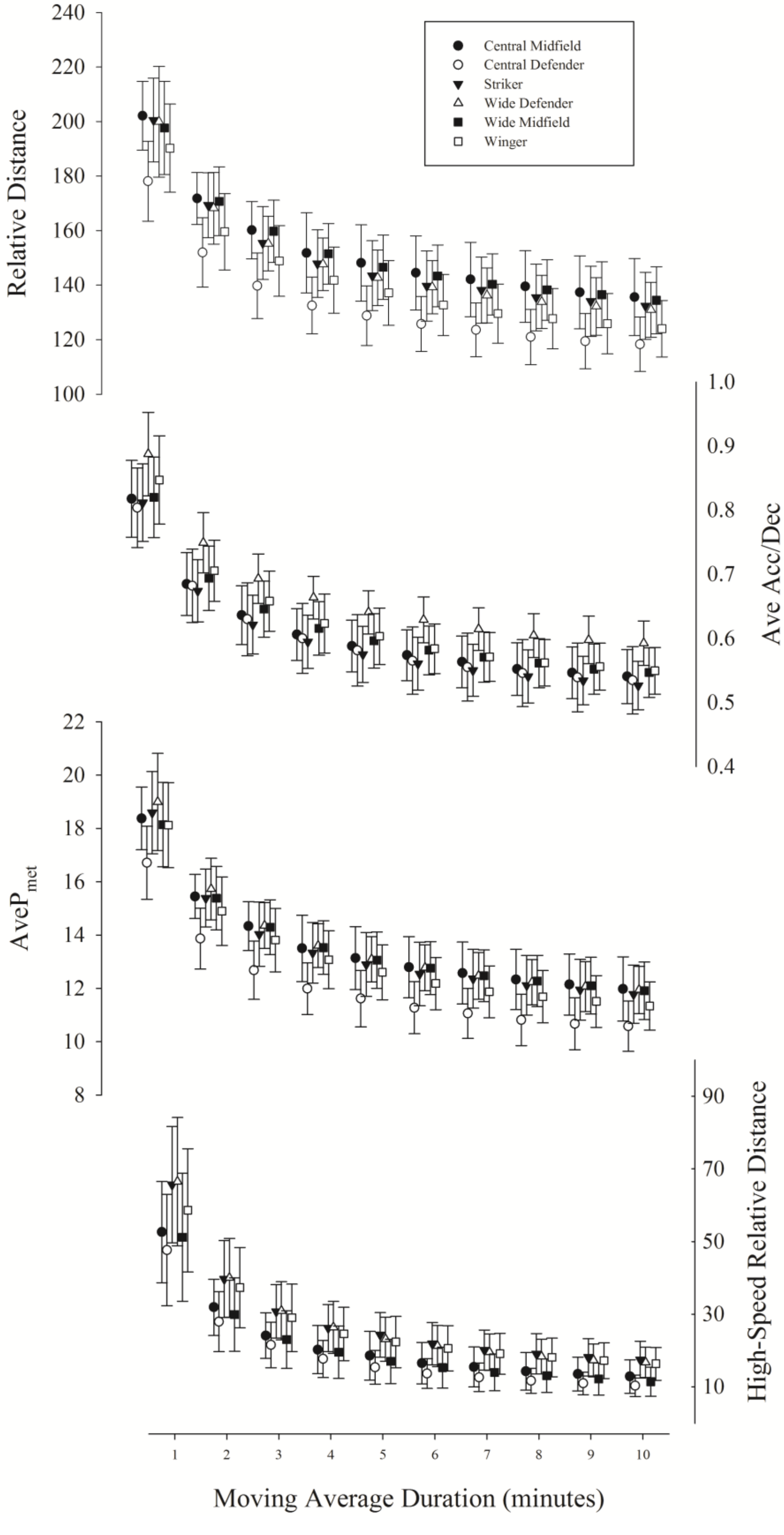

Figure 9.2: Peak running intensity achieved for each position, for each moving average duration. Data are mean ± SD.

Table 9.1: Intercept and slope values for predicting match intensity by duration for professional soccer players (mean ± SD).

Variable		Central Midfield	Central Defender	Striker	Wide Defender	Wide Midfield	Winger	Effect Size > 0.60
Relative Distance	Intercept	196 ± 12[bf]	173 ± 14	193 ± 13[bf]	194 ± 17[bf]	193 ± 14[bf]	184 ± 15[b]	CM, STR, WD & WM > CD & WNG; WNG > CD
	Slope	-0.17 ± 0.06	-0.17 ± 0.03[e]	-0.18 ± 0.03[e]	-0.18 ± 0.04[e]	-0.16 ± 0.03	-0.18 ± 0.04[e]	
Ave Acc/Dec	Intercept	0.79 ± 0.05	0.78 ± 0.06	0.78 ± 0.06	0.86 ± 0.05[abcef]	0.79 ± 0.06	0.82 ± 0.06[abce]	WD > ALL WNG > CD & STR
	Slope	-0.17 ± 0.03	-0.17 ± 0.03	-0.18 ± 0.03	-0.17 ± 0.03	-0.17 ± 0.03	-0.18 ± 0.03[de]	
P_{met}	Intercept	17.8 ± 1.2[b]	16.1 ± 1.2	17.8 ± 1.3[bf]	18.3 ± 1.5[abcef]	17.6 ± 1.3[b]	17.4 ± 1.5[b]	ALL > CD
	Slope	-0.18 ± 0.07[b]	-0.19 ± 0.03[e]	-0.19 ± 0.03[e]	-0.20 ± 0.04[e]	-0.18 ± 0.03	-0.20 ± 0.04[e]	
HS Relative Distance	Intercept	51 ± 16	45 ± 14	61 ± 15[abef]	62 ± 16[abef]	48 ± 16	55 ± 16[bf]	STR & WD > CM; CD, WD & WNG > CD
	Slope	-0.18 ± 0.07	-0.19 ± 0.03[e]	-0.19 ± 0.03[e]	-0.2 ± 0.04[e]	-0.18 ± 0.03	-0.2 ± 0.04[e]	

CM = Central Midfield; CD = Central Defender; STR = Striker; WD = Wide Defender; WM = Wide Midfield; WNG = Winger; ALL = all other positions. Differences were considered real if they were > 75% chance of being greater than the smallest worthwhile difference, calculated as 0.2 × between subject SD. [a] = greater than CM; [b] = greater than CD; [c] = greater than STR; [d] = greater than WD; [e] = greater than WM; [f] = greater than WNG.

DISCUSSION

Using power law, this study has presented a novel method of modelling the running intensity of professional soccer competition as a function of time, providing coaches with a new level of flexibility when monitoring the demands of training relative to peak match intensity. It is well established that the running intensity of soccer experiences declines at various stages throughout a match, most likely due to fatigue or related to specific match situations (Bendiksen et al., 2012; Carling & Dupont, 2011; Edwards & Noakes, 2009; Mohr et al., 2005), however this study was the first to establish a duration-specific profile of the peak running periods of professional soccer. Importantly, knowledge of the peak intensities attained during competition allow coaches to adequately prepare athlete for these demands through appropriate training methodologies. Furthermore, this study provides insight into the rate of decline in peak running intensity (i.e. slope) amongst these players, which was similar across positions. This may indicate that players are not only limited by fatigue in maintaining running intensity, but stoppages when the ball is not in play could limit the running intensity sustained by all players simultaneously.

Knowledge of the most demanding periods players are exposed to during competition allows coaches to prepare their athletes appropriately. This study observed that as time approached zero, relative distance peaked at ~170-200 $m \cdot min^{-1}$, depending on position. This is substantially higher than the values of ~100-120 $m \cdot min^{-1}$ that are typically reported over a half of a match (Bradley & Noakes, 2013), which suggests that prescribing training based on "match intensity" must be done so using the peak running profile of competition, as using whole-match values will not adequately prepare athletes for the rigors of competition. As such, using the calculations presented in this study, coaches may determine "match speed" for any given value of time (i.e. the duration of the drill in question), and monitor these intensity of training drills relative to these values.

However, it is important to note that the peak relative distances covered in this study equate to running speeds of 2.8-3.3 $m \cdot s^{-1}$, well below the maximal aerobic speed (MAS) typically reported amongst professional soccer players (~4.4 $m \cdot s^{-1}$) (Wong, Chaouachi, Chamari, Dellal, & Wisloff, 2010). As soccer is stochastic in nature (Barrett et al., 2015), it is clear that the running requirements of competition fluctuate, and therefore it may also be beneficial to quantify the peak periods of high intensity running.

Amongst professional soccer competition, several researchers have quantified the peak 5-minute period of high-intensity running of match-play using various high-speed thresholds between 4 and 5.5 $m \cdot s^{-1}$ (Bradley & Noakes, 2013; Carling et al., 2016; Mohr et al., 2003). The present study observed that high-speed running peaked at ~50-65 $m \cdot min^{-1}$, depending on position. These data are above the ~45 $m \cdot min^{-1}$ above the same high-speed threshold reported across a 5-minute period (Bradley & Noakes, 2013), outlining an increased sensitivity to absolute peaks in the present study. Despite this, across all previous studies there has been a consistent decrease reported in running intensity in the periods following the peak 5-minute block, that is suggestive of fatigue (Bradley & Noakes, 2013; Carling et al., 2016; Mohr et al., 2003). This is consistent with the findings of the present study, where a negative, non-linear relationship was observed between the duration of the moving average applied, and high-speed relative distance achieved. Whilst the decline in running intensity observed in the present study may be a result of some level of fatigue, it is difficult to ascertain the exact physiological mechanism using only displacement data. Nonetheless, the power law method utilised in this study revealed that although the speed-based running requirements of competition are evidently high amongst WD and STR compared to other positions (indicated by the substantial differences in the intercept value), the rate of decline of these capacities were similar throughout the squad. The exact mechanism behind this is unclear, as differences in aerobic qualities between positions have been previously described (Stolen et al., 2005). Therefore, it may be that the similarity in the rate of decline amongst positions may be a function of all players receiving the same training stimulus, though this notion remains speculative as no measure of training load was considered in this study. Moreover, it may simply be that the tactical strategies of the team in question resulted in a purposeful decrease in running output (i.e. attempting to maintain possession to defend a lead), potentially influencing the running intensity of all players simultaneously.

In addition to the observed differences between positions regarding velocity-based movements, competitive soccer imposes varying acceleration demands on each position (Varley & Aughey, 2013). Large between-unit variations have been observed using GPS to assess the number of acceleration (CV = 10-43%) and deceleration (CV = 42-56%) efforts during a team-sport simulation protocol (Buchheit, Al Haddad, et al., 2014), which might be a result of the "count" technique employed (i.e. a non-substantial difference between units could lead to a substantially different result). The Ave Acc/Dec measure used in this study avoids this issue, as all data points are considered regardless of their magnitude, and pilot data from our laboratory suggests this method possesses adequate reliability (CV = 5.7%, 90% confidence interval = 4.5 to 7.8%). The findings of this study are in line with others (Varley & Aughey, 2013), where the WD position had far greater acceleration requirements compared to other positions. Though these authors did not consider the WNG position as an isolated positional group, the present study found a similar increase in the acceleration/deceleration profile for this position compared to others. The WD positional group is regularly involved in attacking and defending duties, resulting in constant back and forth movements during match play. The WNG position also frequently accelerates into a wide position to have an attempt at goal or cross the ball into position for a goal attempt, which may explain the increased acceleratory demands of this group (Varley & Aughey, 2013). Therefore, it would seem necessary that these players are exposed to the necessary stimulus in training to reflect the increased acceleration and deceleration requirements of competition.

The P_{met} method represents a theoretical model for assessing the estimated energetic cost of team sports activity, where both accelerated and constant velocity running are accounted for (Osgnach et al., 2010). Recently, this metric has been challenged as a valid indicator of metabolic load during non-locomotor activities such as jumping and kicking (Brown et al., 2016; Buchheit et al., 2015), and for quantifying the energetic cost of sprints with changes of direction (Hader, Mendez-Villanueva, Palazzi, Ahmaidi, & Buchheit, 2016). However, with these limitations in mind, 10 Hz GPS units possess the ability to accurately assess these demands, with a strong relationship with the criterion (laser device; typical error = 2.4%; 2.1 to 2.9%) (Rampinini et al., 2015). Therefore, this technique represents an accurate measure for the assessment of the external running demands of team-sport activity, where high-intensity efforts at both high and low speed are incorporated. In this study, the CD positional group exhibited the lowest P_{met} intercept of any position (ES = 1.01-1.65), indicating a lower peak P_{met} of this position. During competition, the tactical requirements of the CD consist of primarily defending the goal area, resulting in the activity profile of this position often being limited by the movements of opposing players. The CD is generally involved in more body contacts and other soccer specific actions such as jumping and heading rather than necessarily a high running-based activity profile (Varley & Aughey, 2013). Nonetheless, the peak P_{met} achieved by soccer players are similar to rugby league (Chapter 6), despite a substantially lower acceleration requirement. This finding demonstrates the application of the P_{met} metric as an overall indication of the running profile of competition. However, information regarding the mechanism of the acquired load (i.e. acceleration/deceleration of high-speed running) is important when prescribing training with a specific physical adaptation in mind, and therefore it is recommended that this metric be used in tandem with other measures.

The peaks in running intensity increased as the length of the moving average decreased in our study, and were substantially higher compared to previous research where pre-defined blocks were analysed (Barrett et al., 2015; Bradley & Noakes, 2013; Mohr et al., 2005). In addition, using the power law (Katz & Katz, 1994) this study was able to establish the relationship between running intensity and moving average duration for each metric. By applying the theory of the power law often applied in sports such as running, cycling and swimming (Katz & Katz, 1994), we have provided coaches and practitioners with a method for estimating peak "match intensity" for any given duration. It is conceded that a number of external factors such as match status, location and opposition strength might influence the running intensity achieved during team-sports competition (Kempton & Coutts, 2015; Paul et al., 2015), a phenomenon that is less prevalent in individual sports. However, the almost perfect relationship between log-transformed running intensity and log-transformed time would indicate little unexplained variance in the model, and therefore it can be suggested that this method is appropriate for estimating the peak demands of high-level soccer.

This study has presented a strong framework for the prescription and monitoring of specific training methodologies. Recent rule changes (*Amendments to the Laws of the Game – 2015/2016*) have permitted the use of GPS technology during matches, allowing teams to directly compare match and training data accurately. By retrospectively analysing competitive matches, a series of simple calculations have been proposed which allow training drills to be assessed relative to the peak running intensities achieved during competition. For example, when prescribing a 5-minute training drill aimed at replicating the demands of competition, using the values given in Table 9.1, match intensity (i.e. relative distance) for a CD could be calculated as a function of time, as:

$$i = 173t^{-0.17}$$

This results in an estimated match intensity of 132 m·min^{-1} for the 5-minute drill, which can then be compared to the individual player's output during training. Importantly, these intensities reflect only the running component of the match or training drill, and are not inclusive of such non-locomotor activity as kicking and jumping, which must be considered when evaluating an athlete's running output. Commonly, coaches are faced with the challenge of providing an environment where physical, technical and psychological and competitive skills can be developed concurrently (Charlesworth, 1994). The techniques presented in the current study allow the intensity of training drills to be assessed over time, which permits coaches to tactically prescribe and periodise sport-specific drills more precisely, relative to the peak match intensity athletes are required to reach during competition, whilst concurrently integrating the necessary skill components into training. Furthermore, if a player is unable to maintain the required running intensity of competition during soccer-specific training drills, they may benefit from the inclusion of traditional running drills to develop their running capacities (Helgerud, Engen, Wisloff, & Hoff, 2001) before they are able to perform in a competitive setting. Whilst it is important to expose athletes to the peak running intensities of competition, it is vitally important that this is done so safely, as part of an appropriately periodised preparation program.

PRACTICAL APPLICATIONS

- Using power law, the peak running demands of professional soccer competition can now be predicted as a function of time.
- A series of simple equations have been presented which can be built into a team's monitoring system, for accurate comparisons between training and the most demanding periods of play.
- Positional differences exist in terms of the peak running capacities achieved, outlining the need to individualise training relative to the match demands.
- The rate of decline in running intensity is much more alike across positions, indicating all positions' running intensity declines at similar rates during match-play.
- Future research investigating peaks in intensity should incorporate both internal and external load metrics, to account for both running and non-locomotor activities concurrently.

Chapter 10

Summary and Conclusions

OVERVIEW

This thesis has presented five studies that have extended the current knowledge of the peak activity profiles of football competition. Initially, a study was conducted to describe the peak running intensities of rugby league competition, using a novel moving average technique (Chapter 3). Next, an assessment of the influence of a range of contextual and environmental factors on the running intensity achieved by interchange rugby league players was performed (Chapter 4). Due to the importance of acceleration in team sports, the reliability and usefulness of a range of acceleration-based measures were assessed (Chapter 5). The purpose of this was to determine the most appropriate measures to describe the peak acceleration-based intensities that occur during professional football competition. The moving average technique outlined in Chapter 3 was the utilised to describe the peak speed and acceleration-based running intensities of professional rugby league competition (Chapter 6). This led to the investigation into the peak running demands of both Australian football and international rugby, in Chapters 7 and 8, respectively. Similarly, this moving average approach was used to assess the peak running intensities of professional soccer within Chapter 9. Using a novel application of power law theorem, the relationship between the peak running intensity achieved and the duration of the moving average applied was also assessed. In the final section of this thesis, the important findings of the present studies are highlighted, and limitations of the current work are discussed. Furthermore, these outcomes are contextualised with reference to previous related work, and implications for future research are outlined.

RESEARCH PROGRESSION

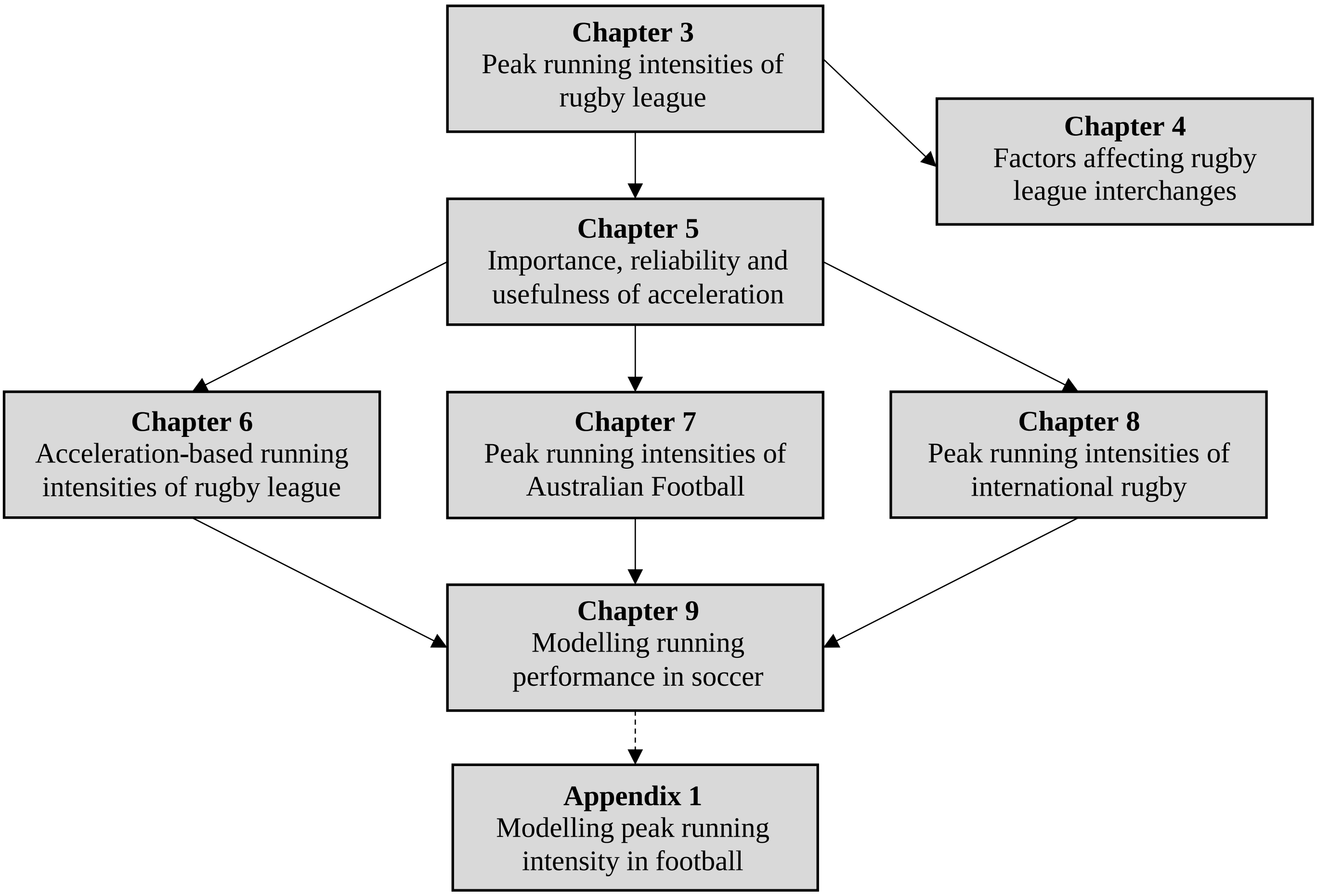

Figure 10.1: Outline of the research progress linking the major studies of this thesis.

SUMMARY

Peak Running Intensity of Rugby League

Commonly, the peak running intensities of team sports have been quantified using discrete periods lasting five to 15 minutes. However, these periods are not likely to detect the true peaks in intensity, as the most demanding periods may not fall completely within the pre-defined block, and therefore a moving average is more appropriate (Varley, Elias, et al., 2012). Whilst this approach has been utilised in team sports elsewhere (Black et al., 2015; Furlan et al., 2015; Garvican et al., 2014; Kempton, Sirotic, & Coutts, 2015), the present research is the first to use a duration-specific framework to identify peaks in intensity for different moving average durations. These methods outlined that other techniques for quantifying the peaks in intensity may have been underestimating the most demanding phases of play, which in turn may have led to an under-preparation of athletes. Using these data, coaches may now prescribe and monitor training drills relative to the true peaks in intensity that occur during professional rugby league competition, for a range of durations.

Factors Affecting Rugby League Interchange Players

During team sports, a complex relationship exists between the running intensity achieved by athletes, and contextual factors such as match importance or recovery cycle between matches (Kempton & Coutts, 2015; Paul et al., 2015). For interchange team-sport athletes, the duration of a bout confounds this interaction further, with week to week variations in time on the field a regular occurrence due to tactical changes, or as a result of an injury. Chapter 4 depicts how linear mixed models were utilised to demonstrate that individual fitness was the largest contributor to running intensity achieved during an on-field bout amongst interchange rugby league players. In addition, running intensity was increased when matches were played following a short recovery period, against strong opponents and involving more physical collisions, but decreased as a result of greater ball-out-of-play time and more time in possession. Based on these findings, interchange strategies may be more appropriately structured and manipulated to account for such environmental and situational variants each match.

Acceleration in Team Sports

Given the prevalence of GPS technology amongst football clubs worldwide, coaches and practitioners have been inundated with a surplus of training monitoring variables and methods, intended to give them a competitive advantage over competing clubs. When used appropriately, GPS allow the accurate monitoring of training demands relative to those exhibited during match play. During team-sport competition, the need for well-developed acceleration capacity is paramount (Varley & Aughey, 2013), as this is vital for pivotal moments of a match such as competing for the ball with an opposition player, or creating or stopping point scoring opportunities (Reilly et al., 2000). Furthermore, regular collisions may impair an athlete's ability to cover large relative distances, due to the presence of opposition players (Waldron, Twist, et al., 2011), are therefore it is important to account for the acceleration-based demands of team-sports activity (Osgnach et al., 2010; Varley & Aughey, 2013). As demonstrated in Chapter 5, that the most demanding periods of competition for acceleration/deceleration and relative distance occur separately from each other, suggesting that they are somewhat independent qualities.

Due to the previously reported poor inter-unit reliability of GPS for measuring acceleration (Buchheit, Al Haddad, et al., 2014), it was an aim of this study to determine a more appropriate method of comparing the acceleration-based running outputs of different players or positions, within the same session or match. This study proposed that averaging acceleration/deceleration data over the duration of a drill or period is a more suitable technique for assessing these demands during team sports, due to an increased inter-unit reliability compared to threshold-based methods. This increased stability came at no cost to the usefulness of the metrics, with similar if not stronger associations with perceived muscle soreness. In addition, these variables were also able to differentiate between the positional demands of competition, and therefore these measures can be recommended for the assessment of the acceleration-based demands of team-sports competition.

Peak Running Intensities of Football

Using the moving average technique proposed in Chapter 3, the acceleration-based running intensities of team-sport competition were described (alongside other commonly used metrics), based on the most appropriate measures established in Chapter 5. Whilst these methods were useful for differentiating positions in the rugby and soccer codes, they added little additional benefit for quantifying the demands of AF (Chapter 8). Alternatively, relative distances at high-speed were shown to differentiate performances more effectively, possibly due to the extensive speed-based running demands during AF match play (Coutts et al., 2015; Coutts et al., 2010). Nonetheless, Chapters 6 to 9 provide coaches and practitioners with a useful tool for monitoring the position- and duration-specific movements demands of training, relative to the peak demands of competition.

Modelling Running Intensity using Power Law

In a practical setting, training drills often deviate from the prescribed duration to allow for coaching interactions to occur, or to achieve a specific skill-based objective. As a result, it is often difficult to assess the intensity of these drills relative to the demands of match play, as peak intensity values throughout literature are reported for rigid timeframes (e.g. 5 or 10 minutes). Power law has been proposed as a method to assess the relationship between two quantities, where one is proportional to a fixed power of the other (Katz & Katz, 1999; Katz & Katz, 1994; Zinoubi, Vandewalle, & Driss, 2016). Whilst this method has been applied to other sports such as running, cycling and swimming (Katz & Katz, 1994), this technique is uncommon to team-sport movement analyses. Using such an approach, the power law theorem was utilised within Chapter 9 to describe the non-linear decrease in peak running intensity for longer moving average durations during profession soccer competition. It was shown that the central defender position exhibited lower relative distance and P_{met} compared to all other positions (ES = 0.79-1.84). Acceleration demands were substantially higher for the wide defender group compared to all other positions (ES = 0.67-1.42), as indicated by a greater intercept value. The intercept represents the theoretical peak running intensity that would occur as time approaches zero, whilst the slope value represents the rate of decline in running intensity and time moves further away from zero. Interestingly, only small, inconsistent differences were observed between positional groups, suggesting that decreases in peak running intensity may be governed by the nature of the game as a whole, rather than fatigue on an individual basis.

Using power law analysis, a series of simple calculations have been attained, where training intensity for a given variable can be matched to peak game intensity, for any given duration (Chapter 9). An example of such a framework is given in Table 11.1 (Appendix 1), where peak running intensity can be estimated, by position and duration, for each of the football codes, using the following equation:

$$i = ct^{n}$$

Where *n* and *c* are constants, and represent the intercept and slope, respectively. For example, for an AF midfielder, match intensity (m·min^{-1}) can be predicted as:

$$i = 211t^{-0.18}$$

For a drill lasting four minutes, this results in an estimated value of ~164 m·min^{-1}, and therefore training intensity can easily be reported as a percentage of match intensity. These simple calculations can be incorporated into a team's databases and monitoring system, to provide coaches with real comparisons to the most demanding periods that athlete may be exposed to during competition.

LIMITATIONS

A limitation of the current research lies in the inconsistency between studies in the monitoring system used. Until recently, soccer clubs were not permitted to wear GPS units during matches, and therefore all previous movement data were recorded using some form of video tracking software, making comparisons between training and match data difficult (Randers et al., 2010). Furthermore, coaches and practitioners must be aware of the limitations in comparing running outputs between GPS manufacturers. These limitations are particularly evident for acceleration-based variables, with large discrepancies observed between units both between and within manufacturers when assessing the number of acceleration or deceleration efforts (Chapter 5).

Whilst the studies reviewed provide coaches and practitioners with useful information regarding the running intensities achieved during competition, no attempt was made to control for the contribution of collisions within these analyses. During small-sided games (SSG), collisions have been shown to decrease total running load, but increase the number of high-intensity efforts, compared to non-contact games (Gabbett, Jenkins, & Abernethy, 2012a). Amongst rugby league players, running intensity has been shown to be negatively affected by contact involvement (Kempton & Coutts, 2015), whilst interchanged rugby league players' running intensity is positively influenced (Chapter 4), which may be due to the high-intensity running effort that precedes these events (Austin et al., 2011d). Whilst no difference has been reported in either attacking or defensive involvements during the peak 5-minute period of running (Kempton, Sirotic, & Coutts, 2015), this finding might be confounded by the inclusion of all positions. Therefore, it can be seen that a complex relationship exists between the collision demands and running intensity during match-play, and therefore this area may be an area for future investigation.

CONCLUSIONS AND RECOMMENDATIONS

Given the prevalence of GPS technology amongst football clubs worldwide, coaches and practitioners have been inundated with a surplus of training monitoring variables and methods, intended to give them a competitive advantage over competing clubs. When used appropriately, GPS allow the accurate monitoring of training demands relative to those exhibited during match play. Transient changes in the running intensity of competition are evident, and are attributed to a number of factors such as fatigue or pacing. It is clear that team-sports athletes possess the ability to self-regulate physical output to recover from bouts of high-intensity activity. Whilst knowledge of the time course of recovery from the most demanding period of play is useful, it is essential that the magnitude of this peak is accurately quantified. Throughout the integration of GPS technology within a sports science program, training prescription and monitoring can now accurately reflect the true demands of competition. Provided these systems are utilised appropriately, coaches and practitioners are now presented with a method that allows training programs to be accurately periodised, exposing athletes to the peak running demands of competition safely. As a result, athletes may become more resilient to the rigors of competition, and when they are faced with such situations during competition, these events will be less “catastrophic”.

In a team-sport setting, coaches are faced with the challenge of providing an environment in which technical, competitive and physical traits can be nurtured optimally (Charlesworth, 1994). As a result, SSG present as an ideal training methodology where athletes are stimulated to perform in a game-specific environment, whilst concurrently developing both physiological and technical abilities (Hill-Haas et al., 2011). These games are commonly used within team sports, however coaches have typically been restricted to prescribing and monitoring these drills relative to whole-match intensities, resulting in a substantial under preparation of their athletes. However, modern match analysis techniques now allow not only the monitoring of training drills relative to peak match demands, but the prescription of the physical loads expected as a result of these methods. These data provide coaches with confidence in incorporating SSG into a periodised program, with the knowledge of how demanding a specific drill is, relative to the most demanding periods of play.

Whilst SSG are a time-efficient method of combining physical and tactical training effectively, the appropriate periodisation of these drills is paramount. Although the monitoring of SSG relative to peak match intensity provides context to the intensity of the drill, and allows athletes to be exposed to the peak demands of competition, these intensities cannot be replicated on every occasion. As such, they must form only part of an overall preparation program, alongside traditional running drills that are aimed to develop athletes' running efficiency and economy. Nonetheless, athletes must be prepared for regular exposure to such intensities, as matches are played on short turnarounds, sometimes as short as just a few days. Furthermore, for athletes that are unable to compete effective during SSG training, the prescription of traditional methods in isolation may be necessary to increase the physical capacities of that athlete, before they will benefit from inclusion in game-based conditioning methods.

DIRECTIONS FOR FUTURE RESEARCH

The outcomes of the present series of studies suggest that areas for further investigation include:

1. Quantifying the intra-unit reliability of acceleration-based variables for within-individual tracking of changes in physical output over time.

2. Examine the possible mechanism(s) that allow athletes to generate high running intensities throughout match play, whether it be certain physical capacities, or if technical and tactical abilities are more important.
3. Determine the efficacy of specific SSG for replicating the demands of competition.
4. Establish an appropriate method for account for collisions when determining the peak demands of football competition.

Chapter 11 - Appendix 1

Modelling peak running intensity in football

Delaney, J. A., Thornton, H. R., & Duthie, G. M. Modelling peak running intensity in football. Poster presentation at the Australian Strength and Conditioning Association Conference, Melbourne, 2016.

INTRODUCTION

Team sports exhibit a chaotic running profile, with fluctuations in intensity due to fatigue, pacing, and match situation. Quantification of the peak running intensities of competition using a moving average allows coaches to prescribe training drills relative to the most demanding phases of play. Further, modelling the relationship between peak running intensity and moving average duration using power law analysis quantifies the non-linear relationship between these factors, and may provide insight into the decline in running intensity with increases in moving average duration.

METHODS

Global positioning systems (GPS) were used to monitor the running demands of elite-level competition for the four primary football codes (rugby league, rugby union, Australian football and soccer). Relative distance was calculated as the distance covered per unit of time ($m \cdot min^{-1}$). All acceleration and deceleration efforts were made to be positive, representative of the overall acceleration/deceleration requirements of the activity (Ave Acc/Dec; $m \cdot s^{-2}$). A moving average was used to determine the peak running intensities for a range of durations (1 to 10 minutes). The relationship between moving average duration and running intensity achieved was modeled using power law analysis to reveal values for the intercept (c) and slope (n) for each match file. Values were compared between positions using a magnitude-based inference network.

RESULTS

Mean intercept (c) and slope (n) values for each outcome measure can be found in Table 11.1. Substantial differences were observed between positions within each sport. Using these values, peak match running intensity for any value of time (t, time in minutes) can be estimated using the formula:

$$i = ct^n$$

DISCUSSION

During team-sport competition, athletes are exposed to bouts of high intensity running at critical periods of the match that are often associated with point scoring or possession winning opportunities. Ideally, athletes should be exposed to these peak running intensities of competition during training. Such exposure increases athletes' resilience to the high physiological stress imposed during the peak running intensities of competition, while also developing the ability to execute technical skills specific to the match requirements. If players are adequately prepared for the most demanding periods of play during training, when faced with these efforts within competition, they will be less "catastrophic" to the athlete. This study quantified the peak demands of the four football codes, across a range of moving average durations. Furthermore, a power law analysis was applied, where a simple calculation for estimating the peak running intensities (velocity- or acceleration-based) of competition was proposed.

PRACTICAL APPLICATIONS

By quantifying the relationship between peak running intensity and moving average duration, the values presented in this study can be built into training monitoring databases, to give context to the intensity of sport specific training drills such as small sided games. These calculations are applicable in tactical periodisation models that use sports specific training drills in the development of athletes' physical, technical and tactical capabilities. In addition to the regular monitoring of training, this new method provides coaches with a viable process for prescribing training intensity and volume. Overall, this study has presented a strong sport and position-specific framework for the prescription and monitoring of football training.

Table 11.1: Positional differences in modelled peak running intensity amongst team-sport athletes (mean ± SD).

Football Code	Position	n	Relative Distance (m·min^{-1})		Average Acc/Dec (m·s^{-2})	
			Intercept	Slope	Intercept	Slope
AFL	1. Midfielders	235	211 ± 21$^{\text{def}}$	-0.18 ± 0.05	1.02 ± 0.18$^{\text{d}}$	-0.16 ± 0.06
	2. Mobile Backs	128	207 ± 21$^{\text{de}}$	-0.18 ± 0.04	1.05 ± 0.24$^{\text{df}}$	-0.16 ± 0.06
	3. Mobile Forwards	94	217 ± 30$^{\text{bdef}}$	-0.19 ± 0.05	1.02 ± 0.23$^{\text{d}}$	-0.16 ± 0.05
	4. Rucks	37	200 ± 14	-0.16 ± 0.04$^{\text{abce}}$	0.93 ± 0.05	-0.12 ± 0.02$^{\text{abcef}}$
	5. Tall Backs	71	194 ± 17	-0.18 ± 0.04	1.00 ± 0.23$^{\text{d}}$	-0.15 ± 0.05
	6. Tall Forwards	58	204 ± 16$^{\text{e}}$	-0.17 ± 0.03$^{\text{abc}}$	0.98 ± 0.2	-0.15 ± 0.05
Rugby League	1. Edge Forwards	81	160 ± 11	-0.20 ± 0.03$^{\text{ef}}$	1.22 ± 0.10$^{\text{bef}}$	-0.20 ± 0.04$^{\text{ef}}$
	2. Fullbacks	39	173 ± 14$^{\text{acef}}$	-0.21 ± 0.03$^{\text{e}}$	1.16 ± 0.14	-0.20 ± 0.04$^{\text{e}}$
	3. Halves	81	165 ± 11$^{\text{aef}}$	-0.19 ± 0.04$^{\text{ef}}$	1.22 ± 0.13$^{\text{bef}}$	-0.19 ± 0.05$^{\text{ef}}$
	4. Hookers	58	169 ± 14$^{\text{acef}}$	-0.20 ± 0.04$^{\text{ef}}$	1.25 ± 0.14$^{\text{bef}}$	-0.20 ± 0.05$^{\text{ef}}$
	5. Middle Forwards	200	160 ± 13	-0.22 ± 0.04	1.18 ± 0.13	-0.22 ± 0.06
	6. Outside Backs	153	161 ± 12	-0.22 ± 0.04	1.16 ± 0.14	-0.22 ± 0.05
Rugby Union	1. Backs	186	169 ± 20$^{\text{d}}$	-0.29 ± 0.05	0.97 ± 0.14$^{\text{d}}$	-0.26 ± 0.05$^{\text{d}}$
	2. Halves	86	180 ± 27$^{\text{acd}}$	-0.30 ± 0.06	0.99 ± 0.18$^{\text{cd}}$	-0.26 ± 0.05
	3. Loose Forwards	102	164 ± 21$^{\text{d}}$	-0.28 ± 0.05$^{\text{b}}$	0.94 ± 0.15$^{\text{d}}$	-0.26 ± 0.07$^{\text{d}}$
	4. Tight 5	196	149 ± 21	-0.29 ± 0.05	0.84 ± 0.17	-0.28 ± 0.06
Soccer	1. Centre Midfielders	49	196 ± 12$^{\text{bf}}$	-0.17 ± 0.06	0.79 ± 0.05	-0.17 ± 0.03
	2. Central Defenders	78	173 ± 14	-0.17 ± 0.03	0.78 ± 0.06	-0.17 ± 0.03
	3. Strikers	33	193 ± 13$^{\text{bf}}$	-0.18 ± 0.03	0.78 ± 0.06	-0.18 ± 0.03
	4. Wide Defenders	83	194 ± 17$^{\text{bf}}$	-0.18 ± 0.04	0.86 ± 0.05$^{\text{abcef}}$	-0.17 ± 0.03$^{\text{f}}$
	5. Wide Midfielders	103	193 ± 14$^{\text{bf}}$	-0.16 ± 0.03$^{\text{df}}$	0.79 ± 0.06	-0.17 ± 0.03$^{\text{f}}$
	6. Winger	88	184 ± 15$^{\text{b}}$	-0.18 ± 0.04	0.82 ± 0.06$^{\text{abce}}$	-0.18 ± 0.03

$^{\text{a}}$ = greater than position 1; $^{\text{b}}$ = greater than position 2; $^{\text{c}}$ = greater than position 3; $^{\text{d}}$ = greater than position 4; $^{\text{e}}$ = greater than position 5; $^{\text{f}}$ = greater than position 6. Differences are considered real if >75% chance of being greater than the SWD, calculated as 0.2 × between subject SD.

Chapter 12 - Appendix 2

Validity of skinfold-based measures for tracking changes in body composition in professional rugby league players.

Delaney, J. A., Thornton, H. R., Scott, T. J., Ballard, D. A., Duthie, G. M., Wood, L. G., & Dascombe, B. J. (2016). Validity of skinfold-based measures for tracking changes in body composition in professional rugby league players. *Int J Sports Physiol Perform, 11*(2), 261-266.

ABSTRACT

High levels of lean mass are important for collision-based sports, for the development of strength and power, which may also assist during contact situations. Whilst skinfold-based measures have been shown to be appropriate for cross-sectional assessments of body composition, their utility in tracking changes in lean mass is less clear. ***Purpose:*** To determine the most effective method of quantifying changes in lean mass amongst rugby league athletes. ***Methods:*** Twenty-one professional rugby league players undertook body composition assessments on 2-3 occasions separated by ≥6 weeks, including bioelectrical impedance analysis (BIA), the lean mass index (LMI) and a skinfold-based prediction equation (SkF). Dual x-ray absorptiometry (DXA) provided a criterion measure of fat-free mass (FFM). Correlation coefficients (r) and standard errors of the estimate (SEE) were used as measures of validity for the estimates. ***Results:*** All three practical estimates exhibited strong validity for cross-sectional assessments of FFM (r >0.9). The correlation between change scores was stronger for the LMI (r = 0.69; SEE = 1.3 kg) and the SkF method (r = 0.66; SEE = 1.4 kg) compared to BIA (r = 0.50; SEE = 1.6 kg). ***Conclusions:*** The LMI is *probably* accurate in predicting changes in FFM as a skinfold-based prediction equation, and *very likely* to be more appropriate than the BIA method. The LMI offers an adequate, practical alternative for assessing in FFM amongst rugby league athletes.

INTRODUCTION

Collision-based team sports such as rugby league require a high body mass for the development of greater impact forces during contact situations (Gabbett, 2009). A high body mass may assist in the generation of absolute force and power, which is important for the pushing, pulling and wrestling associated with each tackle (Meir, Newton, Curtis, Fardell, & Butler, 2001). However, these collision-based sports are likely to benefit more from greater levels of lean, or fat-free mass (FFM), rather than a greater total body mass. Amongst such athletes, the monitoring of body fat levels is common, as excess body fat has been linked to poor aerobic capacities (Meir, Newton, et al., 2001), decreased power to body mass ratio (Gabbett, King, & Jenkins, 2008) and impaired thermoregulatory capabilities (Meir, Newton, et al., 2001). The routine assessment of body composition amongst individual and team-sport athletes provides valuable information for coaches and practitioners, due to the strong links with sports performance. For example, amongst youth rugby league players, Waldron et al. (2014) reported moderate to very large relationships between lean body mass and both vertical jump power (r = 0.55-0.75) and 20 m sprint time (r = -0.39 to -0.57), respectively. Similarly, Gabbett et al. (2011a) observed tackling ability to be negatively correlated to skinfold thickness (r = -0.59), confirming the importance of low fat mass amongst rugby league athletes.

In addition to the benefits associated with cross-sectional comparisons between body composition and performance, investigating this relationship longitudinally may assist in talent identification, or provide a more accurate indication of a player's development. Using a retrospective analysis, Till, Cobley, et al. (2015) identified that lower skinfold thickness partially contributed to career progression from junior to senior representative levels. Furthermore, Till, Jones, Darrall-Jones, Emmonds, and Cooke (2015) cautioned that cross-sectional anthropometric analyses may not account for a junior athlete's stage of maturation, and therefore repeat assessments may be more appropriate. Overall, it would seem beneficial to accurately monitor measures of body composition over time, due to these well-established links with short-term and long-term performance.

In a clinical setting, a range of techniques are used for the assessment of FFM and muscle mass, including metabolic (creatinine, 3-methylhistidine), nuclear (total body potassium, total body nitrogen) and radiographic imaging (computed tomography, magnetic resonance imaging and dual x-ray absorptiometry [DXA]) (Lukaski, 1996). Due to its practicality and speed of measurement, DXA is now commonly used to evaluate the body composition of athletes (Buehring et al., 2014). This method provides a 3-compartment (3C) measure of body composition (i.e. fat mass [FM], fat-free soft tissue mass [FFSTM] and bone mineral content [BMC]), which is of particular interest to sport and exercise scientists. Recently, Bilsborough et al. (2014) questioned the validity of this method for quantifying FM, though it was shown to be an exceptionally valid tool for measuring both FFSTM (r = 1.00; 90% confidence intervals [90% CI] 1.00 to 1.00) and BMC (r = 0.99; 0.98 to 1.00). As such, DXA has been proposed as a practical criterion method for the assessment of FFSTM and BMC. However, these methods do incur a financial and logistical cost, and may therefore be unavailable in an amateur sports environment. Furthermore, the ethical and safety implications of such issues as exposure to radiation also prove difficult in a practical setting. As a result, alternative methods have been proposed for the assessment of body composition amongst team-sport athletes.

A more practical technique for the assessment of body composition may be bioelectrical impedance analysis (BIA). Briefly, this method calculates the FFM of participants using the known electrical resistance of body tissues. However, this method may be affected by the water content of cells, and therefore may not possess the reliability of other methods (Moon, 2013). Moreover, problems have emerged in the use of this method in groups who had undergone changes in body weight, composition, or fluid volume (Lukaski, 2013). This is major limitation when assessing team-sport athletes, as body composition has been shown to change significantly as a preparation program progresses (Morgan & Callister, 2011), and therefore other methods may be preferred.

Typically the assessment of body composition in a team-sport setting involves the use of anthropometric measures such as body mass and subcutaneous skinfold thicknesses (Gabbett, 2009; Slater, Duthie, Pyne, & Hopkins, 2006; Till et al., 2011). From these non-invasive measures, estimates of body density (BD), FM and FFM are calculated using regression equations (Stewart & Hannan, 2000; Withers, Craig, Bourdon, & Norton, 1987), based on a single cross-sectional relationship between anthropometric variables and hydrodensitometry (Cisar, Housh, Johnson, Thorland, & Hughes, 1989). However, the ability of such methods to detect changes in body composition remains unclear. To account for this, the lean mass index (LMI) has been proposed as a simple method for the tracking of within-subject proportional changes in body mass, adjusted for skinfold thickness (Slater et al., 2006). This method was originally developed for rugby union athletes using the following formula, where M is the athlete's body mass in kilograms, S is the Σ7 skinfold thickness, and x is an exponent (0.13 for forwards and 0.14 for backs).

$$\mathrm{LMI} = \frac{\mathrm{M}}{\mathrm{S}^{\mathrm{x}}}$$

(Slater et al., 2006)

However, this novel method is intended to provide an indication of changes in body mass not associated with changes in skinfold thickness. When compared to the criterion 4-C model (hydrodensitometry, deuterium dilution, and DXA), Slater et al. (2006) reported the LMI to almost perfectly estimate FFM before and after 10 weeks of pre-season training amongst rugby union players (pre-training $r = 0.96$; standard error of the estimate [SEE] = 2.2 kg; post-training $r = 0.97$; SEE = 2.0 kg). However, when the LMI was compared to the criterion method for tracking changes in FFM, a much weaker relationship was established ($r = 0.37$; SEE = 2.3 kg). Nonetheless, this method was comparable to several FFM prediction equations ($r = 0.26$-0.42), along with the conventional 2-compartment (2C) model of hydrodensity alone ($r = 0.31$). Taken together, the authors concluded that the LMI appears valid for monitoring moderate to large changes in the lean mass of rugby union athletes. However, the validity of this method is yet to be determined in other team sports, where athletes are of a more homogenous somatotype, such as rugby league. Therefore, the aim of this study was to determine the most effective method for quantifying FFM, and for assessing changes in FFM longitudinally.

METHODS

Design

A repeated-measures approach was used to establish the concurrent validity of several practical measures of FFM against DXA estimates. DXA technology has been shown to possess considerable validity and reliability for the assessment of FFM in team-sport athletes (Bilsborough et al., 2014). Athletes were tested on 2-3 separate occasions throughout the 2014 National Rugby League (NRL) season, with at least six weeks of training dividing each testing block. The testing blocks were spread across the pre-season phase (15, 7 and 2 weeks prior to the first competitive game), where the largest changes in body composition occur, due to higher training loads and a greater focus on dietary intake and nutrition (Gabbett, 2005; Morgan & Callister, 2011). Due to the importance of change scores for assessing the efficacy of a training or nutritional intervention, these practical measures were also validated against the criterion for changes in FFM.

Subjects

Twenty-one NRL players (11 forwards, ten backs) volunteered to participate in this study (26.8 ± 4.2 yr, 1.84 ± 0.06 m, 97.3 ± 8.8 kg). All athletes were in full-time training for the same NRL club at the time of testing, and therefore are considered of a professional standard. Ethics approval was granted by the institutional ethics committee, and all subjects provided written consent prior to testing. All body composition assessments were performed at the Hunter Medical Research Institute, Newcastle.

Methodology

On each testing occasion, subjects presented in a rested, fasted and hydrated state, as per the DXA best practice guidelines outlined by Nana et al. (2016). Each session was performed between 0500 and 0900 prior to the day's training, to ensure the day's activities did not influence the results. Urine specific gravity (USG) was assessed prior to testing to ensure adequate hydration status for each player (Digital Refractometer, Atago, Tokyo). Subjects were then required to complete a typical radiology questionnaire to rule out any possible delimiting factors.

Anthropometry

Body mass was measured to the nearest 0.1 kg, using calibrated electronic scales (Tanita, Kewdale, Australia). Skinfold thickness was measured at seven sites (∑7 SkF; biceps, triceps, subscapular, suprailliac, abdomen, thigh and calf) using calibrated Harpenden calipers (British Indicators LTD., St Albans, England) by a qualified anthropometrist (typical error of measurement [TEM] = 1.61%). All sites were taken on the right side of the body using the methods of Norton et al. (1996). Each thickness was taken twice and the mean of the two measures was used for analysis. If the two measures differed by greater than 5%, a third measure was taken, but only after all measures had been taken in duplicate. In such cases, the median of the triplicate measurements was used for subsequent analysis.

FFM Prediction Equation (SkF)

Anthropometric assessments were used to calculate estimates of BD, relative fat mass (%BF) and FFM, using the following formulae:

$$\mathrm{BD} = 1.0988 - 0.0004(x)$$

(Withers et al., 1987)

Where *x* is equal to ∑7 SkF in mm;

$$\%\mathrm{BF} = \left(\frac{495}{\mathrm{BD}}\right) - 450$$

(Siri, 1961)

Therefore;

$$\mathrm{FFM} = \mathrm{BM} - \left(\mathrm{BM} \times \frac{\%\mathrm{BF}}{100}\right) - 450$$

(Slater et al., 2006)

Where BM is equal to body mass, in kg.

Bioelectrical Impedance Analysis (BIA)

Subjects' body composition was estimated using a single-frequency BIA system (InBody Body Composition analyser, Miami, QLD, Australia). Measurements were conducted with subjects standing in minimal clothing (underwear only) on the metal platforms of the device, holding the grip sensors with arms extended, as per the manufacturer's instructions. Electrical impedance and body mass were simultaneously measured while the subject stood on the scale, and estimates of FFM mass were calculated using proprietary software.

Lean Mass Index

Using the formula developed by Slater et al. (2006), the LMI was calculated on each testing as:

$$\mathrm{LMI} = \frac{\mathrm{M}}{\mathrm{S}^{\mathrm{x}}}$$

(Slater et al., 2006)

Where M = body mass, S = sum of seven skinfold thicknesses and x = the LMI exponent. The research of Slater et al. (2006) proposed two separate exponents of 0.13 and 0.14 for rugby union forwards and backs, respectively. The current research has chosen to use the back's exponent, as this positional group shares the most similarities with the mesomorphic stature of rugby league players. Further, as rugby league backs and forwards do not share the same dissimilarities in body types as rugby union backs and forwards, only one exponent was used to reflect the homogeneity of the current cohort.

Dual x-ray absorptiometry (DXA) assessment

A whole body DXA scan (Lunar Prodigy, GE Healthcare, Madison, WI) was performed, with subjects required to lie horizontally on the scanning table in the supine position, whilst the scanning arm passed over the subject's body from head to toe. Athletes were positioned using custom-made foam aids for the hands and feet, to ensure consistent body placement (Nana, Slater, Hopkins, & Burke, 2012). For players that weighed <100 kg, a whole body scan took approximately six minutes, using standard mode. For larger players (>100 kg), the scan was set to thick mode, as recommended by the manufacturers to accommodate for the greater amount of body tissue, and each of these scans took approximately 11 minutes. If the subject was too wide for the scanning area, two scans were administered (one left side and one right side) and data from these two scans were collaborated. This technique has been shown to adequately accommodate broad subjects, with little difference previously reported between the sum of two halves and a single, whole body scan (Nana et al., 2012). The built-in software provided measures of FM, lean mass (LM) and bone mineral content (BMC) and these regions of interest were confirmed by the technician. Further, measures of LM and BMC were summed to provide an estimated of FFM for comparison with the 2C practical estimates.

Statistical Analyses

The methods used in the present study were intended to track proportional changes in FFM, controlling for fat mass. As such, all measures in the present study were log transformed prior to analysis. Pearson correlation coefficients (r; ±90% CL) were used to compare the straight-line for each of the raw practical estimates and the criterion method (DXA). For all correlations, coefficients were qualitatively ranked by magnitude, according to Hopkins (2006). Correlation coefficients were categorised as: <0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; 0.9-0.99, almost perfect; 1.0, perfect. Measures of centrality and spread are presented as mean ± between subject standard deviation (SD).

Due to the logistical difficulties with assessing professional rugby league players during the pre-season phase, in some cases it was not possible for players to present for all three testing occasions (i.e. T1: n = 16, T2: n = 19, T3: n = 19). Therefore, change scores were calculated for each of the practical measures and the DXA estimate between any two unique time points for each participant (i.e. T1-T2: n = 14, T2-T3: n = 14 and T1-T3: n = 14). No data points were filled, and missing values were excluded from analysis. For the change scores, Pearson's correlation coefficients were also calculated and the line of best fit was forced through the origin (n = 42). As a result, the slope of this line represented the scaling factor for predicting percent change in FFM using the practical estimate, and the standard error of the estimate was the prediction error.

To establish the most effective practical measure of FFM, differences between methods were analysed qualitatively, using a customised spreadsheet (Hopkins, 2000a). The probability of a true difference between methods was classified as: *almost certainly not*, <0.5%; *very unlikely*, 0.5-5%; *unlikely*, 5-25%; *possibly*, 25-75%; *likely*, 75-95%; *very likely*, 95-99.5%; and *almost certainly*, >99.5%. The within-day test reliability was calculated as the SEE, and presented both as an absolute and relative (%) measure. All statistical analyses were carried out in Microsoft Excel (Microsoft, Redmond, WA, USA).

RESULTS

Baseline anthropometric measures are presented in Table 12.1. For players who did not present for the first testing occasion, the anthropometric measures at T2 were considered baseline. Table 12.2 shows the relationship between each practical measure and the criterion, DXA FFM. *Almost perfect*, significant correlations were observed for each of the three practical measures (r >0.9). Both the LMI and SkF methods were *very likely* to be superior to the BIA estimate of FFM. The difference between the LMI and SkF methods was considered *trivial*.

Table 12.1: Baseline values for anthropometric and body composition measures for 21 professional rugby league players.

	Mean	SD	90% CI
Mass (kg)	97.3	8.8	93.6 to 101.0
Height (m)	1.84	0.06	1.82 to 1.86
Sum7 SkF (mm)	73.4	17.7	67.2 to 79.6
SkF FFM (kg)	84.0	7.4	81.4 to 86.6
BIA FFM (kg)	84.6	8.1	81.8 to 87.5
DXA FFM (kg)	81.4	8.0	78.6 to 84.2
LMI ($kg \cdot mm^{-0.14}$)	53.5	4.7	51.4 to 54.7

SD = standard deviation; 90% CI = 90% confidence intervals; kg = kilogram; m = metre; mm = millimetre; SkF = skinfolds; FFM = fat-free mass; BIA = bioelectrical impedance analysis; DXA = dual X-ray absorptiometry; LMI = lean mass index.

Magnitude of change between time points is shown in Table 12.3, for each measurement method. Relationships between changes in each of the practical estimates of FFM and the criterion can be seen in Figure 12.1. Each of the three practical measures showed a large, significant relationship with the DXA FFM estimate (r >0.5). The LMI was *very likely* to be a stronger predictor of FFM compared to the BIA analysis (97% likelihood), and *possibly* superior to the SkF method (63% likelihood). The SkF method was *likely* to predict FFM more accurately than the BIA method (94% likelihood). The SEE for the prediction of DXA FFM was 1.6%, 1.7% and 1.9% for the LMI, SkF method and the BIA, respectively. Both the SkF and LMI methods correctly identified the direction of change (i.e. increased or decreased) in 69% of cases. The BIA analysis was less accurate, correctly predicting 62% of cases.

Table 12.2: Cross-sectional relationship between criterion (DXA) fat-free mass and other practical estimates of fat-free mass (n = 54).

	Correlation (*r*)	**90% CI**	***p*-value**	**SEE (kg)**
LMI	0.97	0.95 to 0.98	<0.001	1.89
SkF	0.97	0.95 to 0.98	<0.001	1.87
BIA	0.93	0.89 to 0.95	<0.001	2.74

CI = confidence intervals; SEE = standard error of the estimate; LMI = lean mass index; SkF = skinfold method; BIA = bioelectrical impedance analysis.

Table 12.3: Magnitude of change in FFM between time points for each measurement method. Data are presented as % change (90% CI).

	T1-T2	**T1-T3**	**T2-T3**
LMI	2.2; 0.7 to 3.7	1.9; 0.6 to 3.1	0.2; -0.6 to 1
SkF	2.2; 0.7 to 3.7	1.9; 0.7 to 3	0.2; -0.5 to 0.9
BIA	0.6; -1.1 to 2.3	0.4; -1.1 to 2	-0.7; -2.4 to 0.9
DXA	2.2; 1.5 to 2.9	3.1; 1.9 to 4.3	0.2; -0.5 to 0.8

FFM = fat-free mass; CI = confidence intervals; LMI = lean mass index; SkF = skinfold method; BIA = bioelectrical impedance analysis; DXA = dual x-ray absorptiometry.

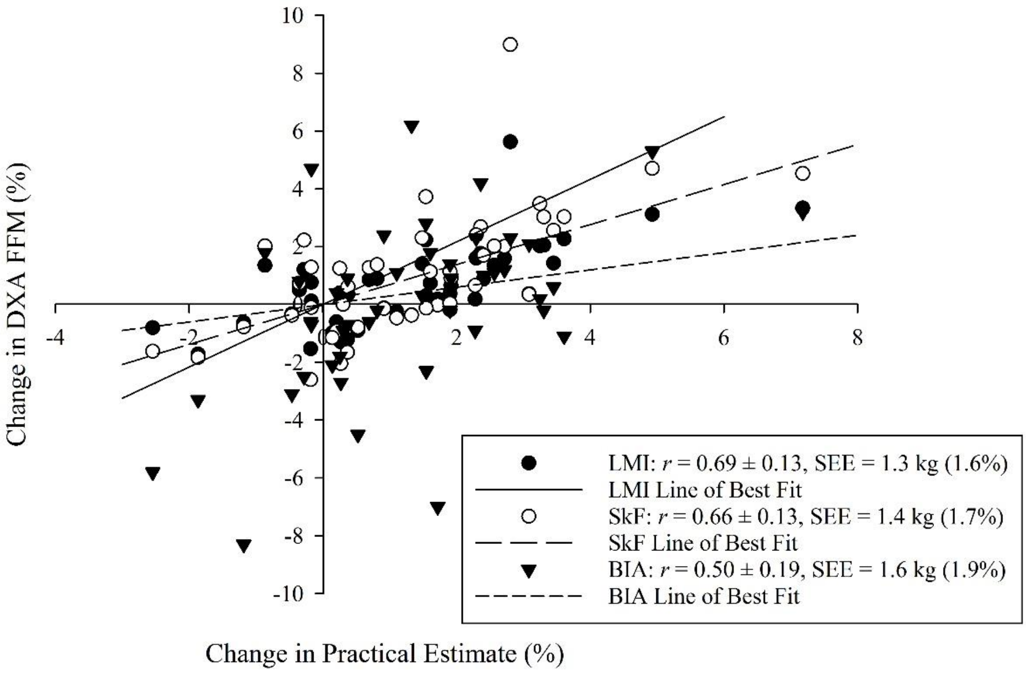

Figure 12.1: Relationship between changes in the criterion measure – dual X-ray absorptiometry fat-free mass (DXA FFM) and changes in each of the practical estimates. LMI = lean mass index; SkF = skinfold-based prediction equation; BIA = bioelectrical impedance analysis.

DISCUSSION

This study aimed to validate a range of practical measures of FFM, due to the established links between body composition and rugby league selection and performance (Gabbett, Jenkins, & Abernethy, 2011b; Gabbett et al., 2011c; Till et al., 2011). For this purpose, the present study compared a range of practical estimates of FFM with the chosen criterion method, DXA technology. Comparisons were made during the pre-season phase of the season, where changes in both FM and FFM were prioritised, to determine the most effective, practical method for quantifying changes in FFM amongst rugby league athletes. The primary finding of this study was that the LMI was *very likely* to be more useful than the BIA method, and *possibly* a better estimate of FFM changes than the SkF technique. Therefore, the LMI methods appears suitable for tracking proportional changes in lean mass amongst rugby league players.

Recently, Bilsborough et al. (2014) assessed the accuracy of a range of techniques for predicting %BF amongst Australian Football players. Using a soccer-specific prediction equation (Sutton, Scott, & Reilly, 2008), the authors reported only moderate correlations with DXA %BF (r = 0.32; 0.11 to 0.51). In comparison, the BIA method used by these authors yielded much stronger results (r = 0.66; 0.46 to 0.80). These findings conflict with those of the present study, where all three practical techniques exhibited considerable validity for the prediction of FFM at any given time point (r >0.9), and both skinfold-based measures were *very likely* to be more accurate than the BIA method. Bilsborough et al. (2014) reported questionable validity (r = 0.67; 0.39 to 0.84) and reliability (coefficient of variation, CV = 17.2%; 13.4 to 24.6) of DXA for quantifying fat mass when compared to a whole body phantom as the criterion. However, it must be noted that the phantom used in this study exhibited substantially low fat mass (0.63-1.41 kg), and the accuracy of densitometry has been suggested to be poor when considering such low ranges (Stewart & Hannan, 2000).

Despite these findings, numerous studies have identified the cross-sectional validity of anthropometric methods for describing the physique of athletes. For example, using a stepwise analysis, Stewart and Hannan (2000) reported that body mass and skinfold measurements taken from 7 sites accounted for 85% of DXA-derived fat mass (coefficient of determination [R^2] = 0.85, SEE = 1.7 kg). In addition, 96% of DXA FFM could be predicted by body mass and 4 skinfold sites (R^2 = 0.96, SEE = 1.7 kg). Our findings are in support of this notion, where both the SkF method and the LMI were able to account for 97% of the variance in DXA FFM. In addition, the BIA was almost as accurate in predicting FFM (R^2 = 0.93), suggesting either of the three methods tested are appropriate for the cross-sectional assessment of FFM in rugby league athletes.

Although this study gives support to the use of such techniques at a single time point, such information does not address the longitudinal tracking of FFM. The present study intended to identify the most appropriate measure for tracking changes in FFM over time. Previously, the validity of skinfold-based estimates of changes in FFM have been reported following an 8-week steroid-enhanced training block (van Marken Lichtenbelt, Hartgens, Vollaard, Ebbing, & Kuipers, 2004). Whilst a strong relationship was reported (r = 0.88), this large correlation is probably reflective of the large variation in body composition resulting from their intervention (~5%). More recently, Slater et al. (2006) reported a much smaller relationship between LMI and the criterion measure (r = 0.37). Whilst this might be interpreted as a decrease in accuracy between studies, it must be recognised that the mean change in FFM observed by Slater et al. (2006) was quite small (-0.2 ± 3.0 kg), which could have contributed to the weaker correlation. In the present study, the relationship between change in LMI and the criterion was strong (r = 0.69; 0.57 to 0.82). The average change in criterion FFM observed in the present study, 1.3 kg (0.9 to 1.8 kg) lies between the two aforementioned studies.

In addition, the present study calibrated each of the practical estimates against the criterion method, revealing an error of the estimate of <2%. As such, the findings of this study suggest that practical estimates of FFM may not be sensitive enough to detect subtle changes <2%, or in absolute terms, around 1.5 kg in this population. Taken together, these data indicate that the accuracy of the practical measures may decrease as the magnitude of change in FFM decreases, and therefore small changes in body composition may be missed due to error in measurement. Nevertheless, in a team-sport setting, changes of this magnitude would likely be considered insignificant to performance, and therefore this investigation provides evidence towards the use of practical measures for quantifying moderate to large, performance enhancing, changes in FFM.

Despite all three practical measures successfully predicting the direction of change in the criterion in >60% of cases, an aim of this study was to find the most appropriate method for quantifying changes in FFM in rugby league athletes. It was observed that the LMI was *possibly* (63% likelihood) and *very likely* (97% likelihood) to be a stronger predictive tool than the SkF and BIA methods, respectively. These findings are comparable to those of (Slater et al. (2006)) amongst rugby union players, where the LMI was found to track changes in FFM as well as several other skinfold-based methods, and predicted the direction of change more accurately than these methods. Taken together, these parallel findings give support to the use of the LMI for the longitudinal assessment of within-subject changes in FFM, controlled for skinfold thickness.

PRACTICAL APPLICATIONS

The accurate quantification of FFM in team-sport athletes can carry a substantial logistical and financial burden for practitioners. Despite the recent trend towards the use of DXA technology as a practical measure, due to the recommendation for athletes to present in a rested and fasted state, problems may arise when attempting to scan an entire team during periods where training volumes are high, such as the pre-season phase. Furthermore, the costs associated with performing these scans could prevent amateur teams and clubs from utilising such technology. The LMI presents as a fast, cost-free, practical method for quantifying FFM amongst team-sport athletes with considerable accuracy.

When considering changes in body composition, further issues arise with using DXA technology as a practical measure. Not only do the financial costs associated compound with every scan, but these methods expose athletes to low doses of radiation. Despite the relatively minute amount of exposure per scan, there remains a limitation in the number of scans allowed per time period to satisfy safety and ethical guidelines. Alternatively, the LMI incurs no financial cost or health risk, and therefore can be used in the routine monitoring of athletes safely. The findings of this study have demonstrated the ability of the LMI to not only quantify FFM accurately, but to track moderate to large changes in FFM longitudinally with confidence.

Chapter 13 - References

Akenhead, R., French, D., Thompson, K. G., & Hayes, P. R. (2014). The acceleration dependent validity and reliability of 10 Hz GPS. *J Sci Med Sport, 17*(5), 562-566. doi: 10.1016/j.jsams.2013.08.005

Akenhead, R., Harley, J., & Tweddle, S. (2016). Examining the external training load of an English Premier League football team with special reference to acceleration. *J Strength Cond Res, 30*(9), 2424-2432. doi: 10.1519/JSC.0000000000001343

Akenhead, R., & Nassis, G. P. (2016). Training load and player monitoring in high-level football: current practice and perceptions. *Int J Sports Physiol Perform, 11*(5), 587-593. doi: 10.1123/ijspp.2015-0331

Amendments to the Laws of the Game – 2015/2016. Zurich, Switzerland http://static-3eb8.kxcdn.com/documents/64/Circular_LoG_Amendments_2015_v1.0_EN.pdf.

Aughey, R. J. (2010). Australian football player work rate: evidence of fatigue and pacing? *Int J Sports Physiol Perform, 5*(3), 394-405

Aughey, R. J. (2011). Applications of GPS technologies to field sports. *Int J Sports Physiol Perform, 6*(3), 295-310

Austin, D., Gabbett, T., & Jenkins, D. (2011a). The physical demands of Super 14 rugby union. *J Sci Med Sport, 14*(3), 259-263. doi: 10.1016/j.jsams.2011.01.003

Austin, D., Gabbett, T., & Jenkins, D. (2011b). Repeated high-intensity exercise in professional rugby union. *J Sports Sci, 29*(10), 1105-1112. doi: 10.1080/02640414.2011.582508

Austin, D., Gabbett, T., & Jenkins, D. (2011c). Tackling in a professional rugby league. *J Strength Cond Res, 25*(6), 1659-1663. doi: 10.1519/JSC.0b013e3181da781c

Austin, D. J., Gabbett, T. J., & Jenkins, D. J. (2011d). Repeated high-intensity exercise in a professional rugby league. *J Strength Cond Res, 25*(7), 1898-1904. doi: 10.1519/JSC.0b013e3181e83a5b

Austin, D. J., & Kelly, S. J. (2013). Positional differences in professional rugby league match-play through the use of global positioning systems (GPS). *J Strength Cond Res, 27*(1), 14-19. doi: 10.1519/JSC.0b013e31824e108c

Austin, D. J., & Kelly, S. J. (2014). Professional rugby league positional match-play analysis through the use of global positioning system. *J Strength Cond Res, 28*(1), 187-193. doi: 10.1519/JSC.0b013e318295d324

Bangsbo, J., Krustrup, P., Gonzalez-Alonso, J., & Saltin, B. (2001). ATP production and efficiency of human skeletal muscle during intense exercise: effect of previous exercise. *Am J Physiol Endocrinol Metab, 280*(6), E956-964

Barbero-Alvarez, J. C., Coutts, A., Granda, J., Barbero-Alvarez, V., & Castagna, C. (2010). The validity and reliability of a global positioning satellite system device to assess speed and repeated sprint ability (RSA) in athletes. *J Sci Med Sport, 13*(2), 232-235. doi: 10.1016/j.jsams.2009.02.005

Barrett, S., Midgley, A., Reeves, M., Joel, T., Franklin, E., Heyworth, R., . . . Lovell, R. (2015). The within-match patterns of locomotor efficiency during professional soccer match play: Implications for injury risk? *J Sci Med Sport, 19*(10), 810-815. doi: 10.1016/j.jsams.2015.12.514

Bellenger, C. R., Fuller, J. T., Nelson, M. J., Hartland, M., Buckley, J. D., & Debenedictis, T. A. (2015). Predicting maximal aerobic speed through set distance time-trials. *Eur J Appl Physiol, 115*(12), 2593-2598. doi: 10.1007/s00421-015-3233-6

Bendiksen, M., Bischoff, R., Randers, M. B., Mohr, M., Rollo, I., Suetta, C., . . . Krustrup, P. (2012). The Copenhagen Soccer Test: physiological response and fatigue development. *Med Sci Sports Exerc, 44*(8), 1595-1603. doi: 10.1249/MSS.0b013e31824cc23b

Billaut, F., Bishop, D. J., Schaerz, S., & Noakes, T. D. (2011). Influence of knowledge of sprint number on pacing during repeated-sprint exercise. *Med Sci Sports Exerc, 43*(4), 665-672. doi: 10.1249/MSS.0b013e3181f6ee3b

Bilsborough, J. C., Greenway, K., Opar, D., Livingstone, S., Cordy, J., & Coutts, A. J. (2014). The accuracy and precision of DXA for assessing body composition in team sport athletes. *J Sports Sci, 32*(19), 1821-1828. doi: 10.1080/02640414.2014.926380

Black, G. M., & Gabbett, T. J. (2014). Match intensity and pacing strategies in rugby league: an examination of whole-game and interchanged players, and winning and losing teams. *J Strength Cond Res, 28*(6), 1507-1516. doi: 10.1519/JSC.0b013e3182a4a225

Black, G. M., Gabbett, T. J., Naughton, G. A., & McLean, B. D. (2015). The effect of intense exercise periods on physical and technical performance during elite Australian Football match-play: A comparison of experienced and less experienced players. *J Sci Med Sport, 19*(7), 596-602. doi: 10.1016/j.jsams.2015.07.007

Bradley, P. S., Di Mascio, M., Peart, D., Olsen, P., & Sheldon, B. (2010). High-intensity activity profiles of elite soccer players at different performance levels. *J Strength Cond Res, 24*(9), 2343-2351. doi: 10.1519/JSC.0b013e3181aeb1b3

Bradley, P. S., & Noakes, T. D. (2013). Match running performance fluctuations in elite soccer: indicative of fatigue, pacing or situational influences? *J Sports Sci, 31*(15), 1627-1638. doi: 10.1080/02640414.2013.796062

Brown, D. M., Dwyer, D. B., Robertson, S. J., & Gastin, P. B. (2016). Metabolic power method underestimates energy expenditure in field sport movements using a GPS tracking system. *Int J Sports Physiol Perform, 11*(8), 1067-1073. doi: 10.1123/ijspp.2016-0021

Buchheit, M. (2008). The 30-15 intermittent fitness test: accuracy for individualizing interval training of young intermittent sport players. *J Strength Cond Res, 22*(2), 365-374. doi: 10.1519/JSC.0b013e3181635b2e

Buchheit, M., Al Haddad, H., Simpson, B. M., Palazzi, D., Bourdon, P. C., Di Salvo, V., & Mendez-Villanueva, A. (2014). Monitoring accelerations with GPS in football: time to slow down? *Int J Sports Physiol Perform, 9*(3), 442-445. doi: 10.1123/ijspp.2013-0187

Buchheit, M., Manouvrier, C., Cassirame, J., & Morin, J. B. (2015). Monitioring locomotor load in soccer: is metabolic power, powerful? *Int J Sport Med, 36*(14), 1149-1155. doi: 10.1055/s-0035-1555927

Buchheit, M., Samozino, P., Glynn, J. A., Michael, B. S., Al Haddad, H., Mendez-Villanueva, A., & Morin, J. B. (2014). Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *J Sports Sci, 32*(20), 1906-1913. doi: 10.1080/02640414.2014.965191

Buehring, B., Krueger, D., Libber, J., Heiderscheit, B., Sanfilippo, J., Johnson, B., . . . Binkley, N. (2014). Dual-energy X-ray absorptiometry measured regional body composition least significant change: effect of region of interest and gender in athletes. *J Clin Densitom, 17*(1), 121-128. doi: 10.1016/j.jocd.2013.02.012

Buglione, A., & di Prampero, P. E. (2013). The energy cost of shuttle running. *Eur J Appl Physiol, 113*(6), 1535-1543. doi: 10.1007/s00421-012-2580-9

Cahill, N., Lamb, K., Worsfold, P., Headey, R., & Murray, S. (2013). The movement characteristics of English Premiership rugby union players. *J Sports Sci, 31*(3), 229-237. doi: 10.1080/02640414.2012.727456

Carling, C., Bradley, P., McCall, A., & Dupont, G. (2016). Match-to-match variability in high-speed running activity in a professional soccer team. *J Sports Sci, 34*(24), 2215-2223. doi: 10.1080/02640414.2016.1176228

Carling, C., & Dupont, G. (2011). Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? *J Sports Sci, 29*(1), 63-71. doi: 10.1080/02640414.2010.521945

Carling, C., Espie, V., Le Gall, F., Bloomfield, J., & Jullien, H. (2010). Work-rate of substitutes in elite soccer: a preliminary study. *J Sci Med Sport, 13*(2), 253-255. doi: 10.1016/j.jsams.2009.02.012

Casamichana, D., Castellano, J., & Castagna, C. (2012). Comparing the physical demands of friendly matches and small-sided games in semiprofessional soccer players. *J Strength Cond Res, 26*(3), 837-843. doi: 10.1519/JSC.0b013e31822a61cf

Castagna, C., Impellizzeri, F., Cecchini, E., Rampinini, E., & Alvarez, J. C. (2009). Effects of intermittent-endurance fitness on match performance in young male soccer players. *J Strength Cond Res, 23*(7), 1954-1959. doi: 10.1519/JSC.0b013e3181b7f743

Cavagna, G. A., Komarek, L., & Mazzoleni, S. (1971). The mechanics of sprint running. *J Physiol, 217*(3), 709-721

Charlesworth, R. (1994). Designer games. *Sports Coach, 17*(4), 30-33

Cisar, C. J., Housh, T. J., Johnson, G. O., Thorland, W. G., & Hughes, R. A. (1989). Validity of anthropometric equations for determination of changes in body composition in adult males during training. *J Sports Med Phys Fitness, 29*(2), 141-148

Coad, A., Gray, B., Wehbe, G., & McCellan, C. (2015). Physical demands and salivary immunoglobulin A responses of elite Australian rules football athletes to match play. *Int J Sports Physiol Perform, 10*(5), 613-617

Cometti, G., Maffiuletti, N. A., Pousson, M., Chatard, J. C., & Maffulli, N. (2001). Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *Int J Sports Med, 22*(1), 45-51. doi: 10.1055/s-2001-11331

Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *J Sci Med Sport, 13*(1), 133-135. doi: 10.1016/j.jsams.2008.09.015

Coutts, A. J., Kempton, T., Sullivan, C., Bilsborough, J., Cordy, J., & Rampinini, E. (2015). Metabolic power and energetic costs of professional Australian Football match-play. *J Sci Med Sport, 18*(2), 219-224. doi: 10.1016/j.jsams.2014.02.003

Coutts, A. J., Quinn, J., Hocking, J., Castagna, C., & Rampinini, E. (2010). Match running performance in elite Australian Rules Football. *J Sci Med Sport, 13*(5), 543-548. doi: 10.1016/j.jsams.2009.09.004

Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Med, 43*(10), 1025-1042. doi: 10.1007/s40279-013-0069-2

Cunniffe, B., Proctor, W., Baker, J. S., & Davies, B. (2009). An evaluation of the physiological demands of elite rugby union using Global Positioning System tracking software. *J Strength Cond Res, 23*(4), 1195-1203. doi: 10.1519/JSC.0b013e3181a3928b

Davies, M. J., Young, W., Farrow, D., & Bahnert, A. (2013). Comparison of agility demands of small-sided games in elite Australian football. *Int J Sports Physiol Perform, 8*(2), 139-147

de Koning, J. J., Foster, C., Bakkum, A., Kloppenburg, S., Thiel, C., Joseph, T., . . . Porcari, J. P. (2011). Regulation of pacing strategy during athletic competition. *PLoS One, 6*(1), e15863. doi: 10.1371/journal.pone.0015863

Delaney, J. A., Scott, T. J., Ballard, D. A., Duthie, G. M., Hickmans, J. A., Lockie, R. G., & Dascombe, B. J. (2015). Contributing factors to change-of-direction ability in professional rugby league players. *J Strength Cond Res, 29*(10), 2688-2296. doi: 10.1519/JSC.0000000000000960

di Prampero, P. E., Botter, A., & Osgnach, C. (2015). The energy cost of sprint running and the role of metabolic power in setting top performances. *Eur J Appl Physiol, 115*(3), 451-469. doi: 10.1007/s00421-014-3086-4

di Prampero, P. E., Fusi, S., Sepulcri, L., Morin, J. B., Belli, A., & Antonutto, G. (2005). Sprint running: a new energetic approach. *J Exp Biol, 208*(Pt 14), 2809-2816. doi: 10.1242/jeb.01700

Di Salvo, V., Gregson, W., Atkinson, G., Tordoff, P., & Drust, B. (2009). Analysis of high intensity activity in Premier League soccer. *Int J Sports Med, 30*(3), 205-212. doi: 10.1055/s-0028-1105950

Dorn, T. W., Schache, A. G., & Pandy, M. G. (2012). Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol, 215*(Pt 11), 1944-1956. doi: 10.1242/jeb.064527

Douge, B. (1988). Football: The common threads between the games. In T. Reilly, A. Lees, K. Davids & W. Murphy (Eds.), *Science and Football* (pp. 3-20). Liverpool: E. & F. N. Spon.

Duhig, S., Shield, A. J., Opar, D., Gabbett, T. J., Ferguson, C., & Williams, M. (2016). Effect of high-speed running on hamstring strain injury risk. *Br J Sports Med, 50*(24), 1536-1540. doi: 10.1136/bjsports-2015-095679

Duthie, G., Pyne, D., & Hooper, S. (2003). Applied physiology and game analysis of rugby union. *Sports Med, 33*(13), 973-991

Edwards, A. M., & Noakes, T. D. (2009). Dehydration: cause of fatigue or sign of pacing in elite soccer? *Sports Med, 39*(1), 1-13. doi: 10.2165/00007256-200939010-00001

Elferink-Gemser, M. T., Visscher, C., van Duijn, M. A., & Lemmink, K. A. (2006). Development of the interval endurance capacity in elite and sub-elite youth field hockey players. *Br J Sports Med, 40*(4), 340-345. doi: 10.1136/bjsm.2005.023044

Farrow, D., Pyne, D., & Gabbett, T. (2008). Skill and physiological dermands of open and closed training drills in Australian football. *Int J Sport Sci Coach, 3*(4), 489-499

Furlan, N., Waldron, M., Shorter, K., Gabbett, T. J., Mitchell, J., Fitzgerald, E., . . . Gray, A. J. (2015). Running intensity fluctuations in elite rugby sevens performance. *Int J Sports Physiol Perform, 10*(6), 802-807. doi: 10.1123/ijspp.2014-0315

Gabbett, T., Abernethy, B., & Jenkins, D. (2012). Influence of field size on the physiological and skill demands of small-sided games in junior and senior rugby league players. *J Strength Cond Res, 26*(2), 487-491

Gabbett, T., Jenkins, D., & Abernethy, B. (2012a). Influence of wrestling on the physiological and skill demands of small-sided games. *J Strength Cond Res, 26*(1), 113-120

Gabbett, T., King, T., & Jenkins, D. (2008). Applied physiology of rugby league. *Sports Med, 38*(2), 119-138

Gabbett, T. J. (2005). Changes in physiological and anthropometric characteristics of rugby league players during a competitive season. *J Strength Cond Res, 19*(2), 400-408. doi: 10.1519/14884.1

Gabbett, T. J. (2009). Physiological and anthropometric characteristics of starters and non-starters in junior rugby league players, aged 13-17 years. *J Sports Med Phys Fitness, 49*(3), 233-239

Gabbett, T. J. (2010). GPS analysis of elite women's field hockey training and competition. *J Strength Cond Res, 24*(5), 1321-1324. doi: 10.1519/JSC.0b013e3181ceebbb

Gabbett, T. J. (2013a). Influence of playing standard on the physical demands of professional rugby league. *J Sports Sci, 31*(10), 1125-1138. doi: 10.1080/02640414.2013.773401

Gabbett, T. J. (2013b). Influence of the opposing team on the physical demands of elite rugby league match play. *J Strength Cond Res, 27*(6), 1629-1635. doi: 10.1519/JSC.0b013e318274f30e

Gabbett, T. J. (2015a). Influence of ball-in-play time on the activity profiles of rugby league match-play. *J Strength Cond Res, 29*(3), 716-721. doi: 10.1519/JSC.0000000000000446

Gabbett, T. J. (2015b). Relationship between accelerometer load, collisions, and repeated high-intensity effort activity in rugby league players. *J Strength Cond Res, 29*(12), 3234-3241. doi: 10.1519/JSC.0000000000001017

Gabbett, T. J. (2015c). Use of relative speed zones Increases the high-speed running performed in team sport match play. *J Strength Cond Res, 29*(12), 3353-3359. doi: 10.1519/JSC.0000000000001016

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2010). Physiological and skill demands of 'on-side' and 'off-side' games. *J Strength Cond Res, 24*(11), 2979-2983. doi: 10.1519/JSC.0b013e3181e72731

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2011a). Correlates of tackling ability in high-performance rugby league players. *J Strength Cond Res, 25*(1), 72-79. doi: 10.1519/JSC.0b013e3181ff506f

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2011b). Relationships between physiological, anthropometric, and skill qualities and playing performance in professional rugby league players. *J Sports Sci*, *29*(15), 1655-1664. doi: 10.1080/02640414.2011.610346

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2011c). Relative importance of physiological, anthropometric, and skill qualities to team selection in professional rugby league. *J Sports Sci, 29*(13), 1453-1461. doi: 10.1080/02640414.2011.603348

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2012b). Physical demands of professional rugby league training and competition using microtechnology. *J Sci Med Sport, 15*(1), 80-86. doi: 10.1016/j.jsams.2011.07.004

Gabbett, T. J., & Mulvey, M. J. (2008). Time-motion analysis of small-sided training games and competition in elite women soccer players. *J Strength Cond Res*, *22*(2), 543-552. doi: 10.1519/JSC.0b013e3181635597

Gabbett, T. J., Polley, C., Dwyer, D. B., Kearney, S., & Corvo, A. (2014). Influence of field position and phase of play on the physical demands of match-play in professional rugby league forwards. *J Sci Med Sport, 17*(5), 556-561. doi: 10.1016/j.jsams.2013.08.002

Gabbett, T. J., Stein, J. G., Kemp, J. G., & Lorenzen, C. (2013). Relationship between tests of physical qualities and physical match performance in elite rugby league players. *J Strength Cond Res*, *27*(6), 1539-1545. doi: 10.1519/JSC.0b013e318274f236

Gabbett, T. J., & Ullah, S. (2012). Relationship between running loads and soft-tissue injury in elite team sport athletes. *J Strength Cond Res*, *26*(4), 953-960. doi: 10.1519/JSC.0b013e3182302023

Galton, F. (1886). Regression towards mediocrity in hereditary stature. *J Royal Anthr Inst, 15*, 246-263. doi: 10.2307/2841583

Gamble, P. (2004). A skill-based conditioning games approach to metabolic conditioning for elite rugby football players. *J Strength Cond Res, 18*(3), 491-497. doi: 10.1519/1533-4287(2004)18<491:ASCGAT>2.0.CO;2

Garvican, L. A., Hammond, K., Varley, M. C., Gore, C. J., Billaut, F., & Aughey, R. J. (2014). Lower running performance and exacerbated fatigue in soccer played at 1600 m. *Int J Sports Physiol Perform, 9*(3), 397-404. doi: 10.1123/ijspp.2012-0375

Gaudino, P., Alberti, G., & Iaia, F. M. (2014). Estimated metabolic and mechanical demands during different small-sided games in elite soccer players. *Hum Mov Sci, 36*, 123-133. doi: 10.1016/j.humov.2014.05.006

Gaudino, P., Iaia, F. M., Alberti, G., Strudwick, A. J., Atkinson, G., & Gregson, W. (2013). Monitoring training in elite soccer players: systematic bias between running speed and metabolic power data. *Int J Sports Med, 34*(11), 963-968. doi: 10.1055/s-0033-1337943

Glaister, M. (2005). Multiple sprint work : physiological responses, mechanisms of fatigue and the influence of aerobic fitness. *Sports Med, 35*(9), 757-777

Gray, A. J. (2011). *Energetic analysis of running demands in Australian Football using Global Positioning Systems technology.* (PhD), The University of Queensland.

Gray, A. J., Jenkins, D., Andrews, M. H., Taaffe, D. R., & Glover, M. L. (2010). Validity and reliability of GPS for measuring distance travelled in field-based team sports. *J Sports Sci, 28*(12), 1319-1325. doi: 10.1080/02640414.2010.504783

Gray, A. J., & Jenkins, D. G. (2010). Match analysis and the physiological demands of Australian football. *Sports Med, 40*(4), 347-360. doi: 10.2165/11531400-000000000-00000

Hader, K., Mendez-Villanueva, A., Palazzi, D., Ahmaidi, S., & Buchheit, M. (2016). Metabolic power requirement of change of direction speed in young soccer players: not all is what it seems. *PLoS One, 11*(3), e0149839. doi: 10.1371/journal.pone.0149839

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Med, 44 Suppl 2*, S139-147. doi: 10.1007/s40279-014-0253-z

Harris, N. K., Cronin, J. B., Hopkins, W. G., & Hansen, K. T. (2008). Relationship between sprint times and the strength/power outputs of a machine squat jump. *J Strength Cond Res, 22*(3), 691-698. doi: 10.1519/JSC.0b013e31816d8d80

Hausler, J., Halaki, M., & Orr, R. (2016). Application of global positioning system and microsensor technology in competitive rugby league match-play: A systematic review and meta-analysis. *Sports Med, 46*(4), 559-588. doi: 10.1007/s40279-015-0440-6

Helgerud, J., Engen, L. C., Wisloff, U., & Hoff, J. (2001). Aerobic endurance training improves soccer performance. *Med Sci Sports Exerc, 33*(11), 1925-1931. doi: 10.1080/07303084.2003.10608354

Higham, D. G., Pyne, D. B., Anson, J. M., Hopkins, W. G., & Eddy, A. (2016). Comparison of activity profiles and physiological demands between international rugby sevens matches and training. *J Strength Cond Res, 30*(5), 1287-1294. doi: 10.1097/JSC.0000000000000212

Highton, J., Mullen, T., Norris, J., Oxendale, C., & Twist, C. (2016). Energy expenditure derived from micro-technology is not suitable for assessing internal load in collision-based activities. *Int J Sports Physiol Perform*. doi: 10.1123/ijspp.2016-0069

Hill-Haas, S. V., Dawson, B., Impellizzeri, F. M., & Coutts, A. J. (2011). Physiology of small-sided games training in football: a systematic review. *Sports Med, 41*(3), 199-220. doi: 10.2165/11539740-000000000-00000

Hopkins, W. G. (2000a). *Analysis of validity by linear regression*. Retrieved from sportsci.org/resources/stats/xvalid.xls

Hopkins, W. G. (2000b). Measures of reliability in sports medicine and science. *Sports Med, 30*(1), 1-15

Hopkins, W. G. (2006). Spreadsheets for analysis of controlled trials with adjustment for a predictor. *Sportscience, 10*, 46-50

Hopkins, W. G. (2007). A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a p value. *Sportscience, 11*, 16-20

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc, 41*(1), 3-13. doi: 10.1249/MSS.0b013e31818cb278

Howatson, G., & Milak, A. (2009). Exercise-induced muscle damage following a bout of sport specific repeated sprints. *The Journal of Strength and Conditioning Research, 23*(8), 2419-2424

Hulin, B. T., Gabbett, T. J., Caputi, P., Lawson, D. W., & Sampson, J. A. (2016). Low chronic workload and the acute:chronic workload ratio are more predictive of injury than between-match recovery time: a two-season prospective cohort study in elite rugby league players. *Br J Sports Med, 50*(16), 1008-1012. doi: 10.1136/bjsports-2015-095364

Hulin, B. T., Gabbett, T. J., Lawson, D. W., Caputi, P., & Sampson, J. A. (2016). The acute:chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *Br J Sports Med, 50*(4), 231-236. doi: 10.1136/bjsports-2015-094817

Hunter, J. S. (1986). The exponentially weighted moving average. *J Quality Technol, 18*, 203-210

Impellizzeri, F. M., & Marcora, S. M. (2009). Test validation in sport physiology: lessons learned from clinimetrics. *Int J Sports Physiol Perform, 4*(2), 269-277

Impellizzeri, F. M., Rampinini, E., & Marcora, S. M. (2005). Physiological assessment of aerobic training in soccer. *J Sports Sci*, *23*(6), 583-592. doi: 10.1080/02640410400021278

Jennings, D., Cormack, S., Coutts, A. J., Boyd, L., & Aughey, R. J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *Int J Sports Physiol Perform, 5*(3), 328-341

Johnston, R. D., Gabbett, T. J., & Jenkins, D. G. (2014). Applied sport science of rugby league. *Sports Med, 44*(8), 1087-1100. doi: 10.1007/s40279-014-0190-x

Johnston, R. J., Watsford, M. L., Austin, D. J., Pine, M. J., & Spurrs, R. W. (2015). Movement demands and metabolic power comparisons between elite and subelite Australian footballers. *J Strength Cond Res, 29*(10), 2738-2744. doi: 10.1519/JSC.0000000000000936

Johnston, R. J., Watsford, M. L., Kelly, S. J., Pine, M. J., & Spurrs, R. W. (2014). Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *J Strength Cond Res, 28*(6), 1649-1655. doi: 10.1519/JSC.0000000000000323

Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., Murphy, A. J., & Pruyn, E. C. (2012). The validity and reliability of 5-Hz global positioning system units to measure team sport movement demands. *J Strength Cond Res, 26*(3), 758-765. doi: 10.1519/JSC.0b013e318225f161

Jones, M. R., West, D. J., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2015). Quantifying positional and temporal movement patterns in professional rugby union using global positioning system. *Eur J Sport Sci, 15*(6), 488-496. doi: 10.1080/17461391.2015.1010106

Katz, J. S., & Katz, L. (1999). Power laws and athletic performance. *J Sports Sci, 17*(6), 467-476. doi: 10.1080/026404199365777

Katz, L., & Katz, J. (1994). Fractal (power law) analysis of athletic performance. *Sports Med Training Rehab, 5*(2), 95-105. doi: 10.1080/15438629409512005

Kempton, T., & Coutts, A. J. (2015). Factors affecting exercise intensity in professional rugby league match-play. *J Sci Med Sport, 19*(6), 504-508. doi: 10.1016/j.jsams.2015.06.008

Kempton, T., Sirotic, A. C., Cameron, M., & Coutts, A. J. (2013). Match-related fatigue reduces physical and technical performance during elite rugby league match-play: a case study. *J Sports Sci, 31*(16), 1770-1780. doi: 10.1080/02640414.2013.803583

Kempton, T., Sirotic, A. C., & Coutts, A. J. (2014). Between match variation in professional rugby league competition. *J Sci Med Sport, 17*(4), 404-407. doi: 10.1016/j.jsams.2013.05.006

Kempton, T., Sirotic, A. C., & Coutts, A. J. (2015). An integrated analysis of match-related fatigue in professional rugby league. *J Sports Sci, 33*(1), 39-47. doi: 10.1080/02640414.2014.921832

Kempton, T., Sirotic, A. C., Rampinini, E., & Coutts, A. J. (2015). Metabolic power demands of rugby league match play. *Int J Sports Physiol Perform, 10*(1), 23-28. doi: 10.1123/ijspp.2013-0540

Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M., & Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc, 38*(6), 1165-1174. doi: 10.1249/01.mss.0000222845.89262.cd

Lacome, M., Piscione, J., Hager, J. P., & Bourdin, M. (2014). A new approach to quantifying physical demand in rugby union. *J Sports Sci, 32*(3), 290-300. doi: 10.1080/02640414.2013.823225

Lacome, M., Piscione, J., Hager, J. P., & Carling, C. (2016). Fluctuations in running and skill-related performance in elite rugby union match-play. *Eur J Sport Sci*, 1-12. doi: 10.1080/17461391.2016.1220986

Lago, C., & Martin, R. (2007). Determinants of possession of the ball in soccer. *J Sports Sci, 25*(9), 969-974. doi: 10.1080/02640410600944626

Larsson, P. (2003). Global positioning system and sport-specific testing. *Sports Med, 33*(15), 1093-1101

Lindsay, A., Draper, N., Lewis, J., Gieseg, S. P., & Gill, N. (2015). Positional demands of professional rugby. *Eur J Sport Sci, 15*(6), 480-487. doi: 10.1080/17461391.2015.1025858

Little, T., & Williams, A. G. (2005). Specificity of acceleration, maximum speed, and agility in professional soccer players. *J Strength Cond Res, 19*(1), 76-78. doi: 10.1519/14253.1

Lockie, R. G., Murphy, A. J., Knight, T. J., & Janse de Jonge, X. A. (2011). Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res, 25*(10), 2704-2714. doi: 10.1519/JSC.0b013e31820d9f17

Lockie, R. G., Murphy, A. J., Schultz, A. B., Knight, T. J., & Janse de Jonge, X. A. (2012). The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *J Strength Cond Res, 26*(6), 1539-1550. doi: 10.1519/JSC.0b013e318234e8a0

Lukaski, H. C. (1996). Estimation of muscle mass. In A. F. Roche, S. B. Heymsfield & T. G. Lohman (Eds.), *Human Body Composition* (pp. 109-128). Champaign, IL: Human Kinetics.

Lukaski, H. C. (2013). Evolution of bioimpedance: a circuitous journey from estimation of physiological function to assessment of body composition and a return to clinical research. *Eur J Clin Nutr, 67 Suppl 1*, S2-9. doi: 10.1038/ejcn.2012.149

MacLeod, H., Morris, J., Nevill, A., & Sunderland, C. (2009). The validity of a non-differential global positioning system for assessing player movement patterns in field hockey. *J Sports Sci, 27*(2), 121-128. doi: 10.1080/02640410802422181

McDermott, V. (2009). *Validity and Reliability. Encyclopedia of Communication Theory*. Thousand Oaks, CA: SAGE Publications, Inc.

McLean, B. D., Coutts, A. J., Kelly, V., McGuigan, M. R., & Cormack, S. J. (2010). Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *Int J Sports Physiol Perform*, *5*(3), 367-383

McLellan, C. P., & Lovell, D. I. (2012). Neuromuscular responses to impact and collision during elite rugby league match play. *J Strength Cond Res, 26*(5), 1431-1440. doi: 10.1519/JSC.0b013e318231a627

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). Performance analysis of elite Rugby League match play using global positioning systems. *J Strength Cond Res, 25*(6), 1703-1710. doi: 10.1519/JSC.0b013e3181ddf678

Meir, R., Colla, P., & Milligan, C. (2001). Impact of the 10-meter rule change on professional rugby league: Implications for training. *Strength Cond J, 23*, 42-46

Meir, R., Newton, R., Curtis, E., Fardell, M., & Butler, B. (2001). Physical fitness qualities of professional rugby league football players: determination of positional differences. *J Strength Cond Res, 15*(4), 450-458

Minetti, A. E., Gaudino, P., Seminati, E., & Cazzola, D. (2013). The cost of transport of human running is not affected, as in walking, by wide acceleration/deceleration cycles. *J Appl Physiol, 114*(4), 498-503. doi: 10.1152/japplphysiol.00959.2012

Minetti, A. E., Moia, C., Roi, G. S., Susta, D., & Ferretti, G. (2002). Energy cost of walking and running at extreme uphill and downhill slopes. *J Appl Physiol, 93*(3), 1039-1046. doi: 10.1152/japplphysiol.01177.2001

Mohr, M., Krustrup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci, 21*(7), 519-528. doi: 10.1080/0264041031000071182

Mohr, M., Krustrup, P., & Bangsbo, J. (2005). Fatigue in soccer: a brief review. *J Sports Sci, 23*(6), 593-599. doi: 10.1080/02640410400021286

Mohr, M., Krustrup, P., Nybo, L., Nielsen, J. J., & Bangsbo, J. (2004). Muscle temperature and sprint performance during soccer matches--beneficial effect of re-warm-up at half-time. *Scand J Med Sci Sports, 14*(3), 156-162. doi: 10.1111/j.1600-0838.2004.00349.x

Montgomery, P. G., & Wisbey, B. (2014). The effect of interchange rotation period and number on Australian Football running performance. *J Strength Cond Res, 30*(7), 1890-1897. doi: 10.1519/JSC.0000000000000594

Moon, J. R. (2013). Body composition in athletes and sports nutrition: an examination of the bioimpedance analysis technique. *Eur J Clin Nutr, 67 Suppl 1*, S54-59. doi: 10.1038/ejcn.2012.165

Mooney, M., Cormack, S., O'Brien, B., & Coutts, A. J. (2013). Do physical capacity and interchange rest periods influence match exercise-intensity profile in Australian football? *Int J Sports Physiol Perform, 8*(2), 165-172

Mooney, M., O'Brien, B., Cormack, S., Coutts, A., Berry, J., & Young, W. (2011). The relationship between physical capacity and match performance in elite Australian football: a mediation approach. *J Sci Med Sport, 14*(5), 447-452. doi: 10.1016/j.jsams.2011.03.010

Morgan, P. J., & Callister, R. (2011). Effects of a preseason intervention on anthropometric characteristics of semiprofessional rugby league players. *J Strength Cond Res, 25*(2), 432-440. doi: 10.1519/JSC.0b013e3181bf43eb

Murray, N. B., Gabbett, T. J., & Chamari, K. (2014). Effect of different between-match recovery times on the activity profiles and injury rates of national rugby league players. *J Strength Cond Res, 28*(12), 3476-3483. doi: 10.1519/JSC.0000000000000603

Nagahara, R., Botter, A., Rejc, E., Koido, M., Shimizu, T., Samozino, P., & Morin, J. B. (2016). Concurrent validity of GPS for deriving mechanical properties of sprint acceleration. *Int J Sports Physiol Perform*. doi: 10.1123/ijspp.2015-0566

Nana, A., Slater, G. J., Hopkins, W. G., & Burke, L. M. (2012). Techniques for undertaking dual-energy X-ray absorptiometry whole-body scans to estimate body composition in tall and/or broad subjects. *Int J Sport Nutr Exerc Metab, 22*(5), 313-322

Nana, A., Slater, G. J., Hopkins, W. G., Halson, S. L., Martin, D. T., West, N. P., & Burke, L. M. (2016). Importance of Standardized DXA Protocol for Assessing Physique Changes in Athletes. *Int J Sport Nutr Exerc Metab, 26*(3), 259-267. doi: 10.1123/ijsnem.2013-0111

Nedelec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2014). The influence of soccer playing actions on the recovery kinetics after a soccer match. *J Strength Cond Res, 28*(6), 1517-1523. doi: 10.1519/JSC.0000000000000293

Newham, D. J., Jones, D. A., & Edwards, R. H. (1983). Large delayed plasma creatine kinase changes after stepping exercise. *Muscle Nerve, 6*(5), 380-385. doi: 10.1002/mus.880060507

Norton, K., Whittingham, N., Carter, L., Kerr, D., Gore, C., & Marfell-Jones, M. (1996). Measurement techniques in anthropometry. In K. Norton & T. Olds (Eds.), *Anthropometrica* (pp. 25-85). Marrickville, NSW: Soutwood Press.

Nosaka, K., & Newton, M. (2002). Concentric or eccentric training effect on eccentric exercise-induced muscle damage. *Med Sci Sports Exerc, 34*(1), 63-69

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: a new match analysis approach. *Med Sci Sports Exerc, 42*(1), 170-178. doi: 10.1249/MSS.0b013e3181ae5cfd

Paul, D. J., Bradley, P. S., & Nassis, G. P. (2015). Factors affecting match running performance of elite soccer players: shedding some light on the complexity. *Int J Sports Physiol Perform, 10*(4), 516-519. doi: 10.1123/IJSPP.2015-0029

Petersen, C., Pyne, D., Portus, M., & Dawson, B. (2009). Validity and reliability of GPS units to monitor cricket-specific movement patterns. *Int J Sports Physiol Perform, 4*(3), 381-393

Portas, M. D., Harley, J. A., Barnes, C. A., & Rush, C. J. (2010). The validity and reliability of 1-Hz and 5-Hz global positioning systems for linear, multidirectional, and soccer-specific activities. *Int J Sports Physiol Perform, 5*(4), 448-458

Pyne, D. B., Mujika, I., & Reilly, T. (2009). Peaking for optimal performance: Research limitations and future directions. *J Sports Sci, 27*(3), 195-202. doi: 10.1080/02640410802509136

Quarrie, K. L., Hopkins, W. G., Anthony, M. J., & Gill, N. D. (2013). Positional demands of international rugby union: evaluation of player actions and movements. *J Sci Med Sport, 16*(4), 353-359. doi: 10.1016/j.jsams.2012.08.005

Rampinini, E., Alberti, G., Fiorenza, M., Riggio, M., Sassi, R., Borges, T. O., & Coutts, A. J. (2015). Accuracy of GPS devices for measuring high-intensity running in field-based team sports. *Int J Sports Med, 36*(1), 49-53. doi: 10.1055/s-0034-1385866

Rampinini, E., Coutts, A. J., Castagna, C., Sassi, R., & Impellizzeri, F. M. (2007). Variation in top level soccer match performance. *Int J Sports Med, 28*(12), 1018-1024. doi: 10.1055/s-2007-965158

Rampinini, E., Impellizzeri, F. M., Castagna, C., Coutts, A. J., & Wisloff, U. (2009). Technical performance during soccer matches of the Italian Serie A league: effect of fatigue and competitive level. *J Sci Med Sport, 12*(1), 227-233. doi: 10.1016/j.jsams.2007.10.002

Randers, M. B., Mujika, I., Hewitt, A., Santisteban, J., Bischoff, R., Solano, R., . . . Mohr, M. (2010). Application of four different football match analysis systems: a comparative study. *J Sports Sci, 28*(2), 171-182. doi: 10.1080/02640410903428525

Reilly, T. (1994). Physiological aspects of soccer. *Biol Sport, 11*, 3-20

Reilly, T., Bangsbo, J., & Franks, A. (2000). Anthropometric and physiological predispositions for elite soccer. *J Sports Sci, 18*(9), 669-683. doi: 10.1080/02640410050120050

Roberts, S. P., Trewartha, G., Higgitt, R. J., El-Abd, J., & Stokes, K. A. (2008). The physical demands of elite English rugby union. *J Sports Sci, 26*(8), 825-833

Roe, G., Darrall-Jones, J., Black, C., Shaw, W., Till, K., & Jones, B. (2016). Validity of 10 HZ GPS and timing gates for assessing maximum velocity in professional rugby union players. *Int J Sports Physiol Perform*, 1-14. doi: 10.1123/ijspp.2016-0256

Rosnow, R. L., Rosenthal, R., & Rubin, D. B. (2000). Contrasts and correlations in effect-size estimation. *Psychol Sci, 11*(6), 446-453

Schutz, Y., & Chambaz, A. (1997). Could a satellite-based navigation system (GPS) be used to assess the physical activity of individuals on earth? *Eur J Clin Nutr, 51*(5), 338-339

Scott, M. T., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: A brief review. *J Strength Cond Res, 30*(5), 1470-1490. doi: 10.1519/JSC.0000000000001221

Scott, T. J., Delaney, J. A., Duthie, G. M., Sanctuary, C. E., Ballard, D. A., Hickmans, J. A., & Dascombe, B. J. (2015). Reliability and usefulness of the 30-15 intermittent fitness test in rugby league. *J Strength Cond Res, 29*(7), 1985-1990. doi: 10.1519/JSC.0000000000000846

Silvestre, R., West, C., Maresh, C. M., & Kraemer, W. J. (2006). Body composition and physical performance in men's soccer: a study of a National Collegiate Athletic Association Division I team. *J Strength Cond Res, 20*(1), 177-183. doi: 10.1519/R-17715.1

Siri, W. E. (1961). Body volume measurement by gas dilution. In J. Brazek & A. Henschel (Eds.), *Techniques for measuring body composition* (pp. 108-117). Washington, D.C.: National Academy of Sciences.

Slater, G. J., Duthie, G. M., Pyne, D. B., & Hopkins, W. G. (2006). Validation of a skinfold based index for tracking proportional changes in lean mass. *Br J Sports Med, 40*(3), 208-213. doi: 10.1136/bjsm.2005.019794

Spencer, M., Lawrence, S., Rechichi, C., Bishop, D., Dawson, B., & Goodman, C. (2004). Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. *J Sports Sci, 22*(9), 843-850. doi: 10.1080/02640410410001716715

St Clair Gibson, A., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C., & Noakes, T. D. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Med, 36*(8), 705-722

Stevens, T. G., de Ruiter, C. J., van Maurik, D., van Lierop, C. J., Savelsbergh, G. J., & Beek, P. J. (2014). Measured and estimated energy cost of constant and shuttle running in soccer players. *Med Sci Sports Exerc, 47*(6), 1219-1224. doi: 10.1249/MSS.0000000000000515

Stewart, A. D., & Hannan, W. J. (2000). Prediction of fat and fat-free mass in male athletes using dual X-ray absorptiometry as the reference method. *J Sports Sci, 18*(4), 263-274. doi: 10.1080/026404100365009

Stolen, T., Chamari, K., Castagna, C., & Wisloff, U. (2005). Physiology of soccer: an update. *Sports Med, 35*(6), 501-536. doi: 10.2165/00007256-200535060-00004

Sutton, L., Scott, M., & Reilly, T. (2008). *Validation of a new anthropometric equation for the prediction of body composition in elite soccer players*. 1st World Conference on Science and Soccer, Liverpool.

Swaby, R., Jones, P. A., & Comfort, P. (2016). Relationship between maximum aerobic speed performance and distance covered in rugby union games. *J Strength Cond Res, 30*(10), 2788-2793. doi: 10.1519/JSC.0000000000001375

Sykes, D., Twist, C., Nicholas, C., & Lamb, K. (2011). Changes in locomotive rates during senior elite rugby league matches. *J Sports Sci, 29*(12), 1263-1271. doi: 10.1080/02640414.2011.582507

Taskin, H. (2008). Evaluating sprinting ability, density of acceleration, and speed dribbling ability of professional soccer players with respect to their positions. *J Strength Cond Res, 22*(5), 1481-1486. doi: 10.1519/JSC.0b013e318181fd90

Tee, J. C., Lambert, M. I., & Coopoo, Y. (2016). Impact of fatigue on positional movements during professional rugby union match play. *Int J Sports Physiol Perform*. doi: 10.1123/ijspp.2015-0695

Till, K., Cobley, S., O'Hara, J., Brightmore, A., Cooke, C., & Chapman, C. (2011). Using anthropometric and performance characteristics to predict selection in junior UK Rugby League players. *J Sci Med Sport, 14*(3), 264-269. doi: 10.1016/j.jsams.2011.01.006

Till, K., Cobley, S., O'Hara, J., Morley, D., Chapman, C., & Cooke, C. (2015). Retrospective analysis of anthropometric and fitness characteristics associated with long-term career progression in Rugby League. *J Sci Med Sport, 18*(3), 310-314. doi: 10.1016/j.jsams.2014.05.003

Till, K., Jones, B., Darrall-Jones, J., Emmonds, S., & Cooke, C. (2015). Longitudinal development of anthropometric and physical characteristics within academy rugby league players. *J Strength Cond Res, 29*(6), 1713-1722. doi: 10.1519/JSC.0000000000000792

Tomlin, D. L., & Wenger, H. A. (2001). The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Med, 31*(1), 1-11

Torreno, N., Munguia-Izquierdo, D., Coutts, A. J., Saez de Villarreal, E., Asian-Clemente, J., & Suarez-Arrones, L. (2016). Relationship between external and internal load of professional soccer players during full-matches in official games using GPS and heart rate technology. *Int J Sports Physiol Perform, 11*(7), 940-946. doi: 10.1123/ijspp.2015-0252

Tucker, R., & Noakes, T. D. (2009). The physiological regulation of pacing strategy during exercise: a critical review. *Br J Sports Med, 43*(6), e1. doi: 10.1136/bjsm.2009.057562

Twist, C., Highton, J., Waldron, M., Edwards, E., Austin, D., & Gabbett, T. J. (2014). Movement demands of elite rugby league players during Australian National Rugby League and European Super League matches. *Int J Sports Physiol Perform, 9*(6), 925-930. doi: 10.1123/ijspp.2013-0270

van Marken Lichtenbelt, W. D., Hartgens, F., Vollaard, N. B., Ebbing, S., & Kuipers, H. (2004). Body composition changes in bodybuilders: a method comparison. *Med Sci Sports Exerc, 36*(3), 490-497

Varley, M. C., & Aughey, R. J. (2013). Acceleration profiles in elite Australian soccer. *Int J Sports Med, 34*(1), 34-39. doi: 10.1055/s-0032-1316315

Varley, M. C., Elias, G. P., & Aughey, R. J. (2012). Current match-analysis techniques' underestimation of intense periods of high-velocity running. *Int J Sports Physiol Perform, 7*(1), 183-185

Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *J Sports Sci, 30*(2), 121-127. doi: 10.1080/02640414.2011.627941

Varley, M. C., Gabbett, T., & Aughey, R. J. (2014). Activity profiles of professional soccer, rugby league and Australian football match play. *J Sports Sci, 32*(20), 1858-1866. doi: 10.1080/02640414.2013.823227

Vaz, L. M. T., Gonçalves, B. S. V., Figueira, B. E. N., & Garcia, G. C. (2016). Influence of different small-sided games on physical and physiological demands in rugby union players. *Int J Sports Sci Coach, 11*(1), 78-84. doi: 10.1177/1747954115624823

Vescovi, J. D., & McGuigan, M. R. (2008). Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci, 26*(1), 97-107. doi: 10.1080/02640410701348644

Vickery, W. M., Dascombe, B. J., Baker, J. D., Higham, D. G., Spratford, W. A., & Duffield, R. (2014). Accuracy and reliability of GPS devices for measurement of sports-specific movement patterns related to cricket, tennis, and field-based team sports. *J Strength Cond Res, 28*(6), 1697-1705. doi: 10.1519/JSC.0000000000000285

Waldron, M., & Highton, J. (2014). Fatigue and pacing in high-intensity intermittent team sport: an update. *Sports Med, 44*(12), 1645-1658. doi: 10.1007/s40279-014-0230-6

Waldron, M., Highton, J., Daniels, M., & Twist, C. (2013). Preliminary evidence of transient fatigue and pacing during interchanges in rugby league. *Int J Sports Physiol Perform, 8*(2), 157-164

Waldron, M., Twist, C., Highton, J., Worsfold, P., & Daniels, M. (2011). Movement and physiological match demands of elite rugby league using portable global positioning systems. *J Sports Sci, 29*(11), 1223-1230. doi: 10.1080/02640414.2011.587445

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011). Concurrent validity and test-retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *J Sports Sci, 29*(15), 1613-1619. doi: 10.1080/02640414.2011.608703

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2014). Changes in anthropometry and performance, and their interrelationships, across three seasons in elite youth rugby league players. *J Strength Cond Res, 28*(11), 3128-3136. doi: 10.1519/JSC.0000000000000445

West, B. T., Welch, K. B., & Galecki, A. T. (2014). *Linear mixed models: a practical guide using statistical software* (Second Edition ed.): CRC Press.

Weston, M., Siegler, J., Bahnert, A., McBrien, J., & Lovell, R. (2015). The application of differential ratings of perceived exertion to Australian Football League matches. *J Sci Med Sport, 18*(6), 704-708. doi: 10.1016/j.jsams.2014.09.001

Wisbey, B., Montgomery, P. G., Pyne, D. B., & Rattray, B. (2010). Quantifying movement demands of AFL football using GPS tracking. *J Sci Med Sport, 13*(5), 531-536. doi: 10.1016/j.jsams.2009.09.002

Withers, R. T., Craig, N. P., Bourdon, P. C., & Norton, K. I. (1987). Relative body fat and anthropometric prediction of body density of male athletes. *Eur J Appl Physiol Occup Physiol, 56*(2), 191-200

Witte, T. H., & Wilson, A. M. (2004). Accuracy of non-differential GPS for the determination of speed over ground. *J Biomech, 37*(12), 1891-1898. doi: 10.1016/j.jbiomech.2004.02.031

Wong, P. L., Chaouachi, A., Chamari, K., Dellal, A., & Wisloff, U. (2010). Effect of preseason concurrent muscular strength and high-intensity interval training in professional soccer players. *J Strength Cond Res, 24*(3), 653-660. doi: 10.1519/JSC.0b013e3181aa36a2

Young, W. B., Hepner, J., & Robbins, D. W. (2012). Movement demands in Australian rules football as indicators of muscle damage. *J Strength Cond Res, 26*(2), 492-496. doi: 10.1519/JSC.0b013e318225a1c4

Zamparo, P., Zadro, I., Lazzer, S., Beato, M., & Sepulcri, L. (2014). Energetics of shuttle runs: the effects of distance and change of direction. *Int J Sports Physiol Perform, 9*(6), 1033-1039. doi: 10.1123/ijspp.2013-0258

Zinoubi, B., Vandewalle, H., & Driss, T. (2016). Modeling of running performances in human: comparison of power laws and critical speed. *J Strength Cond Res*. doi: 10.1519/JSC.0000000000001542