Quantification of physical contact and its influence on simulated performance and recovery in rugby players.

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Quantification of physical contact and its influence on simulated performance and recovery in rugby players.

Thesis submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy

By Jonathan Peter Norris

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Abstract

Norris, J.P. Evaluating the detection of physical contact using wearable microtechnology and the influence on internal and external load in rugby players during a rugby league match simulation.

The aim of this thesis was to investigate the influence of physical collisions on internal (physiological and perceptual) and external (locomotive and accelerometer) load during simulated rugby league performance and fatigue responses in the days after. Chapter 4 examined the influence of physical contact type on internal and external load using a traditional soft tackle bag and custom-built tackle sled. Using a traditional tackle bag to simulate physical collisions resulted in *likely* faster sprint to contact speed (16.1 ± 1.5 c.f. 14.8 ± 1.1 $km \cdot h^{-1}$) but *possibly* lower overall high-speed running distance (27.7 ± 2.4 c.f. 28.4 ± 2.6 $m \cdot min^{-1}$). Also, the heavier tackle sled *likely* increased time at 91-100% HR_{peak} (12:58 ± 13:21 c.f. 6:44 ± 8:06 min:s) and resulted in greater lower limb fatigue reflected by the *likely* larger decrease in counter-movement jump (CMJ) performance (5.9 ± 4.9 c.f. 2.6 ± 5.4%). Also of note was the variation in number of tackles detected using the automatic tackle detection feature compared to the actual number in the match simulation. During the Bag and Sled simulations ~53 and ~59 tackles were detected compared to 48 performed. The purpose of Chapter 5 was to investigate the influence of sprint to contact speed and contact type on automatic tackle detection using microtechnology. Repetitions were divided into three speed categories; walking, jogging and striding (1, 2.5 and 4 $m \cdot s^{-1}$) and four conditions: i) no contact standing upright (NC_{ST}), ii) no contact dropping to the ground in a prone position (NC_{GR}), iii) contact with the tackle bag and remaining upright (C_{ST}), iv) contact with the tackle bag and going to ground (C_{GR}). Similar tackle detection accuracy was observed between NC_{GR} and C_{ST} conditions with one tackle observed in 41 and 43% of trials, respectively. While C_{GR} resulted in the greatest frequency of correct tackle detection (62%), during 16% of trials two tackles were detected. During NC_{ST}, there were no tackles detected and 100% accuracy. The PlayerLoad^{TM} results demonstrated that the metric can detect differences in movement speed, the inclusion of physical contact and changes in orientation during short periods of activity (8-10 s). In Chapter 6 the rugby league movement simulation protocol for interchange players (RLMSP-i) was modified to include a tackle shield collision to investigate the reliability of PlayerLoad^{TM} metrics to quantify collision load. The coefficient of variation (%CV) for locomotive metrics ranged from 1.3 to 14.4%, with greatest variability observed for high-speed running distance (8.0 and 14.4% for Bouts 1 and 2, respectively). Accelerometer metrics CV% were 4.4 to 10.0%, while internal load markers were 4.8 to 13.7%. All variables presented a CV% less than the calculated moderate change during one or both bouts of the match simulation except from high-speed distance ($m \cdot min^{-1}$), %HR_{peak} and RPE (AU). The aim of Chapter 7 was to investigate the influence of contact type on external load metrics including PlayerLoad^{TM} derivatives whilst controlling for total running distance. Participants were randomly assigned to one group to complete the match simulation with either a tackle shield (n = 10), tackle bag (n = 7) or no-contact (n = 10). Total PlayerLoad^{TM}, PlayerLoad^{TM} 2D (AU), PlayerLoad^{TM} slow (AU) and PlayerLoad^{TM} slow-ratio (%) were analysed from the accelerometer in addition to high- and low-speed running and sprint speed. Total PlayerLoad^{TM} was *likely lower* for the Bag group compared to the Run group (498 c.f. 460 AU), with no clear differences between the other groups.

PlayerLoad^{TM} slow for the Shield group (167 ± 26 AU) was *very likely* greater than both the Bag (133 ± 11 AU) and Run groups (128 ± 20 AU) but no clear difference was observed between the Bag and Run groups. No differences were observed in PlayerLoad^{TM} 2D between any groups. High-speed running distance was *likely* lower in the Shield group (1056 ± 225 m) compared to the Bag group (1326 ± 245 m) and *very likely* lower compared to the Run group (1318 ± 175 m). Total PlayerLoad^{TM} is not sensitive to contact type during simulated rugby league activity but does reflect greater high-speed running distance during a rugby league match simulation. However, PlayerLoad^{TM} slow can detect the types of contact and might be preferred for quantifying match and training loads associated with physical contact. The purpose of the final empirical chapter (Chapter 8) was to determine the influence of contact type on in neuromuscular, perceptual and biochemical parameters associated with exercise-induced muscle damage. The participants were again assigned to one of three groups to complete the match simulation with a tackle shield (n = 6), tackle bag (n = 7) or no contact (n = 7). In addition to internal and external load measured during the match simulation, venous blood, muscle function and soreness measures were collected immediately (+0), +24 and +72 hours after the match simulation. Upper body neuromuscular performance and knee flexion torque *likely* decreased in the Shield group +0 and +72 hours after the simulation compared to the other groups while CMJ power *likely* decreased more in the Run group. All three groups demonstrated a *very likely* increase in IL-6 and IL-10 concentration immediately after the match simulation, but differences between the groups were *unclear* and values returned to baseline +24 hours after the simulation. In conclusion, current automatic tackle detection metric should be used with caution, particularly in training sessions where physical contact is replicated. Instead PlayerLoad^{TM} and associated derivatives from the embedded accelerometer can provide a useful measure of contact-specific load during training and competitive matches. Physical contact type affected external load by modifying a participant's running strategy during simulated match performance, thereby influencing site-specific fatigue during and after a simulated rugby league match. However, regardless of contact type, large increases in cytokine and leukocyte concentration are apparent with a return to basal values 24 hours after. Therefore it is not recommended to use such biomarkers in applied settings to quantify the magnitude of muscle damage specifically associated with physical contact.

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“Never give in-never, never, never, never, in nothing great or small, large or petty, never give in except to convictions of honour and good sense. Never yield to force; never yield to the apparently overwhelming might of the enemy.”
— Winston Churchill.

Declaration

The material being presented for examination is my own work and has not been submitted for an award of this or another HEI except in minor particulars which are explicitly noted in the body of the thesis. Where research pertaining to the thesis was undertaken collaboratively, the nature and extent of my individual contribution has been made explicit.

Publications

Norris, J. P., Hughes, S. F., Highton, J., & Twist, C. (2016). The influence of physical contact type on internal and external load during simulated rugby league performance. *Journal of Sport Sciences, 34*(19), 1859-1866.

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Chapter 1

Introduction

1.1 Background

Rugby league is a professional team sport played over two 40-minute periods with a 10-minute changeover at half time. The game is characterized by high-intensity activity, such as sprinting and tackling, interspersed with low-intensity recovery periods of jogging, walking or standing (Gabbett et al., 2008). Two teams of thirteen players contest a match, with each team consisting of three distinct groups: outside backs, adjustables and hit-up forwards (King et al., 2009). The object of the game is to score more points than the opponent by touching the ball down over the opponent's try line and by kicking the ball through the goal posts. In the elite European Super League (ESL), there are typically 5-7 days between matches, but this can be as short as 3 or as long as 14 days, depending on the fixture schedule. In between matches, players are exposed to regular training that comprises conditioning, resistance training and skills (McLean et al., 2010; Twist et al., 2017).

1.2 The movement characteristics of rugby league match play

The movement characteristics of elite rugby league match play have been examined extensively using microtechnology (comprising a global positioning device [GPS] and accelerometer) (Austin & Kelly, 2014; McLellan et al., 2011; Waldron et al., 2011; Gabbett, 2015a; Kempton et al., 2015; Oxendale et al., 2016). Understanding these characteristics is important as it provides objective position-specific data to inform conditioning practice (Hausler et al., 2016) and insight into the determinants of successful match outcomes (Black & Gabbett, 2014) and playing standard (Gabbett, 2013b). The mean distance covered by players is approximately 3000 – 7500 m depending on playing position, with backs covering more total distance and a greater proportion of this distance at higher intensities (Gabbett et al., 2012). While forwards (total playing time ~50 min) and backs (total playing time ~70 min) cover similar relative distances (80-100 $m \cdot min^{-1}$; Waldron et al., 2011; Delaney et al., 2015; Gabbett, 2015c; Kempton et al., 2015), more detailed positional analyses using a rolling average method revealed that movement demands fluctuate during a match, with fullbacks performing the greatest distances compared to other positional groups (Delaney et al., 2016a). In addition to GPS-derived measures, recent introductions of metrics that consider accelerative running (Di Prampero et al., 2008) have enabled consideration of more metabolically demanding movements. Using high-power distance (distance covered >20 $W \cdot kg^{-1}$) rather than high-speed distance (> 14 $km \cdot h^{-1}$) emphasizes particular positional differences dependent on their specific match activities. For example, hit-ups forwards cover relatively little high-speed running distance, but greater high-power distance, because of frequent accelerations at lower speeds when carrying the ball into a collision and making tackles (Kempton et al., 2014).

It should be noted that much of the research on movement demands of rugby league describes the ‘average’ characteristics of a match. However, metrics such as high-speed running and very high-speed running can vary significantly between games (CV = 12-45%; Kempton et al., 2014). This variability might, in part, be due to the time between matches, quality of opposition and the stage of the season (Delaney et al., 2016b). An implication of such variability associated with external influences is that empirical research into the determinants of physical performance during matches is inherently difficult. Consequently, the use of match ‘simulation’ protocols designed to simulate the movement demands of matches, which possess lower variability (i.e. acceptable reliability), are necessary for experimental research into rugby league performance (Sykes et al., 2013; Twist & Sykes, 2011; Waldron et al., 2013a; Mullen et al., 2015; Bradley et al., 2017).

1.3 The collision in rugby league

While movement characteristics are important, a major contributor to the physiological load imposed on players during rugby league match play and training is the collision. The collision is defined as contact made with another player, whether carrying the ball forward into an opponent or attempting to tackle an opposing player carrying the ball (Gabbett & Ryan, 2009). Successful tackle technique is defined by the following criteria: contacting the target in the centre of gravity, contacting the target with the shoulder, body position square and aligned to target, leg drive upon contact, watching the target onto the shoulder and keeping the centre of gravity forward of the base of support (Gabbett & Ryan, 2009). Forwards (~1.0 collision per min) are involved in more collisions during a match than backs (~0.3 collisions per min) because of their positional responsibilities in setting up and preventing attacks (Gabbett et al., 2011; 2012). Superior tackling ability is also reported in players who are older, more experienced, leaner, faster and with better lower-body strength (Gabbett et al., 2011a). Given a player's ability to defend can influence a team's success (Gabbett, 2011; Woods et al., 2017), training practices will involve collisions to closely replicate matches and prepare players for competition, with hit-up forwards performing ~1 tackle per minute compared to < 0.6 for other positional groups during certain training practices (Gabbett et al., 2010). However, the high risk of injury associated with the collision (Booth & Orr, 2017; King et al., 2010) means physical contact is often replicated in training and research studies using tackle bags (Johnston & Gabbett, 2011; Waldron et al., 2013b; Mullen et al., 2015), bump pads (Singh et al., 2011) and tackle shields (Wundersitz et al., 2015b). Understanding the load imposed by various collision types, their influence on player movement and role in fatigue and recovery is of interest, both practically and mechanistically to enable the development and replication of the most appropriate training practices. However, with the large variation in player movements performed by the ball carrier and defender during a tackle, the collision is very difficult to reproduce experimentally and to quantify (Seminati et al., 2017).

1.3.1 Measuring the collision

Analysis of collisions has previously been limited to quantifying their frequency during matches using video analysis (Sirotic et al., 2009; Twist et al., 2012). However, recent advances in wearable technology have enabled the detection of tackle frequencies (McLellan et al., 2011; Gabbett, 2010; Hulin et al., 2017; Cummins & Orr, 2015), while novel, accelerometer-based metrics such as PlayerLoad^{TM} are used to quantify collision loads (Gabbett, 2015a; Roe et al., 2016; Reardon et al., 2017; Hulin et al., 2017; Cummins & Orr, 2015). A large variation has been reported between tackle detection from microtechnology and video analysis because of missed tackles, line breaks and second effort tackles. For example, McLellan & Lovell (2012) reported ~800 physical contacts using microtechnology during match play, which differs greatly to the 20-40 tackles reported using video analysis (Twist et al., 2012). More recent comparison between video and microtechnology derived tackle count has found microtechnology to exhibit high sensitivity (97.6±1.5%) and low variation (CV% = 7.8%) during rugby league matches when low intensity (< 1 PlayerLoad^{TM} AU) and short duration (< 1 s) events were excluded from analysis (Hulin et al., 2017). However, there is still disagreement over the criterion validity of tackle detection during rugby union with high variability between manual and automatic tackle detection (Reardon et al., 2017) and limited research examining the use of contact training apparatus (tackle bags, bump pads). Accordingly, there remains considerable scope to examine the utility of these metrics under controlled experimental conditions.

1.3.2 The influence of the collision on match- and training-related fatigue

Several studies have reported reduced high-speed running in the second half of rugby league matches compared to the first (Sirotic et al., 2009; Waldron et al., 2011; Waldron et al., 2013a; Kempton et al., 2013; Bradley et al., 2016). Similarly, Waldron et al. (2013a) reported large reductions (~54%) in high-speed running for interchange players during a single playing bout lasting ~20 min. These decreases in high-speed running over progressive match quartiles represent fatigue that is mediated by both central and peripheral factors (Bradley et al., 2016; Duffield et al., 2012). However, the precise match actions that cause fatigue, such as physical collisions, have not been extensively researched due to the difficulties in controlling variables and collecting biological samples in field-based testing. Recently glycogen depletion has been investigated during match play (Bradley et al., 2016) but the authors stated that variability in external load limited the conclusions and further research with controlled demands was required (Bradley et al., 2017).

The inclusion of physical collisions increases total running time, heart rate and rating of perceived exertion when added to repeated sprint exercise (Johnston & Gabbett, 2011), a team sport-specific circuit (Singh et al., 2011) and simulated match play (Mullen et al., 2015). While such studies indicate the internal and external load imposed on an individual is increased with the inclusion of contact, the specific contribution of this action to fatigue is unclear. Furthermore, previous match simulations have used soft tackle bags to replicate collisions, but it is apparent that this method does not adequately replicate the intensity of competitive, body-on-body collisions during matches (Waldron et al., 2013a; Bradley et al., 2017). Tacklers experience lower forces when colliding with a static tackle bag (Usman et al., 2011) compared to a dynamic contact (Seminati et al., 2017). Replication of the collision in rugby league training practices include the use of such tackle bags, so the analysis of these tools is highly relevant to understand the influence of collisions on fatigue and running performance.

1.3.3 The influence of the collision on recovery after match play and training

The high collision frequency experienced by rugby league players, most notably forwards, might play a key role in the magnitude of fatigue and the time-course of recovery after matches and training. This would have relevance for professional coaches and sport scientists, enabling them to plan individualised training and recovery schedules dependent on the extent of a player's involvement in physical contact during matches and training. Significant and longer-lasting post-match fatigue in rugby league arises from muscle damage and soreness suffered during high-intensity exercise as well as the blunt impact trauma from collisions (Twist et al., 2012; Fletcher et al., 2016). Mechanical damage to the muscle potentially occurs when the athlete is required to produce a repeated number of high velocity contractions coupled with eccentric lengthening; for example decelerations (Howatson & Milak, 2009). Additionally, the trauma associated with tackling is related to reductions in muscular function during the post-match recovery period (McLellan & Lovell, 2012; Twist et al., 2012; Oxendale et al., 2016). Applied studies have reported that it can take 48-120 h for neuromuscular function to return to baseline values after a rugby league match (McLellan et al., 2011; Twist et al., 2012; Johnston et al., 2013). In these studies, neuromuscular function has been quantified by assessing the stretch-shortening ability of the lower-body using a counter-movement jump (CMJ), which has been widely accepted as a marker of fatigue and recovery in many sports (Cormack et al., 2008; Hoffman et al., 2003; Twist et al., 2012; Gathercole et al., 2015). However, upper body function has not received the same attention, despite ~50% of total offensive collisions occurring on a player's upper body during a match (Twist et al., 2012). Immediate and prolonged reductions in upper body function after matches and training have been reported using a plyometric push up (Johnston et al., 2014c; Johnston et al., 2015b; Johnston et al., 2016; Roe et al., 2017). Impaired upper-body function is linked to the total number of collisions, which is negatively correlated with plyometric push-up flight time 12 hours after a competitive match (Oxendale et al., 2016). While these results indicate a potential relationship between tackles and fatigue responses, high variability in demands between matches and positional groups, the uncontrolled uses of post-match recovery strategies by professional players, and the lack of a non-contact control, limit our current understanding of the role of collisions in inducing long-lasting neuromuscular fatigue.

Changes in circulating myofibrillar proteins and inflammatory markers provide an insight into fatigue and recovery after competitive rugby league matches. Team sport players incur substantial changes in biochemical, immunological and hormonal markers from before to after a match and during the following 72-hour recovery period (Twist et al., 2012; Ascensão et al., 2008). In rugby, players involved in a greater number of collisions during a match also experience greater increases in creatine kinase (CK) after a match (Twist et al., 2012; Cunniffe et al., 2010; Takarada, 2003). Rugby performance can also result in an observable increase in leukocytes and signs of inflammation (Cunniffe et al., 2010). However, CK alone cannot provide a conclusive picture of fatigue and recovery given its different time course of recovery after matches compared to other markers such as perceptual feelings of fatigue, muscle soreness and muscle function (Margaritis et al., 1999). Current markers of muscle damage, such as muscle function tests (e.g. CMJ, isokinetic knee flexion and extension) and blood parameters (e.g. CK), have not yet been able to distinguish between fatigue in players with high contact demands and low running demands compared to those with high running demands and low contact loads (Twist et al., 2012; Mullen et al., 2015). Increases in inflammatory cytokines such as IL-6, IL-10 and TNF-alpha are known to occur after team sport exercise (Andersson et al., 2010; Bishop et al., 2002; Ispirlidis et al., 2008; de Moura et al., 2012); however, the time course of inflammatory markers after movements and activities characteristic of rugby league remains unknown. Managing training load and content between matches is important for coaches and sport science staff to keep players healthy and performing well on the pitch. Therefore, identifying appropriate markers and mechanisms of fatigue and recovery associated with specific match actions is desirable to inform individual training and recovery plans.

1.4 Thesis Aims

1) Identify the influence of physical contact on internal and external load during simulated rugby league performance and the immediate fatigue response (Chapter 4).

2) Evaluate automatic tackle detection using microtechnology (Chapter 4 and 5).

3) Investigate the ecological validity of a rugby league match simulation protocol with different methods of tackle replication and identify microtechnology metrics sensitive the changes in physical contact (Chapter 6,7 and 8).

4) Measure the magnitude of neuromuscular, biochemical and perceptual changes immediately and in the days after a simulated rugby league simulation with different contact types (Chapter 8).

1.5 Organisation of the thesis

Chapter 2 of the thesis is a review of the existing literature on rugby league match demands and mechanisms of fatigue during and after performance. Thereafter, three discrete data chapters present empirical research on the influence of physical contact type on internal and external load (Chapter 3), an analysis of automatic tackle detection using wearable microtechnology (Chapter 4) and the reliability of a rugby league match simulation with a modified physical contact (Chapter 5). Chapters 6 and 7 are derived from a single project aiming to identify appropriate metrics to quantify physical contact during intermittent running (Chapter 6) and analyse the influence of physical contact on neuromuscular, biochemical and perceptual responses to exercise (Chapter 7). Finally, Chapter 8 of the thesis presents overall conclusions on the use of microtechnology to quantify physical contact, the influence of physical contact on fatigue and recovery responses and potential future directions for research.

Chapter 2

Review of literature

2.1 Rugby league: A brief overview

Rugby league is a team sport played over two 40-minute periods with a 10-minute changeover period at half time. The game is characterized by high-intensity activity, such as sprinting and tackling, interspersed with low-intensity recovery periods of jogging or walking (Gabbett et al., 2008; Waldron et al., 2011). Two teams of thirteen players contest a game, with each team consisting of distinct positional groups; hit-up forwards (props), wide running forwards (second row and lock), adjustables (hooker, half back, five-eight and fullback), and outside backs (center and wing). The object of the game is to score points by touching the ball down over the try line and by kicking the ball through the goal posts, with the winner of a game being the team that scores the most points. Each team has the ball for six plays (or tackles). After a tackle, the ball carrier plays the ball back along the ground to a receiver standing directly behind them (play-the-ball). After the six plays are completed the team in possession must handover the ball to the opposition. Most teams elect to kick at this point in order to gain as much ground as possible. Elite standard rugby league in England is contested in the Super League that runs a summer season from February until September, comprising 23 regular season fixtures, seven Super 8 fixtures with a possible additional two playoff matches and a maximum of four Challenge Cup matches.

2.2 Physical performance in rugby league

2.2.1 Measuring physical performance during rugby league match play and training

A number of studies have investigated the physical demands of rugby league match play and training by quantifying movement characteristics and contact demands using time motion analyses (Austin & Kelly, 2013; Gabbett et al., 2012; McLellan et al., 2011; McLellan & Lovell, 2013; Twist et al., 2014; Varley et al., 2014; Waldron et al., 2011; Hausler et al., 2016; Delaney et al., 2016a; Scott et al., 2017; Dempsey et al., 2017). While these data are useful for coaches and conditioners, success in rugby league is determined by a complex combination of physical, tactical, technical and contextual constructs (Delaney et al., 2016b; Kempton & Coutts, 2016).

The locomotive demands of rugby league were originally described using manual video motion analysis (Meir et al., 1993). This method of analysis is limited by subjective assessment of gait and by the time-consuming nature of the data collection and as such, has been largely ignored by researchers as technology progressed. More recently semi-automated and automated multiple camera systems have been used to quantify the movement characteristics in rugby league (Sykes et al., 2011). The use of such systems allows analysis of multiple players per match and does not rely as heavily on observer skill. However, the camera system is often restricted to stadia and so cannot be used to quantify training.

Microtechnology devices comprising global positioning systems (GPS) and accelerometers have become the most commonly used technology to measure match and training demands in rugby league. These devices have enabled the quantification of simple movement characteristics during match play and training, such as distance, speed, acceleration and deceleration (Waldron et al., 2011; Gabbett et al., 2012). In addition, triaxial accelerometers embedded within the devices have provided a means to quantifying the number and intensity of physical collisions (Gabbett, 2010; Gabbett et al., 2012; Gabbett et al., 2015a). While detailed reviews on the use of microtechnology in team sports (see Cummins et al., 2013) and rugby league (see Hausler et al., 2016) are provided elsewhere, a brief commentary on the issues pertinent to measuring the physical demands of rugby league is provided below.

The validity and reliability of the various metrics from microtechnolgy devices for quantifying rugby league performance are well established (Cummins et al., 2013; Hausler et al., 2016). In general, devices with higher sampling frequencies demonstrate better validity for measuring distance and speed <20 $km \cdot h^{-1}$, but are limited at speeds above this threshold (Varley et al., 2012; Johnston et al., 2012). Similarly, greater sampling frequency is associated with improved validity for detecting linear acceleration and deceleration demands (Varley et al., 2012). The embedded accelerometer can produce valid results for whole body acceleration (i.e. PlayerLoad^{TM}) during running (Barrett et al., 2014) and physical contact (Wundersitz et al., 2015b). Automatic tackle detection algorithms have been developed for rugby league, the validity of which has been examined only in match play (Gabbett et al., 2010; Gabbett, 2011b; Hulin et al., 2017). Strong correlations ($r > 0.95$) between automatic microtechnology and video based tackle detection have been reported (Gabbett et al., 2010; Hulin et al., 2017), despite large overestimations for collisions using automatic detection elsewhere (McLellan et al., 2011). Hulin and colleagues (2017) reported that the ability of microtechnology to detect collision events improved as the intensity and duration of the collision increased. Furthermore, the accuracy of detecting a collision during match play was improved when low-intensity (<1 PlayerLoad AU) and short duration (<1 s) collision reports were removed from the analysis (Hulin et al., 2017). Poorer accuracy of the algorithms to detect tackles, most notably low intensity collision events, has also been reported in other collision sports (e.g. Gastin et al., 2014) and suggests difficulties when using these metrics beyond rugby league match play. These inconsistencies confirm the necessity for further research into automatic tackle detection validity.

Test-retest reliability has been reported for distance and speed using GPS, with coefficient of variations (CV%) of 1.6 – 2.3% for 5 Hz devices (Waldron et al., 2011). Greater data acquisition frequency (10 Hz) improves CV% for distance to 0.7-1.3% (Castellano et al., 2011). Similarly, accelerometers have been assessed for retest reliability with CV% of 1.87-2.21 for 3-D acceleration (Kelly et al., 2015) and 4.2-14.8 for individual planes (Barrett et al., 2014). The most common accelerometer variable is PlayerLoad^{TM}, which is derived from 3-D rate of change of acceleration (Boyd et al., 2011). Test-retest reliability studies have reported low CV% for PlayerLoad^{TM} using a controlled mechanical shaker (0.91-1.05%; Boyd et al., 2011) and during treadmill running (3.6-12.6%; Barrett et al., 2014). While such results are encouraging for the use of GPS to quantifying the demands of team sport activity, inter-unit comparisons have been found to be more limited, especially at speeds >14.4 $km \cdot h^{-1}$ (Coutts & Duffield, 2010; Jennings et al., 2010). Furthermore, it is apparent that sampling frequency influences inter-unit variability, with 10 Hz devices producing the lowest variation for measurement of peak speed (1.6%) compared to 1 and 5 Hz (2.3-7.2%) and 15 Hz (8.1%; Johnston et al., 2014d). Accelerometers with the GPS device have also been assessed, with results suggesting high levels of agreement between devices (Boyd et al., 2011; Kelly et al., 2015). The latest microtechnology devices sampling GPS at 10 Hz and including accelerometers produce sufficient accuracy and repeatability to quantify match demands in rugby league.

2.2.2 Physical performance characteristics of rugby league match play

Physical performance during rugby league matches has been analysed in elite, semi-elite, amateur and junior players (McLellen et al., 2010; Waldron et al., 2011; Austin & Kelly, 2013; Johnston et al., 2014a; Kempton et al., 2014, 2015, 2016; Delaney et al., 2016a; Twist et al., 2014; Black & Gabbett, 2014; Varley et al., 2014; Duffield et al., 2012), including a thorough meta-analysis of activity profiles in rugby league match-play which can be found elsewhere (Hausler et al., 2016). Total distance (m) and relative distance covered ($m \cdot min^{-1}$) provide a stable measurement (CV% = 3.6%) of physical performance when measured from match to match (Kempton et al., 2014). Players typically cover 4-8 km during a match (Gabbett et al., 2012; Twist et al., 2014), a value that is influenced by several contextual factors (see section 2.3). When distance is expressed relative to playing time, 85-105 $m \cdot min^{-1}$ is commonly observed in elite players (Hausler et al., 2016). While the majority of match time is spent stationary or performing low speed activity (Waldron et al., 2011), it is often high intensity activity that is associated with key events (Austin et al., 2011a). As noted previously, GPS becomes less reliable when measuring running activity at speeds >20 $km \cdot h^{-1}$ and during accelerations, which must be considered when interpreting such data (Waldron et al., 2011). Large variation in high speed (~15%) and very high-speed running (~37%) between matches also has implications on sample size for research into competitive match demands and identifying the influence of any interventions (Kempton et al., 2014). There is also inconsistency between researchers in the velocity thresholds for high and low speed running distance, with more recent publications suggesting individual thresholds determined from peak sprint speed (Abt & Lovell, 2009; Gabbett, 2015b). Although total distance provides consistent description of the physical performance characteristics of rugby league match play, this metric does not fully describe the demands of a match.

2.2.3 Acceleration and sprinting

To accelerate is more metabolically demanding than constant speed running (Osgnach et al., 2010) while decelerating can place large mechanical stress upon the body (Howatson & Milak, 2009). Maximal accelerations and decelerations can occur at low speeds so do not contribute to total high-speed running distance and may be neglected by traditional analyses. Frequency of accelerations and decelerations have been investigated during National Rugby League (NRL) matches, with players performing ~1 acceleration and ~1 deceleration per minute of match time (Kempton et al., 2015; Sirotic et al., 2009; Varley et al., 2014; Cummins et al., 2016). More successful teams also appear to perform more accelerations and decelerations (Kempton et al., 2017). Sprinting in rugby league can be defined as either distance covered or frequency of efforts >24 $km{\cdot}h^{-1}$ (Sirotic et al., 2009). Similar to deceleration, maximal sprinting is associated with mechanical stress (Howatson & Milak, 2009) and can have an impact on the match outcome (Gabbett, 2013b). Most sprints performed during rugby league matches are over distances of 6-10 m, with 85% of all sprint efforts being shorter than 30 m (Gabbett, 2012). Sprint frequency has also been reported with a mean of 35 per match of which 67.5% have >300 seconds of recovery between each effort (Gabbett, 2012). The prolonged recovery between sprints results in limited repeat sprint bouts that consist of three or more efforts with less than 21 s between each effort. This is most likely due to the high frequency of intense physical collisions that are performed by players during matches (Austin et al., 2011b). The combination of maximal acceleration, high speed running and physical collisions, interspersed with limited recovery, have been termed repeated high intensity effort bouts (RHIE; Austin et al., 2011a). Elite players perform 9-14 RHIE bouts per match, which often occur during important passages of play that can decide the outcome of a match (Gabbett, 2013a). The most RHIE bouts occur when teams are defending close to their own try line and 70% within 5 minutes of a try being scored (Austin et al., 2011a; Gabbett et al., 2014). Furthermore, the most common combination of high intensity activities during a RHIE comprises two tackles and one sprint and reaffirms the importance of physical collisions to rugby league performance in addition to running demands (Austin et al., 2011a).

2.2.4 Physical collisions

During rugby league match-play, high-speed running and sprinting is often interspersed with multiple, intense physical collisions, both with and without the ball (Gabbett et al., 2011). The frequency of physical collisions is position specific and can vary from 30-60 over the duration of match (Gissane et al., 2001; Twist et al., 2012; Gabbett et al., 2012; Gabbett, 2015c; Varley et al., 2014; Gabbett, 2014). All players, except for the two wings and fullback, are involved in more defensive than attacking collisions. While one player can carry the ball into contact, two or more players can be involved in tackles, thus increasing the number of defensive collisions. When interpreted relative to match time, players are involved in 0.3-1.0 tackles per minute (Twist et al., 2012; Gabbett et al., 2012), but this can increase to 1.9 per minute during defensive match-play (Gabbett et al., 2014). The majority of RHIE bouts, including physical collisions, occur within five minutes of a try being scored (Austin et al., 2011a). Given that the most intense periods of a match are associated with defensive play (Gabbett et al., 2014), it follows that a team’s ability to perform RHIE bouts and tackles will influence success. However, a greater number of collisions is associated with both high- and low-success teams (Hulin et al., 2015; Kempton et al., 2017). It has been suggested that high-success teams are involved in a greater number of collisions by committing more players to each tackle to slow the “play-the-ball” while defending. This would result in a greater number of collisions because more players are involved per tackle during the match (Hulin et al., 2015). In contrast, less-successful teams have limited possession of the ball and therefore are required to attempt more tackles in defence and be involved in a greater number of collisions (Kempton et al., 2017). Rather than total number of collisions or greater running distance, technical proficiency appears to differentiate between successful and less-successful teams. In professional rugby league, players with poor tackling technique missed more tackles than players with superior tackling ability (Gabbett & Ryan, 2009). The technical criteria used to quantify tackle performance included making contact with the target player in the centre of gravity, making contact with the shoulder, achieving a body position that was aligned with the target, initiating leg drive upon contact, watching the target onto the shoulder and ensuring centre of gravity was forward of base of support (Gabbett & Ryan, 2009). Attainment of these criteria during a one-on-one tackle drill has been correlated with making dominant tackles during match play (slowing down the play-the-ball) but not to missed tackles (Speranza, Gabbett, Johnston & Shepperd, 2015). Furthermore, achieving specific tackle criteria including head placement, shoulder usage and leg drive was linked with less concussive events during contact (Hendricks et al., 2015). Therefore, replicating match-like collisions in training is important for coaches and sport science practitioners to improve team performance and reduce injury risk.

2.3 Factors influencing physical performance characteristics

Variation in a player’s physical performance during a match is influenced by several contextual factors (Kempton et al., 2014). Such variation can result from internal factors (e.g. fitness qualities, fatigue) or external factors (e.g. position, tactics, opponent, environment).

2.3.1 Playing position

Rugby league players can be broadly categorized as forwards or backs or further divided into more specific groups; hit-up forwards (props), wide running forwards (second row and lock), adjustables (hooker, half back, five-eight and fullback), and outside backs (center and wing). Forwards are generally heavier, with greater skinfold thickness than other positional groups (Gabbett, 2002), whilst backs are most often lighter and quicker (Till et al., 2013). Anthropometric characteristics are likely influenced by specific roles for each positional group, for example forwards are typically in the middle of field and expected to perform high numbers of physical collisions through frequent tackles and ball carries (Sirotic et al., 2011; Gabbett, 2015a; Varley et al., 2014; Gabbett, 2014, Hulin et al., 2015; Kempton et al., 2017). Contrastingly, wide running forwards and outside backs operate on the edges of the field which are relatively less congested so fewer collisions are performed but there is greater expectancy for sprinting faster over longer distances.

Outside backs and adjustables can cover 5-8 km compared to 3-6 km for hit-up forwards in total distance (Gabbett et al., 2012; Waldron et al., 2011). Positional differences in total distance are influenced by playing time, with outside backs (70-80 min) and adjustables (55-73 min) on the field for longer compared to hit-up forwards (40-50 min; Gabbett et al., 2012; Waldron, et al., 2011; Twist et al., 2012). When total playing time is taken into consideration, relative distance covered per minute is similar between all positions in elite rugby league, with players typically achieving 80-100 $m \cdot min^{-1}$ (Waldron et al., 2011; Gabbett et al., 2012; Twist et al., 2014).

While total distance is similar between groups, outside backs frequently perform greater distance at high speeds compared to hit-up forwards (907 ± 225 m c.f. 513 ± 298 m; Waldron et al., 2011). Total playing time can again influence a player's ability to accumulate distance; however, it is also likely that pitch constraints could impact on high speed running with forwards operating in central areas where space is often limited. Indeed, forwards perform the highest frequency of sprints over 6-10 m whereas backs perform the highest frequency of sprints over 40 m (Gabbett, 2012). Both hit-up forwards (~3 $n \cdot min^{-1}$) and wide-running forwards (~3 $n \cdot min^{-1}$) also produced a greater number of accelerations compared to outside backs (~2 $n \cdot min^{-1}$; Cummins et al., 2016). The congested centre of the field results in match demands dominated by multiple short sprints and accelerations for hit-up forwards. Outside backs are frequently required to chase and return kicks that occur in open field positions that enable higher velocities and greater distances to be covered.

Physical collisions are a key component of rugby league performance, both with and without the ball (see section 2.2.4). Forwards perform a greater frequency of collisions compared to backs during matches (Gissane et al., 2001; Sirotic et al., 2011; Twist et al., 2012; Gabbett et al., 2012). More specifically, wide running forwards perform the greatest number of physical collisions (47) per match compared to hit-up forwards (36), adjustables (29) and outside backs (24) (Gabbett et al., 2011). Forward players tend to be used for "impact" bouts as a result of the interchange laws that allow 10 substitutions to be made throughout the match. Frequently, forward players will perform two ~20 minute bouts in the first and second halves where their role is to perform high frequencies of physical collisions in attack and defence (Waldron et al., 2013a). Accordingly, the total number of physical collisions per minute of playing time is much higher for such players with hit-up forwards performing ~1 collisions per minute compared to ~0.6, ~0.5 and ~0.5 for wide running forwards, adjustables and outside backs, respectively (Gabbett et al., 2012). While these results are taken from NRL competition, in the English Super League total frequency is similar with 0.3 and 0.7 collisions per minute for backs and forwards, respectively (Twist et al., 2012).

Variability in the number of collisions a player is involved in might partly explain differences in the movement characteristics between positions. Kempton & Coutts (2016) reported small reductions in running intensity for players involved in a higher number of physical collisions during match play, which seems logical given the increased physiological cost associated with physical contact (Johnston et al., 2014c). However, these findings contrast with studies that have examined only interchange movements during actual (Delaney et al., 2016a) and simulated match play (Mullen et al., 2015), both of which have observed increases in running demands. Delaney et al. (2016a) proposed that during matches interchange players are involved in more high-speed running compared to wider players as they are expected to move quickly back and forth around the ruck area. This idea is supported by findings reporting that collisions are typically preceded by a period of high-speed running (Austin et al., 2011b). Increased high-speed running during a simulation with contact compared to without contact is likely caused by the method used to replicate the tackle situation. Further work is needed to examine the influence of physical contact on the movement demands and fatigue responses during rugby league match play.

2.3.2 Fitness Qualities

Improved physical qualities in team sports players are associated with the total distance covered during a match, frequency of high-intensity efforts performed and improved tackling ability (Reilly, 1994; Johnston et al., 2015a; Gabbett et al., 2013; Gabbett & Seibold, 2013; Gabbett et al., 2011a; 2011b). Well developed repeated sprint ability is associated with more playing minutes and faster 20 m sprint speed was associated with number of tries scored (Gabbett et al., 2011). Furthermore, players with greater intermittent running ability were able to cover more total distance and high-speed distance during a match (Gabbett et al., 2013). In rugby league, a high physical work rate is associated with more successful teams (Gabbett, 2013d) and higher competition standards (Gabbett, 2014). The physical capacity of players is also crucial to the outcome of key match events, for example repeat high-intensity bouts frequently occur during the minutes immediately preceding points being scored (Austin et al., 2011a) and it is associated with increases in high-speed running and improved post-match recovery (Johnston & Gabbett, 2014). Better tackling ability is also reported in players who are older, more experienced, leaner, faster and with better lower-body muscular function (Gabbett et al., 2011a).

Elite rugby league players possess estimated $\dot{V}O_{2\max}$ values 45 – 60 $\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}$ (Gabbett et al., 2011; Gabbett, 2002; Gabbett et al., 2007). More recently, the YoYo intermittent recovery test (Bangsbo et al., 2008) has been used by applied practitioners to measure high intensity running ability, with elite and sub-elite rugby league players achieving mean values of ~1000-1600 m (Atkins, 2006; Johnston et al., 2014a; Till et al., 2016; Gabbett & Seibold, 2013; Johnston et al., 2015b).

Repeat sprint ability (RSA) has been cited as a key physical quality in high intensity, intermittent team sports such as soccer and hockey (Gabbett & Mulvey, 2008; Spencer et al., 2004; Girard et al., 2011). A common test of RSA is performing 12 x 20 m sprints within 20 s cycle and summating the total sprint time and percentage decrement in sprint speed (Gabbett et al., 2011). However, the physical demands of rugby league are increased as a consequence of the high number of collisions and wrestling for dominance in the tackle during a match (Austin et al., 2011b). Multiple sprints, tackles and accelerations with minimal recovery have been termed RHIE bouts (Austin et al., 2011b), but the ability to perform such bouts is a separate fitness quality to that of RSA (Johnston & Gabbett, 2011). RHIE ability is associated with acceleration and upper body muscular endurance which suggests that isolated running ability does not appropriately prepare players for the most demanding aspects of rugby league performance (Gabbett & Wheeler, 2015). Furthermore, RHIE frequency discriminates between winning and losing teams (Gabbett, 2013c) and senior and academy teams (Gabbett, 2013b), demonstrating the importance of those physical qualities to success in match play. RHIE ability can be reliably measured using total sprint time during a specific test incorporating sprinting and tackling (Austin et al., 2013), but it is, as yet, unknown whether this test can differentiate between playing standards.

Speed and acceleration are also key attributes for rugby league players (Gabbett, 2012). While relative sprint frequency during match play is similar between positional groups (~0.4 sprints per minute), total frequency is greater for outside backs (~35) compared to adjustables (~21) and forwards (~15; Waldron et al., 2011). During matches, 40% of sprints are performed over 6-10 m and 85% are less than 30 m (Gabbett et al., 2007). Sprinting performance is also related to collision success with improved tackling ability players who possess better acceleration (Gabbett et al., 2011a) and sprinting force (mass x acceleration) over 10 m positively related with the frequency of successful carries (Waldron et al., 2014). Elite rugby league players achieve sprint times 1.71 – 2.06 s and 5.15 – 5.86 s for 10 and 40 m, respectively (Gabbett et al., 2011; Gabbett, 2002; Comfort et al., 2011; Gabbett et al., 2008; Gabbett, et al., 2007) with backs achieving faster sprint times than forwards (Kirkpatrick & Comfort, 2013). Peak velocity increases with age in junior rugby league players and influences the interpretation of high-speed running data when totals are expressed relative to an individual's peak velocity (Gabbett, 2015b). Differences in peak speed could go some way to explain positional differences in high-speed running when defined with absolute velocity thresholds as backs are consistently found to achieve higher velocities (Gabbett, 2002; Comfort et al., 2011). High-speed running is commonly used to quantify external load for elite athletes, but this might not be appropriate for positional groups that perform short sprints and frequent collisions such as hit-up forwards. Other metrics based on acceleration, such as PlayerLoad^{TM}, could be more useful to determine match demands for forwards but require further investigation to ascertain suitability.

Muscular strength and power in the lower- and upper-body differentiate between playing standards (Baker, 2009; Baker & Newton, 2008; Gabbett et al., 2009) and are associated with greater high-speed running distance, tackle quality, frequency of collisions and repeat high intensity effort bouts (Gabbett et al., 2011a; Johnston et al., 2015b; Gabbett & Seibold, 2013; Gabbett & Wheeler, 2015). Well-developed lower body strength also reduces fatigue responses to rugby league matches despite players performing greater external load during a match (Johnston et al., 2015b). Lower-body muscular power is commonly assessed using vertical jump procedures (Johnston et al., 2015b; Gabbett et al., 2009; Comfort et al., 2011) and loaded jump squats (Baker & Newton, 2007; de Lacey et al., 2014), while isometric and isoinertial testing is prevalent for strength assessment (Comfort et al., 2011; Baker & Newton, 2008). The back squat exercise is predominantly used to test lower-body strength, with elite players possessing 1RM scores from 170-200 kg (Baker & Newton, 2008; Comfort et al., 2011). Comparatively, semi-elite players achieve 150 kg (Baker & Newton, 2008) and junior players ~140 kg (Gabbett et al., 2009; Till et al., 2013, Baker, 2001). Within elite players, forwards tend to be stronger than backs, however differences are minimal when considered relative to body mass (Comfort et al., 2011). Isometric lower body strength assessment in elite rugby league players reveals higher absolute values in forwards compared to backs (3121 ± 611 N c.f. 2927 ± 607 N, respectively) (Comfort et al., 2011). However, backs outperformed forwards when isometric strength was expressed relative to body mass (34.32 $N{\cdot}kg^{-1}$ c.f. 30.65 $N{\cdot}kg^{-1}$, respectively). Jump squat peak power consistently discriminates between playing standard with elite players achieving ~1900 W (Baker & Nance, 1999) compared to ~1700 W for sub-elite players. Forwards also produce greater absolute power output compared to backs (~2100 c.f. ~1700 W), however this is reversed when body mass is considered (19.9 c.f. 20.7 $W{\cdot}kg^{-1}$; Comfort et al., 2011). Plyometric press-up (Johnston et al. 2013; Johnston et al., 2014c; Johnston et al., 2015b) or bench throw performance (Baker & Nance, 1999; Baker, 2001; Baker, 2002; Baker & Newton, 2008; Comfort et al., 2011) are both used to assess upper-body power. Peak power for bench throw is greater in elite players compared to sub-elite (610 c.f. 515 W; Baker, 2001). Greater bench press strength does not appear to provide a protective effect against fatigue after a rugby league match, which is in contrast with lower body strength (Johnston et al., 2015b). However, high back squat strength does preserve upper body function compared to players with lower strength. Furthermore, players with greater back squat strength also performed more physical collisions during a match (Johnston et al., 2015b). It is possible that players with greater lower body strength are able to preserve upper body function despite greater collision frequency by better recruiting their lower limb musculature when tackling and wrestling.

2.3.3 Fatigue

During team sports, fatigue can be defined as a decline in physical output as a match progresses or after an acute bout of very intense activity (Mohr et al., 2003; Sykes et al., 2011; Waldron et al., 2013; Hulin et al., 2015). Physical output, and therefore fatigue, can be measured as distance covered, the intensity or the frequency of activity performed. Specifically, analysis of rugby league has focused around high-speed running (distance covered above an arbitrary speed threshold, i.e. >14.1 $km{\cdot}h^{-1}$), sprinting, tackling and performance of RHIE (Johnston et al., 2014a). While such measures are now easily quantified using video analysis or wearable microtechnology, these measurement tools do not provide an insight into the complex and multifaceted mechanisms of fatigue. Furthermore, fluctuations in physical output can be as a consequence of macro- or micro-pacing strategies adapted by individual players in an attempt to optimize their performance during a match (Edwards & Noakes, 2009) or as a result of technical or tactical determinants (Carling, 2013). Mechanisms of fatigue can be broadly divided into central or peripheral factors according to the location in which they act. Central fatigue refers to a progressive reduction in voluntary activation during exercise that is a combination of reduced drive from the motor cortex and also reduced activation of the muscle motor units (Gandevia, 2001). Peripheral mechanisms act distal to the neuromuscular junction but can influence centrally mediated mechanisms via afferent nerve feedback (Minett & Duffield, 2014).

2.4 The examination of match related fatigue in rugby league

Studies examining match related fatigue during rugby league performance quantify physical output during discrete periods within a match. Decreases in relative high-speed running, very high-speed running and sprinting distance have been observed during the second half compared to the first using video notation methods of analysis (Sirotic et al., 2009). Similar findings have also been reported using wearable microtechnology in both ESL and NRL, with 9-27% decreases in high-, moderate- and low-speed running from the first to second half (Twist et al., 2014). Dividing the match into quartiles elicits similar responses, with decreases after quartile one in high-speed running for whole match and interchange players (Waldron et al., 2013a; Sykes et al., 2011). While such analyses demonstrate clear reductions in physical output, it is unclear to what extent the changes are as a result of fatigue or pre-determined pacing strategies (Waldron et al., 2013a) or influenced by match score line (Black & Gabbett, 2014). Acute fluctuations in physical performance have also been investigated using 5 or 10-minute periods during a match, however during shorter periods the ball-in-play time can affect the opportunity for players to perform physical activity (Kempton et al., 2015). While it has been observed that physical output is lower after the peak 5-minute period of activity in rugby league, Kempton et al. (2015) postulated that the ball out of play rather than transient fatigue explained reduced running. For example, a break in play occurs after a try is scored, and is supported by studies reporting high-intensity periods that occur in close proximity to point-scoring opportunities (Austin et al., 2011a; Hulin & Gabbett, 2015). More recently, Waldron and colleagues (2017) observed reductions in high-speed running between peak 5-min and subsequent 5-min periods during rugby league match play. However, no relationship (r = 0.01 to -

0.13; *P* > 0.05) was reported between ball-in-play time and high-speed running and that ball-in-play time was not independent of the match period. The authors suggested that ball-in-play was not a cofounding factor and that a player's inability to maintain high-speed running indicates transient fatigue is a genuine occurrence during elite rugby league matches (Waldron et al., 2017).

Fatigue is frequently characterized by decreases in physical performance measures compared to the opening passages of play (Kempton et al., 2015). After the initial 10-minute period of the first and second half in rugby league match play, there is a reduction in both total and high-speed running distance, although no further decrement was observed over the remaining 30 minutes (Kempton et al., 2015). It has been suggested that the opening 10-minute period of rugby league matches distorts the identification of fatigue related changes in physical performance because the reduction that follows is a result of a tactical shift after attempting to gain an early advantage (Carling, 2013). However, interchange players who might not be active on the field during the first 10-minute period, also perform very high-intensity activity during the first quarter of their time in play (Waldron et al., 2013a). Therefore, it is still not clear whether decrements in physical output are as a consequence of fatigue or tactical considerations; hence future research should attempt to identify the mechanisms behind reductions in performance.

2.4.1 Mechanisms of peripheral fatigue during rugby league match play

Glycogen depletion has been cited as a key fatigue mechanism in team sports such as soccer (Saltin, 1973; Jacobs, Westlin, Karlson, Rasmussen & Houghton, 1982; Smaros, 1980; Krustrup et al., 2006; Krustrup et al., 2011). Despite distinct differences in match demands compared to soccer (Varley et al., 2014), glycogen depletion has also been reported as a potential mechanism of fatigue in rugby league. In a novel study that used muscle biopsies before and after actual match play. Bradley et al. (2016) reported competitive rugby league cause ~40% depletion of muscle glycogen that reflected concomitant reductions in high-speed running distance during the second half of a match. In contrast, the same research group reported that muscle glycogen was only depleted by ~21% during a simulated rugby league match despite similar internal and external load compared to match play (Bradley et al., 2017). Lower glycogen depletion after the simulation compared to a match is likely a consequence of lower intensity collisions with a soft tackle bag as opposed to true body-on-body tackles. Frequent physical collisions during simulated performance increased blood lactate concentration compared to a non-contact protocol, which could indicate greater anaerobic metabolism and increased glycogen usage (Mullen et al., 2015). Collectively, these findings suggest that there is clearly a large metabolic cost to competitive physical contact and that the replication of the tackle in training and research scenarios must account for this. Scope exists to further consider the influence of tackle type on player fatigue.

Low concentrations of muscle glycogen immediately after team sports could contribute to impaired sarcoplasmic reticulum (SR) function and result in impaired muscle function (Krustrup et al., 2011). Evidence suggests that after glycogen depleting exercise, Ca^{2+} release rate is depressed (Gejl et al., 2014). The results indicated that there may be a critical concentration of muscle glycogen at 250 – 300 $mmol \cdot kg^{-1}$ d.w., below which SR Ca^{2+} function is impaired. Furthermore, resynthesis of muscle glycogen appears to reverse the detrimental effects to SR Ca^{2+} and is also associated with recovery of peak power output (Gejl et al., 2014). It is likely that impaired Ca^{2+} function as a result of low muscle glycogen contributes to reduced muscle function, as previous research found concentrations less than the cited critical threshold after rugby league performance with reduced CMJ height (Bradley et al., 2016).

High intensity activity of short duration does not rely heavily on muscle glycogen stores and instead energy is derived from muscle creatine phosphate (PCr; Gaitanos, 1993). In maximal cycle ergometry sprints of 6 s, muscle PCr can be depleted to 14% of pre-exercise, resting values. During a bout of ten sprints, power output was reduced to 73% of that achieved during the first sprint. Supplementing an athlete's diet with creatine monohydrate was also found to increase total work done during intermittent, maximal intensity exercise, further underlining the importance of PCr in maximal and near maximal intensity activity (Casey, 1996). However, over longer duration activity and greater sprint durations the dependency on PCr stores is reduced, as aerobic glycolysis provides greater contributions to the required ATP resynthesis (Bangsbo et al., 2001). Moreover, in soccer, power output and sprint performance are impaired, despite no change in concentrations of muscle PCr (Krustrup, 2006). In this study, biopsies and blood samples were taken approximately ten minutes after activity finished, in which time PCr stores could be replenished as the resynthesis rate is very high (~2 $\text{mmol}\cdot\text{kg}^{-1}\ \text{d}\cdot\text{w}\cdot\text{s}^{-1}$; Harris et al., 1976). As mentioned previously, high-speed running distance is impaired immediately after the peak 5-minute period during a rugby league match (Kempton et al., 2015). It is possible that muscle PCr stores play a role in acute fatigue during a match after intense periods. However, aerobic metabolism is the predominant energy pathway during rugby league (Waldron et al., 2011; Coutts et al., 2003) and as such PCr depletion is unlikely to contribute to sustained fatigue experienced with extended periods of performance.

Traditionally, reduction in blood and muscle pH as a result of an accumulation of H^+ ions has been linked with fatigue but the contribution during team sport performance has been questioned (Krustrup et al., 2006). Rugby league match-play results in elevated blood lactate concentration after both the first and second half (8.4 and 5.9 $mmol \cdot l^{-1}$ respectively) indicating a high reliance on anaerobic glycolysis (Coutts et al., 2003). Furthermore, simulated rugby league performance also results in elevated blood lactate concentration (Waldron et al., 2011) with larger increases associated with contact compared to no contact trials (Mullen et al., 2015). Acidosis can act both centrally by stimulating afferent feedback resulting in lower motor drive and peripherally by impairing Ca^{2+} activity within sarcolemma (Cairns, 2013). However, modest increases in blood lactate concentration compared with continuous exercise and no correlation with detriments in performance suggest that accumulation of such metabolites does not adversely affect athletes during a match (Krustrup et al., 2006).

Accumulation of K^+ during high-intensity activity has also been suggested to cause fatigue by depolarizing sarcolemma and impairing excitability (Cairns, 2013). However, evidence suggests that this is also not a major determinant (Mohr et al., 2003) and the influence of K^+ is determined by simultaneous changes to Na^+ and Cl^- concentrations. The majority of data is representative of highly controlled laboratory-based studies, but results also suggest that muscle acidosis and metabolic disturbances do not account for the detriments found in team sports physical performance either acutely or transiently (Krustrup et al., 2003; 2006).

2.4.2 Centrally-regulated mechanisms of fatigue during rugby match play

Reductions in maximal voluntary contraction (MVC) and voluntary activation (VA) of the leg extensors have been reported up to 24 h after 2 x 30 min bouts of intermittent sprint exercise (Pointon & Duffield, 2012; Pointon et al., 2012). These findings suggest that intermittent exercise results in immediate and prolonged impairments to central drive that limits force production (Pointon et al., 2012). However, VA was not altered after an amateur rugby league match (Duffield et al., 2012). Such differences could be explained by the specific sport demands and the length of time between performance and neuromuscular measurement (Froyd et al., 2013). Considering the neuromuscular demands of rugby league (McLellan & Lovell, 2012) and the presence of pacing strategies during matches (Waldron et al., 2013a), physical performance appears partly influenced by centrally regulated mechanisms. Besides rugby league, impaired MVC and sprint performance relates to reduced EMG activity the day after a soccer match (Rampinini et al., 2011). Whilst the role of the brain in nueromuscular fatigue after rugby league matches is still unclear, peripheral changes that influence acute and prolonged recovery are likely intrinsically linked via feedback pathways. Such feedback could affect perceived recovery and supress voluntary force production (Noakes, 2012). The restoration of peripheral contributors to fatigue could mediate any central changes to muscle function (De Pauw et al., 2013), however this relationship has yet to be fully understood. Clearly physical performance during and after rugby league performance is a multifaceted phenomenon that can be attributed to central and peripheral mechanisms.

2.5 Physiological demands of rugby league

Mean heart rate during a semi-professional rugby league match was 166 ± 10 beats·min^{-1} (84.3 ± 4.8% of heart rate peak), with no difference between the first (167 beats·min^{-1}) and second half (165 beats·min^{-1}) (Coutts et al., 2003). More recent investigations into differences between positional groups suggest that $\%HR_{peak}$ values are similar between positions with values ranging 81.5 – 84.1% during elite matches (Waldron et al., 2011). When each quarter of a match was analysed, significant differences in $\%HR_{peak}$ were reported between the first and second quarters compared to the third and fourth (Waldron et al., 2013a). These findings suggest reduced physiological work rate in the second half that reaffirms the decreases in external load measures, such as high-speed running distance, during later phases of a match (Sirotic et al., 2009; Sykes et al., 2011; Waldron et al., 2011; Waldron et al., 2013a). The authors also reported summated heart rate (Edwards, 1993) observing that, due to differences in time on the field and their locomotive demands, outside backs performed more sustained work at higher intensity than either adjustables or forwards (Waldron et al., 2011).

A mean blood lactate concentration of 7.2 $mmol \cdot l^{-1}$ has been reported during a match for semi-professional rugby league players, with blood lactate concentration being higher in the first half of matches (8.4 vs. 5.9 $mmol \cdot l^{-1}$; Coutts et al., 2003). These results provide further evidence in addition to $\%HR_{peak}$ that both internal and external load are reduced during the second half of matches. The blood lactate concentration during competition is also higher in forwards (8.5 $mmol \cdot l^{-1}$) than backs (6.5 $mmol \cdot l^{-1}$; Coutts et al., 2003). Higher lactate concentration in forwards indicates greater performance of anaerobic activity which supports the findings from microtechnology that forwards perform at higher intensity for shorter periods compared to backs. However, these data should be interpreted with some caution given that blood lactate values are likely to be influenced by the intensity of exercise performed immediately before sampling and the potentially limited role blood lactate plays in fatigue during prolonged intermittent exercise (Krustrup et al., 2006). Therefore, limited conclusions can be drawn on the metabolic responses during competitive rugby league.

The use of session RPE (Foster et al., 2001) is known to provide valid measurement of the internal load characteristics of rugby league (Lovell et al., 2013; Weaving et al., 2014). Accordingly, the measure has been used to quantify the internal strain of match play and training practices in rugby league players (Gabbett & Jenkins, 2011; Waldron et al., 2011; Lovell et al., 2013; Johnston et al., 2013; Gabbett, 2013c; Weaving et al., 2014). Similar to other load measures, outside backs and adjustables had higher “match loads” than forwards as a result of longer playing times. Indeed, total and high-speed running distance was very highly correlated with sRPE during rugby league training sessions (Lovell et al., 2013; *r* = 0.82 and 0.62, respectively). Furthermore, greater accelerometer load and impacts were moderately correlated with higher sRPE loads highlighting a variety of factors that contribute to overall perception of effort. Physical contact also increased RPE during simulated rugby league, a repeated sprint test and small-sided games compared to trials without contact (Mullen et al., 2015; Johnston et al., 2011; Johnston et al., 2013). Increases in RPE reflects greater physiological load during contact compared to non-contact exercise protocols. It is possible that greater perception of effort during caused by physical contact could mediate exercise intensity and influence external load markers in addition to the known physiological changes associated with collisions. Differences in “match load” were also observed when matches were played against different standard of opposition (Gabbett, 2013c). Against top 4 ranked teams, mean match RPE was 8.5 ± 0.2 compared to 7.9 ± 0.2 against bottom 4 ranked teams. These data suggest that if teams are winning comfortably, work rate may decrease whereas if matches are close, players will continue to work hard to achieve the desired result.

2.6 Simulation of rugby league match play

The simulation or replication of team sport activity is particularly appealing from a research and training perspective given the large match-to-match variability in high-speed running observed in these sports (Gregson et al, 2010; Kempton et al., 2014). Reliable match simulations provide controlled replication of movements similar to those performed by players in matches, and have been reported for soccer (Nicholas et al., 2000), basketball (Scanlan et al., 2012), rugby union (Roberts et al., 2010) and rugby league (Sykes et al., 2013; Waldron et al., 2013b).

Rugby league specific simulation protocols have been described for full match (RLMSP; Sykes et al., 2013) and interchange players (RLMSP-i; Waldron et al., 2013b). These protocols were based on mean match demands from elite rugby league and were found to be reliable and produce valid replications of the physiological and perceptual loads associated with match play (Sykes et al., 2013; Waldron et al., 2013a). While the physiological demands appear similar to those reported for elite players (heart rate values range from ~82 – 84 %HR_{peak}; Waldron et al., 2011), high speed running in simulated match play was greater compared to actual match demands (RLMSP, 11 – 15 $m{\cdot}min^{-1}$ and 4 – 8 $m{\cdot}min^{-1}$; RLMSP-i, 26 – 29 $m{\cdot}min^{-1}$ and 14 – 18 $m{\cdot}min^{-1}$). Similarly, Bradley et al. (2017) reported smaller depletions in muscle glycogen (~21%) during an 80-minute simulation compared to match play (~40%; Bradley et al., 2016). Lower glycogen depletion was reported despite heart rate (~83 %HR_{peak}) and PlayerLoad^{TM} (~7.7 $AU{\cdot}min^{-1}$) during the simulation replicating values similar to matches (Waldron et al., 2011; Gabbett, 2015a). In the period immediately after the simulation, lower creatine kinase (CK) concentration and muscle soreness have also been observed (Mullen et al., 2015; Bradley et al., 2017). While CK has previously been used to quantify the magnitude of muscle damage after rugby (Jones et al., 2014; Oxendale et al., 2016), high match-to-match variability (Russell et al., 2015), a poor temporal relationship with performance (Margaritis et al., 2015) and a weak relationship with physical performance variables (Scott et al., 2016) suggest that CK might not be suitable to measure the magnitude of EIMD or the time course of recovery. Collectively these data suggest an inability of the simulation to replicate the physicality of collisions in matches, with an increase in internal load resulting from a higher external load (likely high-speed running) and an insufficiency in blunt force trauma.

In the simulation's present format, the participant is required to tackle a soft, tackle bag (~35 kg) with maximal intensity. The contact is performed by sprinting 8 m and tackling the bag with the shoulder at approximately hip height. The bag is then driven to the floor with the participant landing in a prone position, still grasping the bag. Once landed, the participant is instructed to roll 360º laterally whilst holding the bag, touching it on the floor, before rolling laterally 360º back to the original position. Players also perform a 'flapjack' movement once per cycle, similar to the contact method used by Sykes et al. (2013). While the simulation provides a controlled tool to evaluate rugby league activity, evaluation of the existing literature suggests the contact event employed currently lacks the required intensity and is unlikely to result in the same blunt force trauma associated with match contacts. Further work is therefore required to develop a more appropriate and reliable simulation that better replicates match and training related contact activity.

2.7 Player recovery after rugby league performance

A consequence of high intensity intermittent running combined with collisions is the immediate and prolonged symptoms of muscle damage and soreness that manifest in the days after. Numerous studies have examined these symptoms and their time course of recovery after rugby league match play, including losses in muscle function, increased muscle soreness, impaired well-being and alterations in blood proteins (McLean et al., 2010; McLellan et al., 2011; Duffield et al., 2012; Twist et al., 2012; Johnston et al., 2013; Oxendale et al., 2016). What remain less clear are the mechanisms that are responsible and the role the different activities performed has on player recovery.

2.7.1 Muscle function

Objective assessment of muscle function evaluates the extent of muscle damage and rate of recovery (Byrne et al., 2004; Warren et al., 1999; Damas et al., 2016). Torque assessment requires the participants to perform a maximal voluntary contraction (MVC) against a fixed arm (for isometric actions) or an arm moving at a constant velocity (for isokinetic movements). While single joint isometric or isokinetic strength testing fails to replicate the dynamic, multi-jointed nature of sport movements (Falvo & Bloomer, 2006), the aforementioned measures remain recognised as the most appropriate indirect measure of exercise-induced muscle damage (Warren et al., 1999; Damas et al., 2016). In addition, the use of isoinertial methods of strength assessment are perhaps more practically relevant and easier to employ in a field-based setting. Hence, these procedures appear more routinely in the literature and include various vertical jump procedures (Johnston et al., 2013; Duffield et al., 2012; Johnston et al., 2014c; McLean et al., 2010; McLellan et al., 2011; Twist et al., 2012;

Oxendale et al., 2016), plyometric press-ups (Johnston et al., 2013; Oxendale et al., 2016) and loaded ergometer sprints (Wehbe et al. 2015).

Reductions of 2-8% in knee extension MVC torque have been reported after amateur rugby league match performance (Duffield et al., 2012; Skein et al., 2013) and simulated rugby league (Twist & Sykes, 2011; Mullen et al., 2015). These findings suggest that extended periods of intermittent running result in mechanical muscle damage, the result of knee flexors controlling hip flexion during sprinting and knee extensors controlling the centre of mass during deceleration and changes of direction. Physical contact does not appear to influence decrements in extensor or flexor torque after simulated rugby league with unclear differences between contact and non-contact trials (Mullen et al., 2015). The authors identify the method of contact replication as a potential explanation for unclear differences between groups. While soft tackle bags are commonly used to replicate physical contact (Mullen et al., 2015; Johnston et al., 2011; Wundersitz et al., 2015b; Singh et al., 2011), it is thought that this collision does not reflect the neuromuscular actions associated with competitive tackles and wrestling. The lower body has a key role in successful tackle execution (Gabbett & Ryan, 2009), therefore it is likely that more severe neuromuscular responses would be observed after competitive physical collisions.

Vertical jump performance (drop jump [DJ], CMJ and squat jump [SJ]) has been used extensively to assess the effect of exercise-induced muscle damage (EIMD) and sports performance on the stretch shortening cycle (Komi, 2000). The time course to recovery after damaging exercise, such as resistance exercise (including plyometrics) and downhill running, generally follows a bimodal pattern of recovery (Byrne & Eston, 2002; Byrne et al., 2004). That is, an initial decline in jump performance followed by an early recovery and a secondary decline that might be indicative of the inflammatory response (Byrne et al., 2004). However, vertical jump performance after rugby league match play has not identified the same bimodal pattern. Most studies have used the CMJ to detect changes in lower-body function after matches (Johnston et al., 2013; Duffield et al., 2012; McLean et al., 2010; McLellan et al., 2011; Twist et al., 2012; Oxendale et al., 2016), training (Johnston et al., 2014c) and simulated performance (Mullen et al., 2015). CMJ height and peak power has been shown to decrease immediately after rugby league and remain impaired for 24-48 hours before returning to baseline.

Involvement in collisions means that players experience considerable load to the upper body from pushing, pulling and blunt force impact (Twist et al., 2012). While assessing upper body function of rugby players is appropriate, the measurement methods available are limited compared to those of the lower body. Immediate and prolonged reductions in upper body function after matches and training have been reported using a plyometric push up (Johnston et al., 2014c; Johnston et al., 2015b; Johnston et al., 2016; Roe et al., 2017). Moreover, total collision frequency is negatively correlated with plyometric push-up flight time 12 hours after a competitive match (Oxendale et al., 2016). Peak power and force during a plyometric push up can decrease by ~15% after small-sided games with added physical contact, whereas no changes were observed without contact (Johnston et al., 2013). Impaired upper-body neuromuscular function after physical contact suggests that maximal strength training should be avoided until recovery is apparent. For example, tackle bags and shields are commonly used by professional teams to prepare for matches, but the recovery time course after using these apparatus has yet to be described. A better understanding of how the tackle type influence a player's recovery could inform training organisation for professional athletes.

2.7.2 Muscle soreness

Muscle soreness measured on a visual analogue scale is the most commonly used marker to assess EIMD (Warren et al., 1999) undoubtedly owing to its ease of use. Soreness is indicated by feelings of pain and tenderness upon movement or palpation of the muscle (Cheung et al., 2003) and is caused by unaccustomed muscular work, particularly eccentric muscle contractions (Newham, 1988). Repeated sprints, decelerations and changes in direction are known to result in structural damage to the muscle and influence perception of muscle soreness (Howatson & Milak, 2009). In rugby league, players report muscle soreness in the days after a match, the symptoms of which are known to remain throughout the season (Fletcher et al., 2016). Therefore, understanding the causes of muscle soreness is vital for planning training between matches for professional players to optimise performance. Playing duration, the number of tackles and repeated high-intensity effort bouts are all positively correlated with perceptions of muscle soreness in the days after professional rugby league match (Twist et al., 2012; Oxendale et al., 2016; Fletcher et al., 2016). Increased muscle soreness has also been observed after small-sided games and a simulated rugby league match, with greater soreness apparent when physical contact was included (Johnston et al., 2013; Mullen et al., 2015). An increase in perceived muscle soreness is likely to alter an athlete’s sense of effort, causing them to down-regulate their exercise capacity (Cheung et al., 2003) and has implications for psychological wellbeing (Fletcher et al., 2016).

2.7.3 Blood proteins

Increased concentration of enzymes in the blood plasma and serum are often used as indirect markers of muscle damage (Warren et al., 1999). EIMD may disrupt the sarcolemma and lead to leakage of intracellular proteins into the blood for example, creatine kinase (CK). Several studies have used CK as an indirect marker of EIMD after rugby league matches (McLellan et al., 2010; Twist et al., 2012; Oxendale et al., 2015; Johnston et al., 2013), with positive correlations observed between collision frequency and CK concentration after rugby league match play (Twist et al., 2012; Oxendale et al., 2015; McLean et al., 2010). However, that CK is also increased in players who performed fewer collisions during a match suggests other mechanisms alongside blunt force trauma are responsible the response of this biochemical marker (Twist et al., 2012). Increased concentrations of CK are evident for up to 96 hours after elite performance (McLellan et al., 2010), but can have a poor temporal relationship with muscle function changes after EIMD (Margaritis et al., 1999). Furthermore, CK can also display very large individual variability (Hartmann et al., 2000). The use of CK concentration to quantify the magnitude of muscle damage assumes the extent of damage is associated with the disruption to the sarcolemma and the resulting permeability to intracellular proteins. However, weak relationships were evident between locomotive load markers and CK concentration 48 hours after elite soccer matches (Scott et al., 2016). These results indicate that CK might not be appropriate to provide an indication of athlete recovery or the specific actions completed during matches.

2.7.4 Inflammation

After severe muscle damaging activity, a systemic inflammatory response is initiated. Cytokines, such as IL-6, mediate the onset of inflammation in response to stress from prolonged, strenuous exercise and muscle damage (Steensberg et al., 2003). There are also compensatory anti-inflammatory responses after strenuous exercise including elevated IL-10 that blunt production of further pro-inflammatory cytokines and return the system to homeostasis (Ostrowski et al., 1999). Increases in inflammatory cytokines such as IL-6, IL-10 and TNF-alpha are known to occur after team sport exercise (Andersson et al., 2010; Bishop et al., 2002; Ispirlidis et al., 2008; de Moura et al., 2012); however, the time course of inflammatory markers after movements and activities characteristic of rugby league remains unknown. Strong correlations have been found between elevated IL-6 and EIMD (Bruunsgaard et al., 1997), while duration and intensity also influence the magnitude of change after exercise (Peake et al., 2005). Systemic IL-6 concentration usually returns to pre-exercise concentrations within 24 hours after sports performance (Souglis et al., 2015) but can remain elevated for several days after severe eccentric muscle contractions (Phillips et al., 2003). Increased IL-6 concentration has been observed after an elite rugby union match, indicative of an acute phase response to exercise (Cunniffe et al., 2010). Indeed, IL-6 concentration could provide a useful marker to quantify total external load and muscle damage after blunt force trauma associated with physical contact in rugby league. Time to recovery appears dependant on the specific demands imposed on the players, most notably those that experience greater physical contact load (Twist et al., 2012; Johnston et al., 2013; Oxendale et al., 2016), greater external loads (Oxendale et al., 2016) and total match time (Duffield et al., 2012). However, such findings are based on the responses to match activity where players are exposed to variable loads dependent on their playing role. Further work is necessary using more controlled models to elucidate the mechanisms that explain the inflammatory response to rugby league activity.

2.8 Conclusions

The purpose of this review was to examine physical performance during rugby league and post-match recovery time course. This includes consideration for methods to quantify physical performance and factors that influence differences in performance metrics. Finally, the review discusses post-match recovery symptoms and mechanisms that can be measured to identify the contribution of specific match actions to the time course of recovery.

A large number of studies have examined external load during rugby league matches. Early analyses of locomotive demands were described using manual video motion analysis, which was more recently replaced by semi-automated and automated multiple camera systems. Microtechnology devices comprising global positioning systems (GPS) and accelerometers have become the most commonly used technology to measure match and training demands in rugby league. Triaxial accelerometers embedded within the devices have provided a means to quantify the number and intensity of physical collisions as well overall “global-load”. However, there has been debate into the validity and sensitivity of such metrics to quantify physical contact. Furthermore, microtechnology devices are worn during training sessions as well as matches, but there is less research to indicate whether accelerometer metrics are appropriate to quantify training demands and modified physical contact.

A consequence of high intensity intermittent running combined with collisions is the immediate and prolonged symptoms of muscle damage and soreness that manifest in the days after. Numerous studies have examined changes in muscle function, muscle soreness, wellbeing and increased concentration of blood proteins after rugby league match play and match simulations. However, it is less clear what mechanisms are responsible and the role of specific match activities on player recovery. Extended periods of intermittent running result in mechanical muscle damage that can be quantified with various tests of lower-body muscle function whilst plyometric push-ups appear sensitive to the number of physical collisions. While glycogen depletion has been cited as a key fatigue mechanism in team sports immediately after a match, prolonged decrements in muscle function have been attributed to an inflammatory response. Yet, limited research has investigated the change in inflammatory cytokines after rugby league activity. Of interest is the response to blunt force trauma that is associated with intense physical contact.

Identifying a valid and reliable simulation tool would provide a method to isolate specific aspects of performance such as physical contact and high-speed, intermittent running. While previous versions of the rugby league match simulation have been limited by replicating contact with a soft tackle bag, other methods commonly used by professional teams can be explored such as a tackle shield. Accelerometer metrics such as PlayerLoad^{TM} can be examined by controlling locomotive load and varying physical contact. Such measures could provide useful information on external load associated with contact. Responses to rugby league activity can then be related to specific aspects of performance for example greater contact load or greater high-speed running load. Understanding the magnitude and time course of physiological responses can inform training and recovery practices in professional rugby league to prevent injury and improve performance.

Chapter 3

General Methods

A general methods section is included below detailing the movement and contact demands of the match simulation protocol used in Chapters 4, 6, 7 and 8 and subsequent data acquisition.

3.1 The rugby league match simulation protocol for interchange players (RLMSP-i)

After a standardised pre-match warm-up, participants were required to move between a linear series of cones (Figure 3.4), with movement speed controlled by an audio signal (Table 3.1). Two bouts were interspersed with a 20-minute passive recovery period to replicate the average match demands of elite interchanged rugby league players as identified by Waldron et al. (2013a). Each bout was identical and consisted of 12 repeated cycles of activity. The simulation was designed to reproduce total relative running demands of ~100 $m \cdot min^{-1}$, 0.7 contacts per minute and average HR of 85-90% heart rate peak (HR_{peak}). Participants were habituated to the protocol beforehand, comprising six cycles of the protocol including the specific contact type.

The original method of tackle replication as described by Waldron and colleagues (2013) involved making contact with a soft tackle cylinder (~23 kg) using the dominant shoulder at approximately hip height. The participant was instructed to secure both arms around the tackle bag and drive to the floor, landing in a prone position. Still grasping the bag, the participant was instructed to roll laterally 360° whilst holding the bag, touching the bag on the floor, before rolling back to the original position. After completing the tackle exercise, participants were required to return the bag to standing. The second contact event in each cycle required the participant to perform a “flapjack” exercise that involved dropping into a prone position on the ground before rolling laterally 360° to the left and then rolling back to the original prone position. This was included in the original simulation to replicate going to ground after being tackled as opposed to being the tackler (Waldron et al., 2013b).

Figure 3. 1. Original method of tackle replication using soft tackle cylinder.

3.1.1 Modified tackle using a weighted tackle sled (Chapter 4)

Contact was modified from the previous protocol (Waldron et al., 2013b) to involve a collision with a weighted tackle sled (Sled trial) which incorporated a cushioned tackle arm onto a metal frame weighing ~70 kg (Figure 3.2). Participants were instructed to sprint into the collision and make contact with the sled at hip height. At contact, the participant was instructed to flex the hips, knees and ankles whilst making contact with their preferred shoulder and wrapping both arms around the padded tackle arm. Immediately after contact, participants performed the flapjack exercise. This exercise was included in the tackle sled condition to meet criteria for tackle detection that requires the GPS unit to change orientation, to simulate tackling an opponent to the ground and competing for dominance and to match the bag trial where the participant performs the roll with the tackle bag. Once complete, participants returned to standing and awaited the next audible instruction. The second contact event in each cycle required the participant to perform the flapjack exercise without colliding with the tackle sled.

Figure 3. 2. Modified tackle using a weighted tackle sled.

3.1.2 Modified tackle using person-to-person contact (Chapters 6, 7 and 8)

Contact was modified to involve a collision between two participants that were matched for body mass (Figure 3.3). The collision event comprised one participant performing a defensive tackle on their opponent holding a tackle shield. Participants were instructed to sprint 8 m towards their opponent and contact the tackle shield between hip and chest height with their shoulder. At the point of contact the participant was instructed to wrap their arms around the tackle shield and their opponent and attempt to turn 180° to gain dominance whilst their opponent resisted. After three seconds the researcher called "held" and both participants were instructed to perform the flapjack exercise. In the second contact in each cycle, participants alternated from offensive (holding the tackle shield) to defensive (performing the tackle) contacts. Participants performed 24 defensive and 24 offensive efforts over the duration of the simulation.

Figure 3. 3. Modified tackle using person-to-person contact.

Table 3. 1. The chronological ordering of audio cues during the rugby league match simulation protocol for interchange players (RLMSP-i).

Instructions
Part A (starting at the yellow cones)
Sprint to white cone (20.5 m)
Decelerate (8 m)
Sprint and contact the tackle bag (8 m)
Jog to yellow cone (20.5 m)
Jog to red cone (13.5 m)
Walk to yellow cone (13.5 m)
Sprint to white cone (20.5 m)
Decelerate (8 m)
Sprint and perform a flapjack (8 m)
Jog to yellow cone (20.5 m)
Part B (starting at the yellow cones)
Walk to red cone (13.5)
Walk to yellow cone (13.5 m)
Rest (0 m)
Jog to red cone (13.5 m)
Walk to yellow cone (13.5 m)
Rest (0 m)

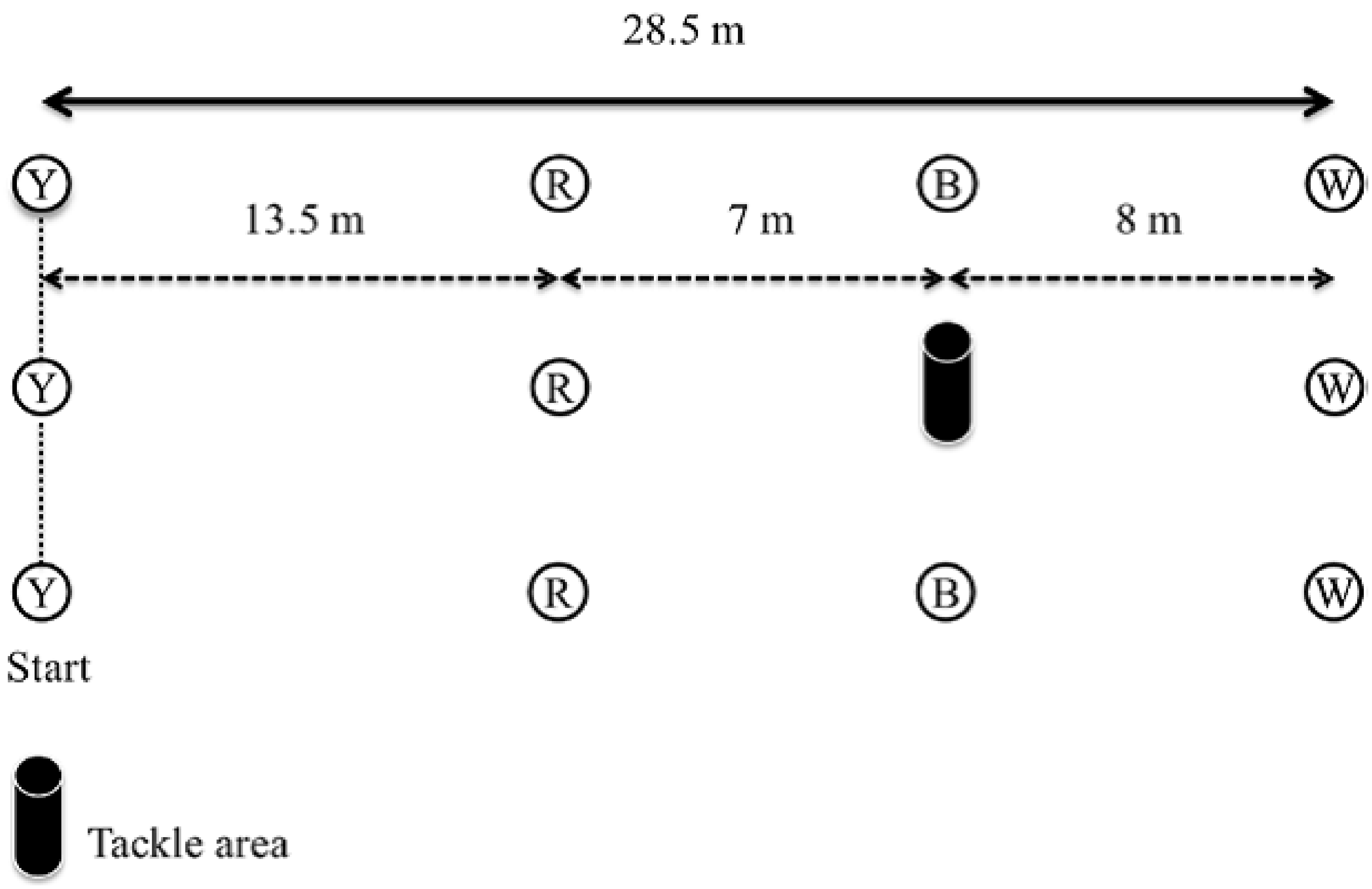


Figure 3. 4. Schematic of the RLMSP-i (not to scale). Y = yellow cone; B = blue cone; W = white cone.

3.2 External load measurement

Movements were recorded using a 10 Hz GPS device (Optimeye S5, Catapult Innovations, Melbourne, Australia) fitted into a vest that was securely positioned between the participant's scapulae. All running and external load data was downloaded to a laptop and analysed using the manufacturer's software (Sprint, Version 5.1, Catapult Sports, Australia). Total distance run was recorded and then categorised into low (<14.0 km·h^{-1}) and high-speed (≥ 14.0 km·h^{-1}) distance covered to correspond with previous research on rugby league demands (Waldron et al., 2011). Typical error of measurement for distance and velocity is 0.8% at slow speeds and up to 13.7% during very high speed running (Johnston et al., 2014d). Peak velocity (km·h^{-1}) of sprint A (first 20.5 m sprint), sprint to contact (8 m sprint into contact with sled, bag or opponent) and sprint B (second 20.5 m sprint) were identified in the GPS data and recorded from every cycle of the simulation. Total PlayerLoad^{TM}, PlayerLoad^{TM} 2D, and PlayerLoad^{TM} slow were also recorded from which PlayerLoad^{TM} slow-ratio and PlayerLoad^{TM} distance-ratio were calculated for the entire simulation and per 5.8 min period.

3.3 Internal and perceptual load measurement

A HR monitor (Polar Electro Oy, Kempele, Finland) was wirelessly paired to the GPS device and fitted around the chest of the participant. Both movement and HR data were downloaded to a laptop and analysed (Sprint, Version 5.1, Catapult Sports, VIC, Australia). HR data were analysed as a percentage of the participant's peak HR determined from final heart rate during the multi-stage fitness test or YoYo intermittent recovery level 1 test (%HR$_{peak}$). Blood lactate concentration was measured before and after each bout of the simulation protocol from a finger prick sample (Lactate Pro;

Arkray KDK Corp., Kyoto, Japan). Rating of perceived exertion (RPE) using the 6-20 scale (Borg, 1998) was retrieved on four occasions in each bout, after three complete cycles. Participants were habituated to the scale beforehand and were asked to provide a rating during a low intensity phase with only the researcher present.

Chapter 4

Influence of physical contact type on internal and external load during simulated rugby league performance

4.1 Abstract

Background: Rugby league match simulation protocols are a reliable method to replicate match demands. However, high-speed running distance is often greater during a match simulation compared to a competitive performance. The discrepancy is potentially caused by lower intensity physical collisions during the simulation. **Purpose:** Examine the influence of physical contact on internal and external loads during a match simulation. **Methods:** Eleven male university rugby league players were required to complete two trials of the rugby league movement simulation protocol for interchange players (Waldron et al., 2013b), one with a traditional tackle bag and one with a custom tackle sled to replicate physical contact. High- and low-speed running distance, sprint speed, contact load and HR were measured during the simulation using 10Hz micro-technology device (Omptimeye S5, Catapult) and neuromuscular performance was assessed before and immediately after the simulation. **Results:** The weighted sled trial resulted in lower high-speed running distance (27.7 ± 2.4 cf. 28.4 ± 2.6 m·min^{-1}), principally through a reduction in sprint to contact speed (14.8 ± 1.1 cf. 16.1 ± 1.5 km·h^{-1}). However, high-speed running distance was still greater compared to that observed during matches. Large variation was observed between micro-technology detected tackles and the actual number of tackles performed. **Conclusion:** Contact type influences running performance during simulated rugby league activity but further modification to tackle replication is required to adequately simulate match performance. Automatic tackle detection warrants further investigation to clarify causes of high variability.

4.2 Introduction

Despite differences in running and contact requirements, average heart rate (HR) during a match is similar (~80% maximum) for both forwards and backs (McLellan et al., 2011). Contact added to small-sided games increases the internal load on players that causes players to reduce the amount of running when compared to non-contact games (Johnston et al., 2014c). This effect can be measured during match simulation protocols that provide a tool to replicate match demands reliably, enable measurements that are deemed to be invasive, and control the frequency of high-intensity activities such as sprints and collisions. However, relative high-speed running (~27 c.f. ~17 $m \cdot min^{-1}$) and total running distance (~107 c.f. ~95 $m \cdot min^{-1}$) are greater than those reported in matches (Waldron et al., 2013a). A potential cause of the greater running volume in the simulation protocol might be the reduced intensity of the simulated contact relative to elite rugby league matches (Waldron et al., 2013b; Mullen et al., 2015). The authors speculated that the higher running speed was because the type of contact used in the simulation (i.e. 23 kg soft tackle bag) encouraged a faster running speed into impact compared to running into a human body. Examining the running kinematics into contact might provide further insight to the role of collision on fatigue and running performance during intermittent activity. We hypothesised that the inclusion of a weighted tackle sled would more closely resemble a body-on-body contact and result in external load that is similar to elite rugby league match play. Therefore, the aim of this study was to examine how the type of physical contact influenced the internal and external loads during and after a simulated rugby league match.

4.3 Methods

4.3.1 Overview

The study was a randomised, repeated-measures crossover design, in which 11 male university rugby league players (mean ± standard deviation [SD]; body mass = 86.4 ± 6.9 kg; stature = 186.5 ± 7.4 cm; age = 21.8 ± 1.3 y; predicted $\dot{V}O_{2\max}$ = 47.9 ± 2.1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) were required to complete two trials of the rugby league movement simulation protocol for interchange players (Waldron et al., 2013b) on an outdoor synthetic grass pitch (3G all-weather surface) with 7 – 10 days between each trial (See Chapter 3). In one trial contact was replicated using a soft tackle cylinder (Gilbert Rugby, East Sussex, England; mass = 23 kg), while the other trial used a modified weighted tackle sled (mass = ~70 kg). Before the first trial, participants signed a written consent form and completed a health screening questionnaire to ensure suitability to participate in the study. The Faculty of Life Sciences Research Ethics Committee granted ethical approval for the study.

Before the first trial, participants completed a 20 m multistage fitness test to estimate maximal oxygen uptake ($\dot{V}O_{2\max}$). To be included in the study, participants had to achieve level 9 (~45 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) to replicate the characteristics of elite rugby league players (Gabbett et al., 2011). One familiarisation session of the protocol was completed where participants performed six cycles of the match simulation, including three cycles of both conditions. Participants were asked to refrain from any strenuous exercise in the 36 hours before the first trial, as well as to avoid caffeine and alcohol intake.

On each visit, participants' body mass was recorded after which they performed three counter-movement jumps (CMJ) in the laboratory before completing the simulation protocol with the nominated contact condition. During the simulation, movement demands, HR, blood lactate concentration and RPE were measured. Immediately after completing the simulation, body mass was recorded again and CMJ measurements repeated. Trials were conducted at similar times of the day (± 1 h) for each participant.

4.3.2 Multi-stage fitness test

After a standardised warm-up, participants completed the multistage fitness test on an indoor wooden surface (Ramsbottom et al., 1988). The test consisted of shuttle running between two markers placed 20 m apart at increasing running speeds (0.14 $m \cdot s^{-1}$) until exhaustion (Leger & Gadoury, 1989). Maximal HR was recorded immediately after the test via an HR monitor (Polar Electro, Oy, Finland). Maximal oxygen uptake ($\dot{V}O_{2\max}$) was estimated from the level and stage reached using the table of Ramsbottom et al. (1988).

4.3.3 External responses

Movements were recorded using a 10 Hz micro-technology device (Optimeye S5, Catapult Innovations, Melbourne, Australia) fitted into a vest that was securely positioned between the participant’s scapulae. See Chapter 3 for full description of external load markers (3.2 External load measurement, page 67).

Contact intensity (AU), measured as the accumulated PlayerLoad™ during the contact event with a scaling factor, was determined from every contact with both the sled and bag and summated for the entire simulation in addition to total contact count.

4.3.4 Perceptual and internal responses

A HR monitor (Polar Electro Oy, Kempele, Finland) was wirelessly paired to the GPS device and fitted around the chest of the participant. Both movement and HR data were downloaded to a laptop and analysed (Sprint, Version 5.1, Catapult Sports, VIC, Australia). A full description of perceptual and internal load measurements can be found in Chapter 3 (3.3 Internal and perceptual load measurement, page 67).

4.3.5 Lower-body power assessment

The baseline jump was performed in the laboratory before the protocol, so participants warmed up with five minutes of light cycling, 10 bodyweight squats and five submaximal jumps. Jump height was estimated from flight time during a counter-movement jump (CMJ). Depth of counter-movement and foot position were self-selected and participants were instructed to jump as high as possible with each attempt while maintaining hands firmly placed on hips throughout. A 90 s rest period was allowed between three maximal attempts. Jump height was measured using an infrared timing system (Optojumo, Microgate S.r.l., Boozano, Italy) connected to a laptop. Jump height was estimated from flight time as (9.81 x flight time^2) / 8 (Bosco, 1983). This method of estimating jump performance has been previously found to be both valid and reliable (CV = 2.7%; Glatthorn et al., 2011). The mean of the two closest jump heights was taken for analysis (Jennings, 2005).

4.3.6 Statistical Analyses

Between-trial differences in muscle function, blood lactate concentration, RPE, peak sprint speed, relative distance measures and tackle intensity were determined using magnitude-based inferences based on effect sizes and 90% confidence intervals (ES ±90% confidence interval). Effect sizes were calculated as the difference between trial means divided by the pooled standard deviation and supplemented with qualitative descriptor of the mechanistic effect. Threshold probabilities for a mechanistic effect based on 90% confidence intervals were: <0.5% most unlikely, 0.5–5% very unlikely, 5–25% unlikely, 25–75% possibly, 75–95% likely, 95–99% very likely and >99.5% most likely. Effects with confidence limits across a likely small positive or negative change were classified as unclear. All calculations were completed using a predesigned spreadsheet (Hopkins, 2006).

4.4 Results

4.4.1 Running demands

High-speed running distance was *possibly* lower during the bag trial over the total simulation (ES = -0.23 ± 0.35). Sprint to contact speed was *likely* faster during the bag trial in total (ES = 1.03 ± 0.92), whilst Sprint B speed was *possibly* slower during the same trial (ES = -0.33 ± 0.44). *Unclear* differences were found in total distance, low intensity distance and sprint A speed between trials. Relative running demands are shown in Table 4. 1. Mean ± SD relative distance, low-speed running and high-speed running for tackle sled (Sled) and bag (Bag) trials. Data are effect size ±90% CI and qualitative descriptor for Sled c.f. Bag comparisons.**Error! Reference source not found.**. and sprint speeds are presented in Figure 4. 1.

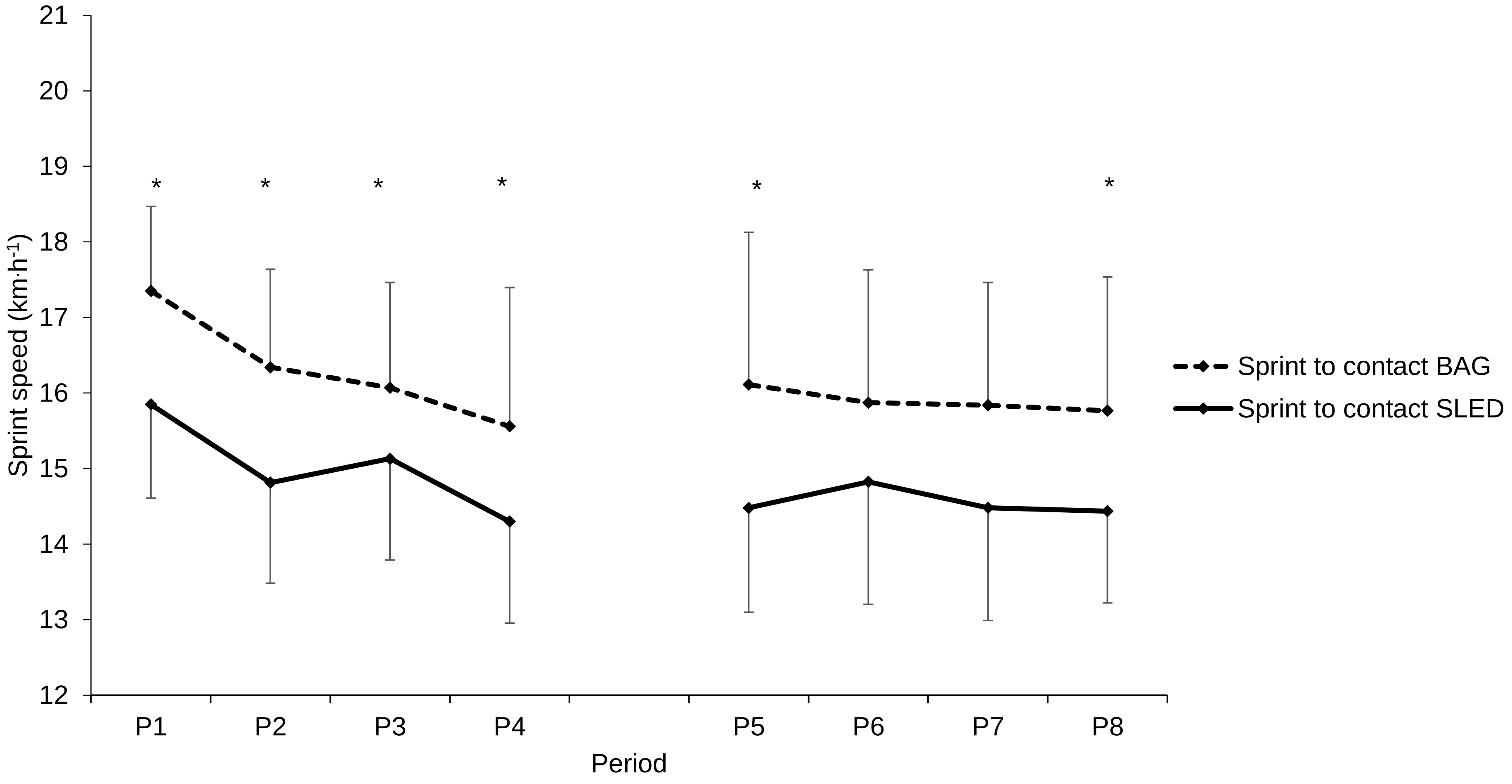


Figure 4. 1 Change in sprint to contact speed by period during the first and second bouts of simulation. Values are mean ± SD. * denotes *likely* difference in sprint speed between trials.

4.4.2 Internal responses

No clear differences were observed in blood lactate concentration after either the first (ES = 0.24 ± 0.53) or second bout (ES = -0.10 ± 0.34). Time with HR in the range 91 – 100 %HR_{peak} was *likely* longer for the Sled trial compared to the Bag trial (12:58 ± 13:21 c.f. 6:44 ± 8:06 min; ES = -0.41 ± 0.48). Despite greater time spent at 91 – 100% HR_{peak} during the Sled trial, there were no clear differences in summated HR between trials (ES = -0.01 ± 0.81). Perceptual and internal demands are presented in Table 4. 2.

Table 4. 1. Mean ± SD relative distance, low-speed running and high-speed running for tackle sled (Sled) and bag (Bag) trials. Data are effect size ±90% CI and qualitative descriptor for Sled c.f. Bag comparisons.

		Whole simulation
Total ($m \cdot min^{-1}$)	Sled	104.2 ± 4.9
	Bag	104.3 ± 4.6
		0.01 ± 0.58
		Unclear
Low ($m \cdot min^{-1}$)	Sled	75.4 ± 5.7
	Bag	76.1 ± 4.2
		0.11 ± 0.55
		Unclear
High ($m \cdot min^{-1}$)	Sled	28.4 ± 2.6
	Bag	27.7 ± 2.4
		-0.21 ± 0.34
		Possible ↓

Low-speed running: <14 $km \cdot h^{-1}$.

High-speed running: ≥14 $km \cdot h^{-1}$.

4.4.3 CMJ performance

Relative change in jump height *likely* decreased to a greater degree (ES = 0.60 ± 0.69) after the Sled trial (-5.9 ± 4.9%) compared to the Bag trial (-2.6 ± 5.4%).

4.4.4 Contact demands

Summated contact load over the total simulation was *possibly* greater during the Bag trial compared to that with the Sled (ES = 0.14 ± 0.28). Overall, contact detection had a CV% of 11.9 and 7.0% respectively for the Sled and Bag trials when compared with the actual contact frequency.

Table 4. 2. Mean ± SD percentage of peak heart rate (%HR$_{peak}$) and summated heart rate (HR) for tackle sled (Sled) and bag (Bag) trials. Data are effect size ±90% CI and qualitative descriptor for Sled vs. Bag comparisons.

		Whole simulation
Time at 91 – 100 %HR$_{peak}$	Sled	12:58 ± 13:21
	Bag	6:44 ± 8:06
		-0.41 ± 0.48
		Likely ↓
Summated HR (AU)	Sled	182 ± 20
	Bag	182 ± 26
		-0.01 ±0.81
		Unclear

4.4.5 Correlations

There was a *large* negative correlation (r ± 90% CI = -0.672 ± 0.114) between high intensity running and summated heart rate during the Bag trial, which was *trivial* for the Sled trial (r ± 90% CI = -0.020 ± 0.206,). Correlations can be found in Figure 4. 3 and 4. 4.

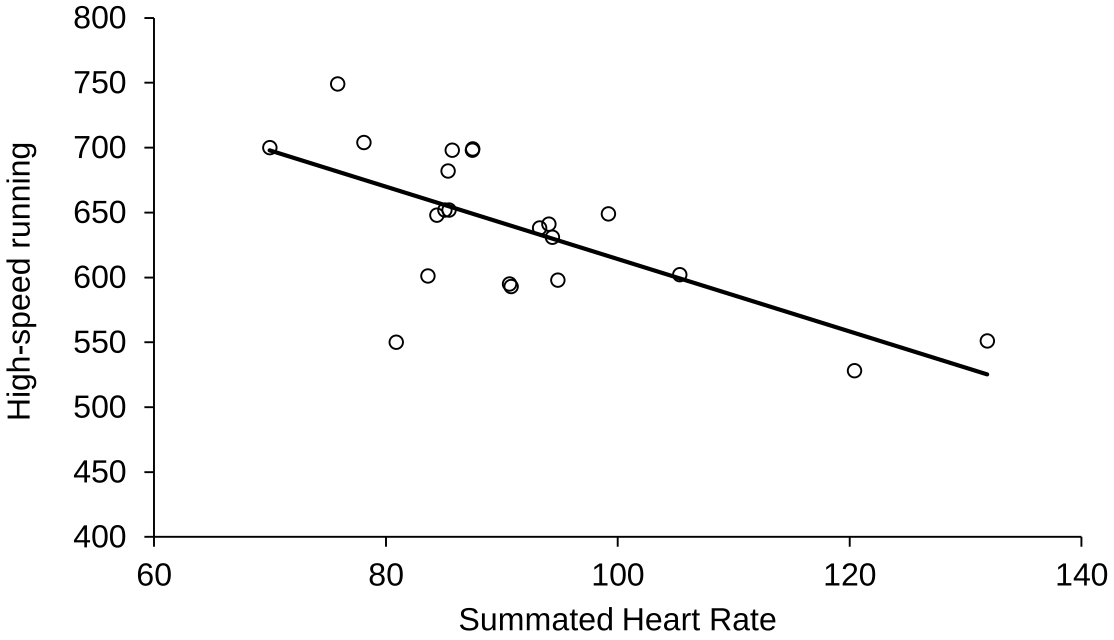


Figure 4. 2. Correlation between high-intensity running and summated heart rate during Bag (*r* = -0.672, *P* < 0.001).

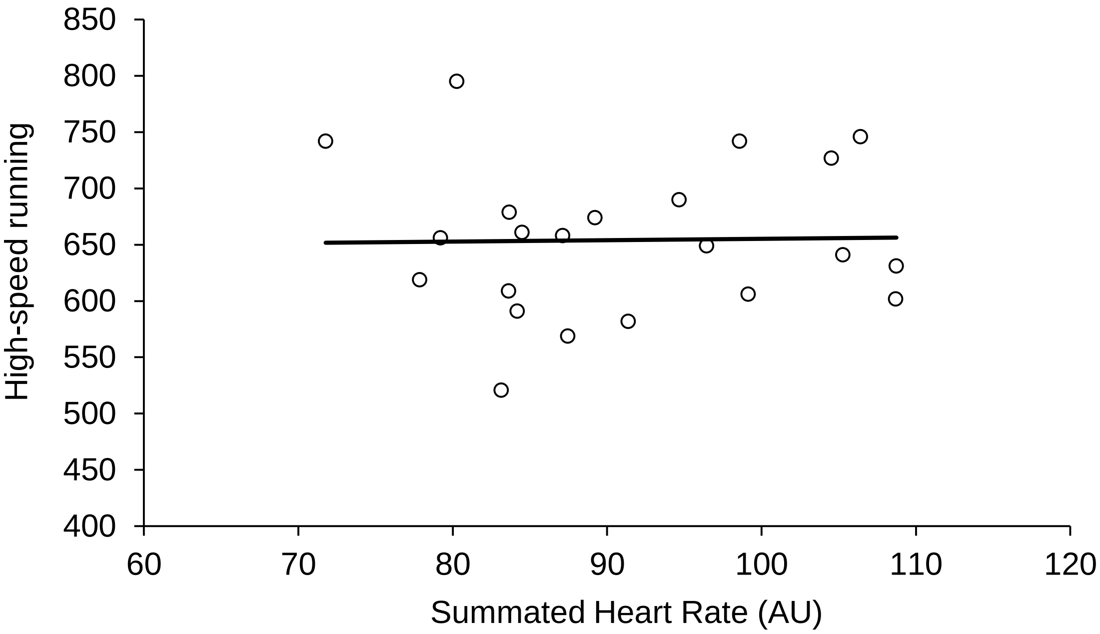


Figure 4. 3. Correlation between high-intensity running and summated heart rate during Sled (*r* = -0.020, *P* = 0.930).

4.5 Discussion

The aim of this study was to investigate the influence of physical contact type on internal and external load during a rugby league match simulation. The findings illustrate subtle differences in the load when contact during intermittent running is replicated using a traditional tackle bag or a weighted tackle sled. More specifically, the use of a weighted tackle sled seemingly elevated the internal load and altered the pacing strategies associated with simulated rugby league performance. The weighted tackle sled increased the time spent in higher HR zones, suggesting a greater internal load is associated with a heavier contact object. Larger decrements in CMJ performance after the Sled trial indicated that post-trial neuromuscular responses are also influenced by the nature of contact. Therefore, when simulating competition, researchers and conditioning coaches should be aware of the limitations of traditional tackle bags for replicating contact demands.

Previous studies have reported lower external load during running with contact compared to non-contact (Johnston & Gabbett, 2011; Johnston et al., 2013). Our data suggest a small, *possible* decrease in high-speed running during the lighter Bag trial (28 ± 2 $m \cdot min^{-1}$) compared to the heavier Sled trial (29 ± 3 $m \cdot min^{-1}$). These small differences in high-speed running are in part explained by changes in sprint activity between conditions, which was the only true self-paced element of the simulation. While sprint to contact was ~9% faster into the tackle bag, the same condition's Sprint B speed, i.e. after contact, was slower (22.8 ± 0.8 $km \cdot h^{-1}$) compared to the Sled trial (23.2 ± 1.0 $km \cdot h^{-1}$). A faster sprint to contact into the tackle bag is likely to have resulted in greater metabolic disturbance immediately after the sprint compared to during the Sled trial. Therefore, we propose that the greater sprint speed into contact with the tackle bag led participants to employ a pacing strategy throughout the rest of the cycle to maintain sprint performance that resulted in less high-speed running overall compared to the Sled trial. This is supported by correlational analysis indicating a *large* negative association between summated HR and high-speed running during the Bag trial. This is to say, participants who maintained a lower HR could perform more high-speed running. This association was not observed during the Sled trial, which indicates that the observed higher physiological load was not associated with running and instead is likely a consequence of contact with a heavier tackle object. Despite the results of this study contradicting previous literature on the effects of contact on locomotive demands (Johnston et al., 2014c) elevated HR response during the Sled trial indicates greater internal load associated with more intense contact.

To the authors' knowledge, this is the first study to analyse individual sprint performances using GPS technology during a simulated rugby match and has led to an important observation in the replication of contact in simulated match activity or training. It seems participants in this study altered their sprint kinematics depending on the type of contact. Contact with the tackle sled is likely to have required greater technical proficiency compared to the tackle bag and provided more resistance due to the size and weight of the tackle arm and steel frame. Consequently, the participants reduced sprint to contact speed to ensure successful execution of skill performance and to reduce any discomfort associated with the physical collision. Velocity before a front-on tackle in competitive rugby union is ~18 $km \cdot h^{-1}$, with higher velocity attributed to the tackler (Hendricks et al., 2014). These velocities are faster than those into the tackle sled (14.8 $km \cdot h^{-1}$) and bag (16.1 $km \cdot h^{-1}$) in this study; however, the mean from both trials falls within the standard deviation of the observed match velocity (~7 $km \cdot h^{-1}$). Differences in velocity between match play and the simulation might be as a consequence of the fixed 8 m sprint into contact during the protocol, which would limit the maximum attainable velocity. It is also likely that participants were less motivated to sprint into contact during the simulation than during a match where tackling performance can influence the outcome of a match.

The *likely* greater decrements in CMJ performance (~5.9%) after the Sled trial indicate greater neuromuscular fatigue associated with this form of contact compared to that with the tackle bag (~2.6%). These findings reaffirm those of Mullen et al. (2015) who reported no change in CMJ flight time after a simulated rugby league match using the same contact bag as described here. More importantly, using the tackle sled appears to better replicate the lower limb fatigue observed in rugby players immediately after matches when measured using jump procedures (McLellan & Lovell, 2012; Twist et al., 2012; West et al., 2014). Acute reductions in jump performance after rugby match play has been attributed to low-frequency fatigue that impairs excitation-contraction coupling (McLellan & Lovell, 2012). This fatigue seems to be greater when intermittent running is combined with contact and driving of a heavy object and highlights the importance of the type of collision when replicating match play in simulations and training (Morel et al., 2015). Indeed, despite greater acute fatigue caused by faster sprint speeds, the heavier contact during the Sled trial resulted in larger detriments to jump performance suggesting that sprinting and high-intensity running do not contribute as greatly to post-match fatigue. It is likely, however, that the inclusion of a body-on-body contact with a contested wrestle would further elevate the internal load and lead to greater decrements in neuromuscular performance. Further research is needed on the relative contribution of running and tackling to acute and prolonged fatigue after rugby league performance.

Contact intensity was measured in this study using tackle load as calculated by the microtechnology device. The results contrasted with the hypothesis that the tackle sled would increase the tackle intensity and found that tackle load was *possibly* greater during the Bag (53.4 ± 10.3 AU) compared to Sled trail (51.4 ± 13.9 AU) across the entire simulation. Tackle detection requires three conditions to be met; the orientation of the device must become non-vertical, accelerometer load must be above a threshold before the change of orientation and there must be a sudden increase in accelerometer load before the change of orientation. Despite participants completing the same number of simulated tackles between conditions, the microtechnology tackle detection feature also reported fewer tackles in the Bag compared to Sled trial as well as underestimating the actual number completed in both. Accordingly, our findings challenge previous research that has reported a strong correlation ($r = 0.96$) with video detection when using microtechnology to measure contact frequency and intensity (Gabbett et al., 2010). A potential cause of this discrepancy is the nature of contact, with the previous study employing body-on-body rather than simulated contacts. It is possible that body-on-body contacts cause the participant to decelerate more when approaching the collision, an action that provides a more potent stimulus to trigger the microtechnology's tackle detection. Tackle load is calculated as the accumulated accelerometer load during the contact event, which is determined as the time from the sudden increase in accelerometer load until the device returns to vertical. Faster sprint to contact speed during the Bag trial compared to the Sled trial could influence the accelerometer load before the contact and artificially inflate the tackle load. Additionally, the time in contact is an important factor in calculating tackle load, which would therefore attribute greater tackle load to a "longer" tackle as opposed to larger impact forces. Less time is spent non-vertical in contact with the sled because the participant remains upright during the collision, unlike the contact with the tackle bag where the participants immediately go to ground. These findings suggest that the tackle load algorithm embedded within the microtechnology software should be used with caution when quantifying tackle intensity in contact sports. Moreover, further research using body-on-body tackles in a controlled environment is required.

Previously, the rugby league simulation has been found to produce comparable HR responses, peak running speeds and low intensity running to Super League match performances but larger total and high intensity running distance (Waldron et al., 2013a). The authors proposed that reduced intensity of collision with a tackle bag relative to match collisions could contribute to the observed greater running demands. This study has again found similar HR responses during the sled simulation (82-89 $\%HR_{peak}$) to values reported for competitive matches (81-85 $\%HR_{peak}$; Waldron et al., 2011), but has failed to replicate running demands (105 $m \cdot min^{-1}$ c.f. 101 $m \cdot min^{-1}$). The disparity in distance covered could still be attributed to limited contact intensity, as only small differences were observed between contact types in this study. This is a limitation for the current study as it is unlikely that participants experienced blunt force trauma to the muscle associated with competitive rugby league that contributes to post-match muscle damage and, the contact protocol still does not account for the wrestle and contest for dominance. It is also likely that pacing strategies play a key role in the differences between competitive and simulated matches. Competitive matches vary greatly and periods of high intensity can occur at any moment, which can lead to conservative pacing strategy to maintain high-intensity performance (Sampson et al., 2015). Contrastingly, during the simulation, participants have detailed knowledge of the task and the fixed end point, which allows an even distribution of effort and might enable the participants to work at a higher intensity during self-paced sprints. Finally, the linear nature of the simulation does not include rapid, unexpected changes of direction that would challenge participant's ability to decelerate and accelerate. Such movement patterns require large eccentric contractions that are both mechanically and metabolically challenging and would likely increase internal load over matched distances. The lack of such movements might enable participants to perform at higher intensities during the simulation compared to competitive match play.

4.6 Conclusions

Modifying the type of contact in a rugby league match simulation subtly alters the internal and external load on participants caused principally by a modification of high-speed running. Participants also appear to modify their sprint behaviour into contact when a heavier object is employed. Despite incorporating collisions with a heavier object, the external load during a forward specific rugby league simulation protocol remains greater than those observed in elite matches. These findings therefore reaffirm the challenges of replicating the collision scenario for contact sports. From a practical perspective, conditioning coaches should be aware of the influence the type of contact has on running performance, internal load and neuromuscular fatigue when planning the purpose of a training session. Previous literature suggests that traditional soft tackle bags provide an additional metabolic challenge to running alone, but does not appear to adequately challenge the cardiovascular or neuromuscular system to prepare players for physical contact. While the tackle sled did not impair high-speed running as hypothesised, it might be able to provide a stimulus that more resembles match intensities; however further research into methods of tackle replication is still required. Finally, the ability of GPS devices to accurately quantify collision events in contact sports remains an area of contention and further research on the use of such technology is warranted.

Chapter 5

The influence of movement speed and contact type on automatic tackle detection and PlayerLoad^{TM} using microtechnology

5.1 Abstract

Background*:* Having identified high variability between the frequency of tackles detected by the GPS device and the actual number of tackles performed in Chapter 4, further investigation of automatic tackle detection is warranted. The automatic tackle detection algorithm requires three conditions to be met; the orientation of the device must become non-vertical, accelerometer load must be above a threshold before the change of orientation and there must be a sudden increase in accelerometer load before the change of orientation. However, it is not currently clear how manipulation of these three factors influence tackle detection accuracy. **Purpose:** Investigate the influence of approach speed and change of orientation on PlayerLoad^{TM} and automatic tackle detection. **Methods:** Five male rugby players performed 60 repetitions of an 8 m shuttle with and without the inclusion of physical contact, whilst wearing two micro-technology devices (Optimeye S5, Catapult). Repetitions were divided into three speed categories; walking, jogging and striding (1, 2.5 and 4 $m{\cdot}s^{-1}$) and four conditions: i) no contact standing upright (NC_{ST}), ii) no contact dropping to the ground in a prone position (NC_{GR}), iii) contact with the tackle bag and remaining upright (C_{ST}), iv) contact with the tackle bag and going to ground (C_{GR}). Tackle detection (n), peak speed ($m{\cdot}s^{-1}$) and accumulated PlayerLoad™ (AU) were analysed from the micro-technology device for each repetition. **Results:** Accuracy, determined by the number of correctly detected trials, was 16-76% across the range of speeds and contact conditions. PlayerLoad^{TM} was greater during C_{GR} at all speeds (ES = 1.24-2.55) and was greater for faster speeds (ES = 1.01–15.71). **Conclusion:** While automatic tackle detection does not appear accurate for use in simulated contact team sports, PlayerLoad^{TM} could be a useful metric that is sensitive to both speed and physical contact.

5.2 Introduction

The accurate quantification of physical collisions in contact team sports is desirable for coaches and sport scientists to plan training and recovery appropriately. Microtechnology has provided a time-efficient method to measure both kinematic and kinetic quantities of team sport activity. Collisions recorded in this way and those recorded from video analysis were significantly correlated (*r* = 0.96), with no differences reported between the device and the video for mild, moderate or heavy collisions. However, further research is required to validate automatic tackle detection during a range of collision events common to training and research settings given microtechnology is currently limited by the inability to distinguish between the types of collision performed (Cummins et al., 2013).

Microtechnology has also been shown to underestimate the total number of tackles during simulated rugby league performance where a known number of tackles were performed (Chapter 4). Given the uncertainly on the utility of this metric, a thorough examination of automatic tackle detection from microtechnology is required.

PlayerLoad™ is derived from the microtechnology device's embedded tri-axial accelerometer and is presented as an arbitrary value based on the combined rate of change of acceleration in three planes of movement; forward, lateral and vertical (Boyd et al., 2011). The metric provides an alternative method to quantify training and match loads in team sports beyond that provided by the GPS (Gabbett, 2015a; Dalen et al., 2016; Boyd et al., 2013). However, using PlayerLoad™ to quantify the frequency and intensity of individual collisions is not possible without separate video analysis. In rugby league it has been suggested that PlayerLoad™ provides an adequate surrogate measure of match or training load for positional groups that perform frequent physical collisions in addition to movement demands (Gabbett, 2015a). Relative

PlayerLoad^{TM} was greater for forward players compared to outside backs during rugby league competition, which could be indicative of greater collision and repeat high-intensity bouts (9.6 ± 2.0 $AU \cdot min^{-1}$ c.f. 7.2 ± 0.8 $AU \cdot min^{-1}$). However, the influence of combined physical contact and locomotor activity on PlayerLoad™ has not been investigated in a controlled manner. Accordingly, the primary aim of this study was to investigate the influence of movement speed and contact condition on automatic tackle detection using a microtechnology device (Optimeye S5, Catapult Innovations, Melbourne, Australia). The secondary aim was to assess the influence of speed, and contact condition on accumulated PlayerLoad^{TM}.

5.3 Methods

5.3.1 Overview

With institutional ethics approval, five male, recreational rugby players (Age: 29.6 ± 6.2 y, stature: 1.80 ± 0.07 m, mass: 85.4 ± 4.8 kg, 3 backs and 2 forwards) performed five repetitions of four different contact conditions, each at three different approach speeds. After a standardised warm-up, contact conditions were performed in a random order with each repetition separated by ~5 min rest to avoid any effect of fatigue on the running and tackle performance. Participants wore a custom designed vest fitted with a microtechnology device (Optimeye S5, Catapult Innovations, Melbourne, Australia) positioned between the right and left scapulae that contained 10 Hz GPS and 100-Hz triaxial accelerometer. Tackle detection (n), peak speed ($m \cdot s^{-1}$) accumulated PlayerLoad™ (AU) and anterior-posterior peak acceleration (g) were analysed from the device for each repetition. All data were downloaded to a laptop and analysed with manufacturer-supplied software (Sprint, Version 5.1, Catapult Sports, Melbourne, Australia).

5.3.2 Protocol

A pilot study was completed beforehand that enabled participants to become accustomed to the audio track, movement speeds and contact conditions. A fourth speed (5.5 $m{\cdot}s^{-1}$) was removed from the study at this stage because participants could not consistently achieve the desired outcome. To control the peak movement speed over an 8 m linear course into the contact, a predesigned audio track comprising five 'bleeps' and the instruction "contact" was created to indicate when the participants should pass cones that were spaced 2 m apart and perform the designated contact condition. The "bleeps" were preceded by 3 further bleeps separated by 1 s each to provide a countdown and allow the participant a short acceleration phase. The desired speeds were 1, 2.5 and 4 $m{\cdot}s^{-1}$ that were chosen to represent "walking", "jogging" and "striding", respectively (Austin & Kelly, 2014). Furthermore, 4 $m{\cdot}s^{-1}$ represents the self-selected mean velocity when running into contact during a match simulation (Chapter 4), and falls within the range of velocities observed during match play (Hendricks et al., 2014).

PlayerLoad^{TM} is a vector magnitude with scaling factor calculated as the square root of the sum of the squared instantaneous change in acceleration from three planes of movement dived by 100 (Boyd et al., 2011). PlayerLoad^{TM} is expressed in arbitrary units (AU) and is presented as an accumulated total combining the movement and contact condition, which is approximately 4 – 10 s of activity. Anterior-posterior acceleration is also presented as a single vector with the peak value measured during contact (g). Automatic tackle detection requires three conditions to be met: the microtechnology device must become non-vertical for > 2 s (i.e. tackling a player to the ground). PlayerLoad^{TM} must be above a threshold before the change of orientation (i.e. jogging or striding before the tackle) and there must be a spike in instantaneous

PlayerLoad^{TM} immediately before the orientation change (i.e. physical contact with another player). In order to satisfy the non-vertical condition, further cues were added to the audio track to instruct the participant on how long to remain “in contact”.

The four contact conditions were performed to replicate actions that could occur in rugby league training and have been previously used in match simulations (Chapter 3; Waldron et al., 2013b; Mullen et al., 2015), whilst isolating specific components of the automatic tackle detection algorithm. For example, during matches and training, tackles can be completed without the ball-carrier being taken to ground, without change of orientation. The conditions were divided into those that involved no contact (standing upright or dropping to the ground in a prone position) or contact (colliding with the tackle bag and remaining upright or colliding with the tackle bag and going to ground). In the no contact conditions, participants moved 8 m and either decelerated to remain upright (NC_{ST}, n = 25) or decelerated and dropped to the ground in a prone position (NC_{GR}, n = 25). Participants were instructed to perform the decelerations as rapidly as possible by moving at the desired speed for 6 m and stopping within 2 m. Therefore, participants had between 0.5 and 2 s to decelerate, depending on the target speed. In the contact conditions, participants moved 8 m and collided with the tackle bag and either remained upright (C_{ST}, n = 25) or went to the ground (C_{GR}, n = 25). In both contact conditions, the same researcher resisted the tackle bag so that no further forward movement was possible. In the C_{GR} condition, the researcher provided initial resistance to the tackle bag to attenuate the forward momentum before allowing the participant to take the bag to ground. The participants were instructed to collide with the tackle bag with their preferred shoulder at waist height whilst flexing the knees and hips and wrap both arms around the bag and researcher. During the contact trials, participants were also instructed to collide with the bag without decelerating from the desired speed. If the participants did not adhere to these instructions, the repetition was repeated and the initial trial was excluded from analysis.

5.3.3 Statistical analysis

To analyse differences in the frequency of automatic tackle detection between speed and condition it was necessary to perform log-linear modelling where the tackle detection frequency was modelled according to speed and contact condition. The suitability of the data for log-linear analyses was examined in accordance with the recommendations of Tabachnick & Fidell (2013). To satisfy expected cell frequencies, NC_{ST} condition and trials that resulted in two tackles were eliminated from the analysis. Starting with the saturated model within hierarchical log-linear analysis, backwards elimination was applied to remove non-significant three- and two-way interactions between speed, contact condition and tackle detection, using a statistical significance cut-off of 0.05 to identify the simplest fitting model. The resulting model therefore includes only those associations necessary to reproduce the observed frequencies. The likelihood ratio statistic was used to determine whether the expected frequencies produced by the model were significantly ($P < 0.05$) different from the observed data. Statistical procedures were carried out using a computer-based statistics package (Version 21, IBM SPSS, USA).

Differences in PlayerLoad^{TM} between contact conditions and speeds were determined using magnitude-based inferences based on effect sizes and 90% confidence limits (ES ± 90% confidence limit). Effect sizes were calculated as the difference between trial means divided by the pooled standard deviation and supplemented with qualitative descriptor of the mechanistic effect. Threshold probabilities for a mechanistic effect based on 90% confidence intervals were: <0.5% most unlikely, 0.5–5% very unlikely, 5–25% unlikely, 25–75% possibly, 75–95% likely, 95–99% very likely and >99.5% most likely. Effects with confidence limits across a likely small positive or negative change were classified as unclear. All calculations were completed using a predesigned spreadsheet (Hopkins, 2006).

The observed accuracy of tackle detection was considered as a percentage based on the number of trials with correct detection of the tackle frequency divided by total number of trials.

5.4 Results

5.4.1 Measured speed

The measured peak speed (mean ± SD) over 8 m during walking (1 $m \cdot s^{-1}$), jogging (2.5 $m \cdot s^{-1}$) and striding (4 $m \cdot s^{-1}$) were 1.1 ± 0.1, 2.6 ± 0.4 and 4.1 ± 0.4 $m \cdot s^{-1}$, respectively.

5.4.2 Tackle detection

Log-linear analysis resulted in a model for tackle detection that comprised the two-way interaction contact condition x tackle detection and the one-way effects contact condition and tackle detection ($\chi^2(24) = 3.74$, $P = 1.0$). The two-way interaction of contact condition x tackle detection ($\chi^2(6) = 47.2$, $P < 0.001$) showed that tackle detection was influenced by the type of contact but not movement speed.

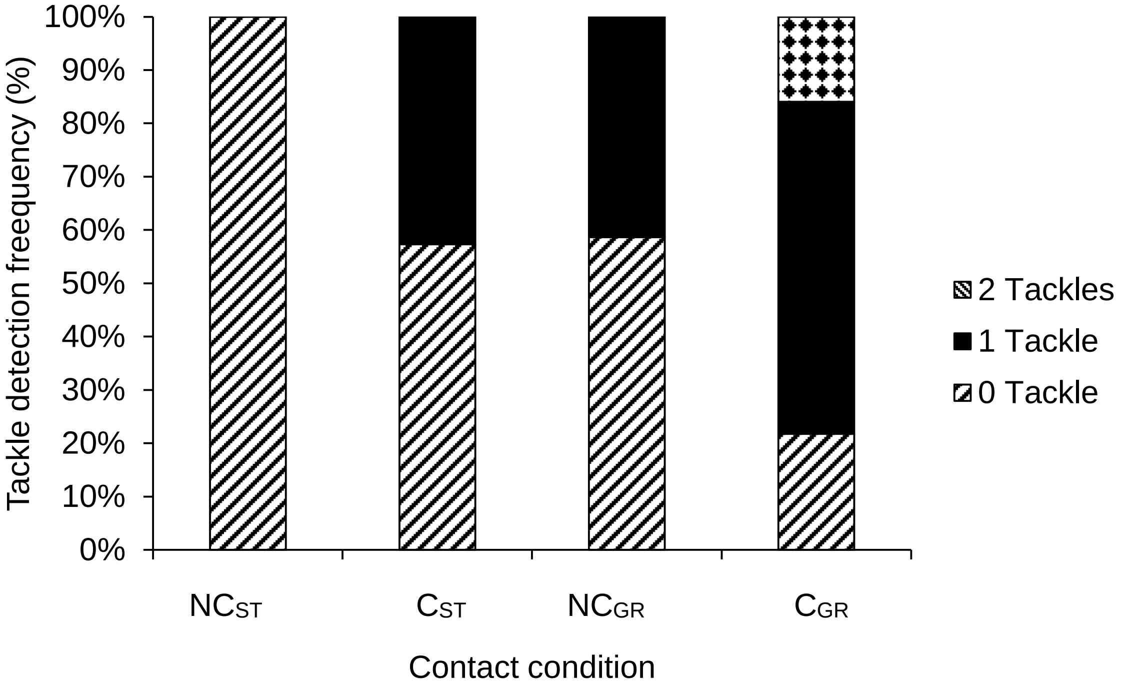


Figure 5. 1. Automatic tackle detection frequency (expressed as a percentage) for all speeds between each contact condition. Percentage calculated as n / 75 x 100. Abbreviations: NC$_{ST}$, no contact stand; C$_{ST}$, contact stand; NC$_{GR}$, no contact ground; C$_{GR}$, contact ground.

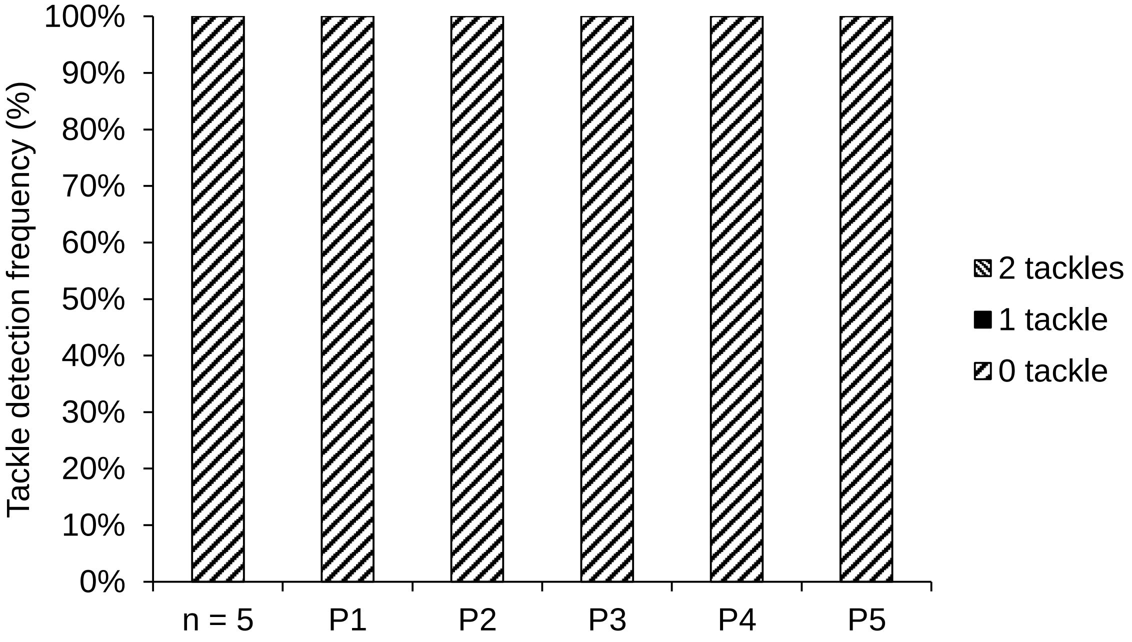


Figure 5. 2. Automatic tackle detection frequency (expressed as a percentage) during the no contact stand scenario (NC$_{ST}$) for all speeds between each participant and the total population. Percentage calculated as n / 75 x 100.

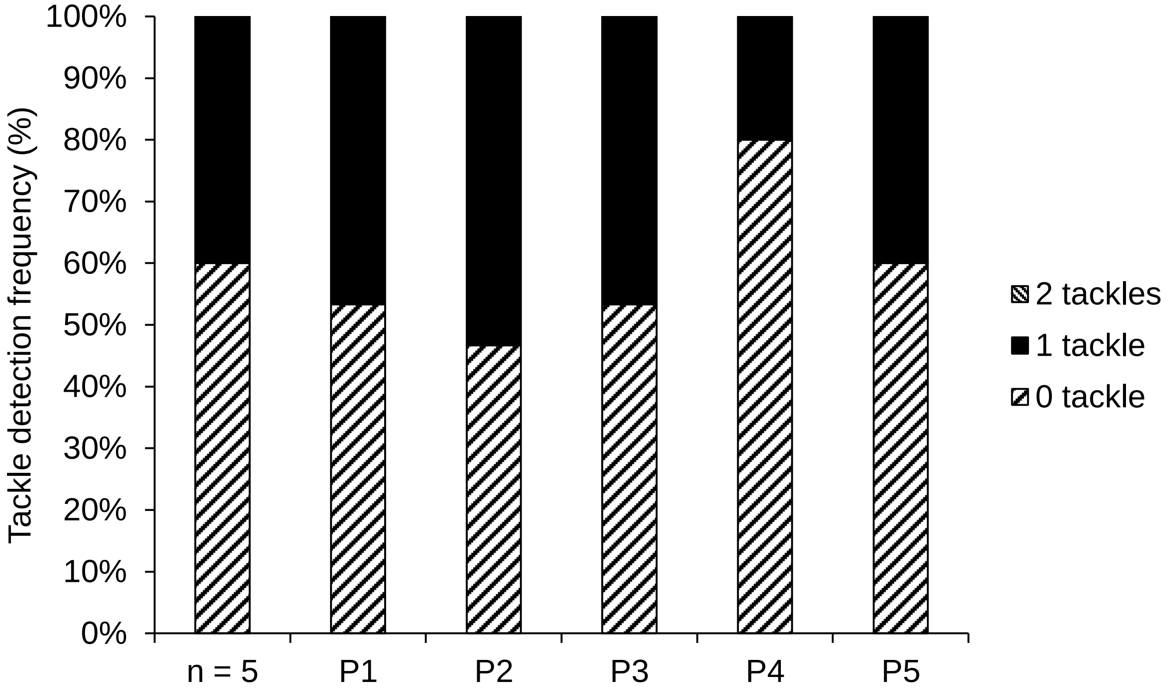


Figure 5. 3. Automatic tackle detection frequency (expressed as a percentage) during the no contact ground scenario (NC_{GR}) for all speeds between each participant and the total population. Percentage calculated as n / 75 x 100.

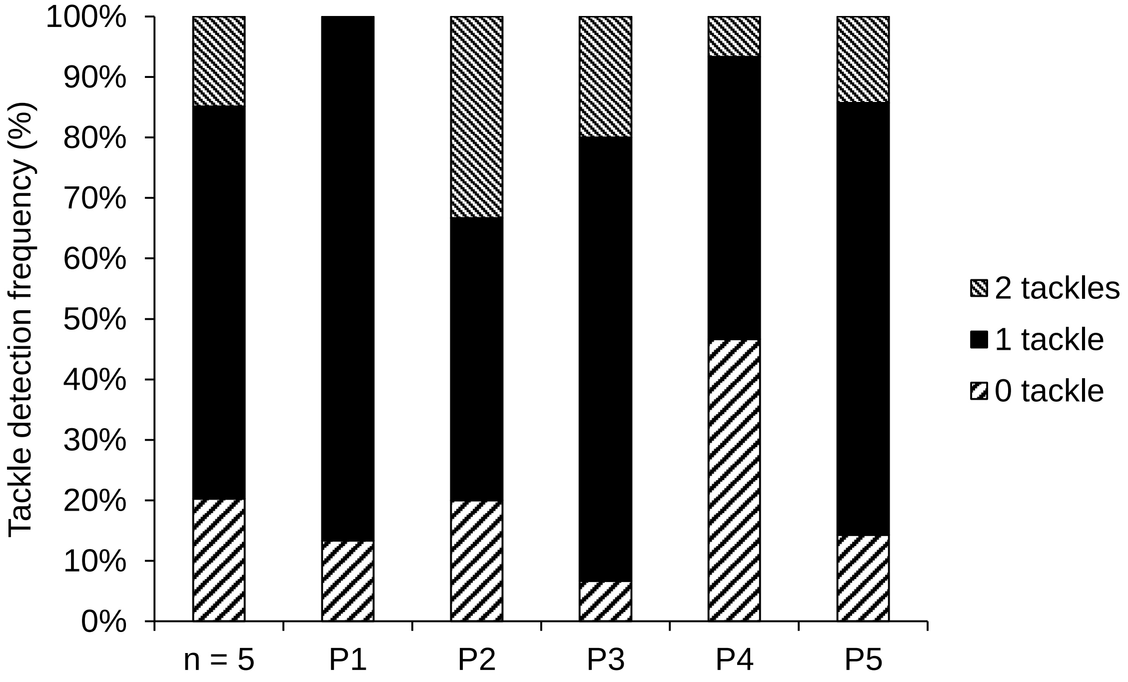


Figure 5. 4. Automatic tackle detection frequency (expressed as a percentage) during the contact ground scenario (C_{GR}) for all speeds between each participant and the total population. Percentage calculated as n / 75 x 100.

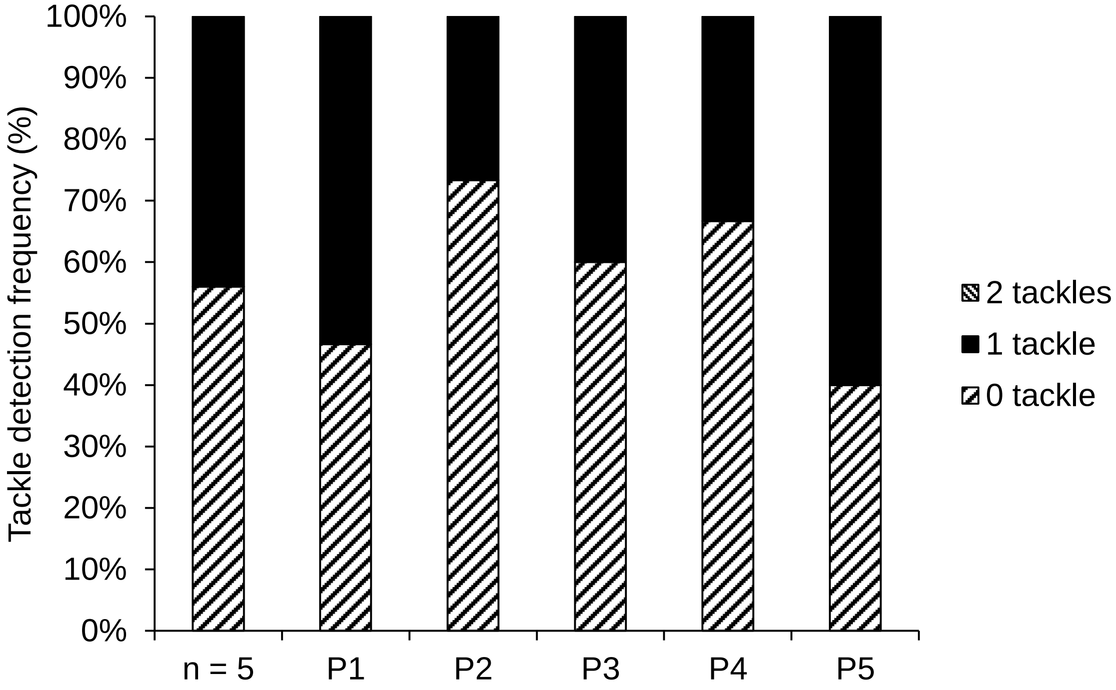


Figure 5. 5. Automatic tackle detection frequency (expressed as a percentage) during the contact stand scenario (C_{ST}) for all speeds between each participant and the total population. Percentage calculated as n / 75 x 100.

5.4.3 PlayerLoad^{TM}

PlayerLoad^{TM} was greatest during C_{GR} at all speeds (Table 4). During walking the NC_{GR} condition resulted in *possibly* greater PlayerLoad^{TM} compared to C_{ST} (ES = 0.21 ± 0.33) and *most likely* greater PlayerLoad^{TM} compared to NC_{ST} (ES = 1.77 ± 0.32), while C_{ST} was also *most likely* greater than NC_{ST} (ES = 1.70 ± 0.33). During jogging and striding, there were *unclear* differences between NC_{GR} and C_{ST} (ES = 0.16 ± 0.40 and 0.31 ± 0.53, respectively). PlayerLoad^{TM} was *most likely* greater during NC_{GR} compared to NC_{ST} for jogging (ES = 1.32 ± 0.40) and striding (ES = 1.37 ± 0.53) and between C_{ST} and NC_{ST} whilst jogging (ES = 1.48 ± 0.36) and striding (ES = 1.68 ± 0.45).

Table 5. 1. Mean ± SD for PlayerLoad^{TM} (AU) when walking, jogging and striding during each contact condition. Effect sizes between C_{GR} and NC_{GR}, C_{ST} and NC_{ST} conditions, respectively.

	PlayerLoad^{TM} (AU)				C_{GR} c.f. NC_{GR}	C_{GR} c.f. C_{ST}	C_{GR} c.f. NC_{ST}
	C_{GR}	NC_{GR}	C_{ST}	NC_{ST}	Effect Size	Effect Size	Effect Size
Walking	0.99 ± 0.26	0.65 ± 0.16	0.61 ± 0.12	0.36 ± 0.06	1.25; ±0.28 *most likely* greater	1.31; ±0.35 *most likely* greater	2.20; ±0.34 *most likely* greater
Jogging	1.79 ± 0.34	1.31 ± 0.16	1.34 ± 0.17	1.10 ± 0.12	1.37; ±0.36 *most likely* greater	1.24; ±0.29 *most likely* greater	1.91; ±0.36 *most likely* greater
Striding	2.16 ± 0.33	1.48 ± 0.14	1.53 ± 0.23	1.28 ± 0.23	2.00; ±0.34 *most likely* greater	1.85; ±0.25 *most likely* greater	2.55; ±0.23 *most likely* greater

Abbreviations: C_{ST}, contact stand; NC_{GR}, no contact ground; C_{GR}, contact ground; NC_{ST}, no contact stand.

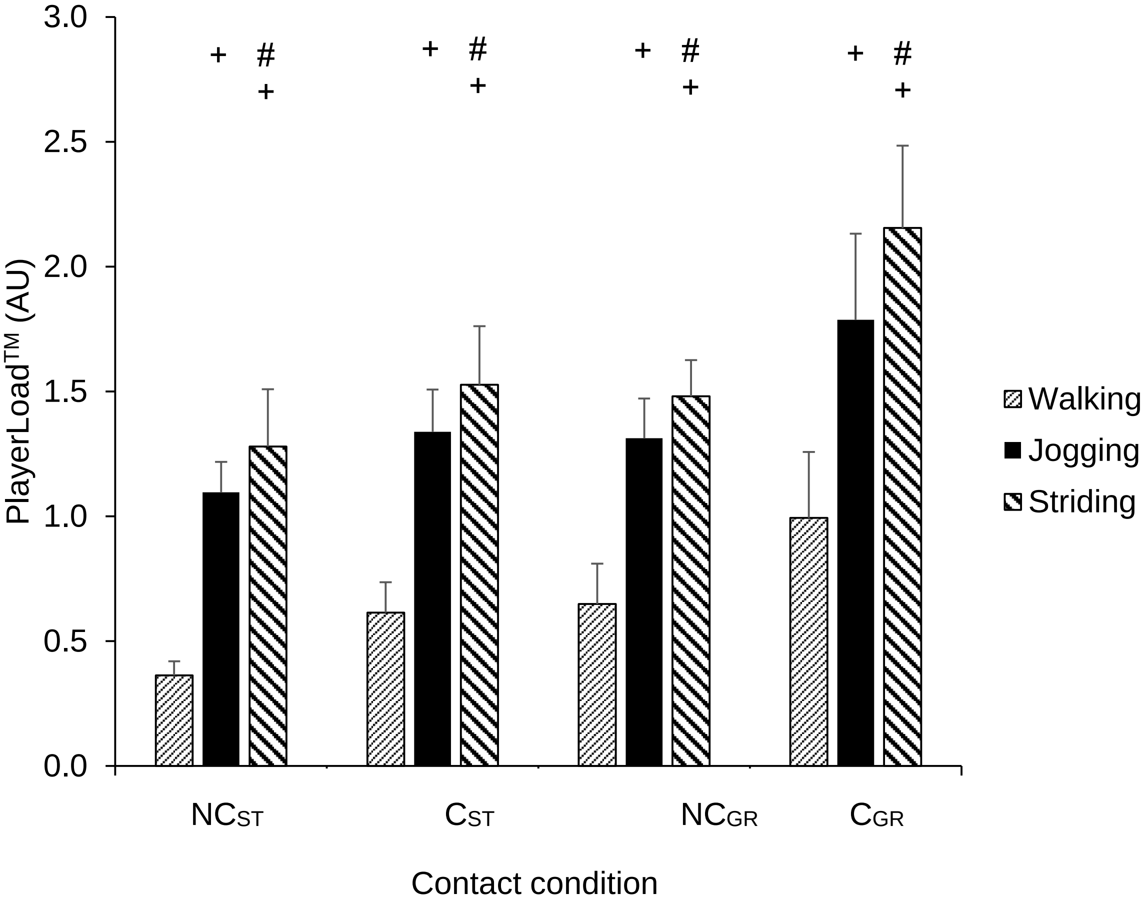


Figure 5. 6. Difference in PlayerLoad^{TM} during C$_{GR}$ and NC$_{GR}$, C$_{ST}$ and NC$_{ST}$ conditions at each speed. + denotes *most likely* greater effect compared to walking; # denotes *most likely* greater effect compared to jogging.

Abbreviations: NC$_{ST}$, no contact stand; C$_{ST}$, contact stand; NC$_{GR}$, no contact ground; C$_{GR}$, contact ground.

During the C$_{GR}$ condition, striding resulted in *most likely* greater total PlayerLoad^{TM} compared to walking (ES = 4.11 ± 0.42) and jogging (ES = 1.30 ± 0.42), while PlayerLoad^{TM} during jogging was *most likely* greater than walking (ES = 2.81 ± 0.38). During C$_{ST}$, striding lead to *most likely* greater total PlayerLoad^{TM} compared to walking (ES = 7.26 ± 0.44) and jogging (ES = 1.50 ± 0.32), while PlayerLoad^{TM} during jogging was *most likely* greater than walking (ES = 5.76 ± 0.28). The NC$_{ST}$ condition resulted in striding accumulating *most likely* greater total PlayerLoad^{TM} compared to walking (ES = 15.71 ± 1.29) and jogging (ES = 3.11 ± 1.29), while PlayerLoad^{TM} during jogging was *most likely* greater than walking (ES = 12.6 ± 0.59). Finally, during NC_{GR}, striding resulted in *most likely* greater total PlayerLoad^{TM} compared to walking (ES = 4.99 ± 0.40) and jogging (ES = 1.01 ± 0.38), while PlayerLoad^{TM} during jogging was *most likely* greater than walking (ES = 3.98 ± 0.37).

5.4.4 Peak anterior-posterior acceleration

Anterior-posterior acceleration was greatest during C_{GR} at all speeds. During the walking trials C_{GR} was *most likely* greater than C_{ST} (ES = 1.45 ± 0.41) and NC_{ST} (ES = 2.42 ± 0.35) and *very likely* greater than NC_{GR} (ES = 0.75 ± 0.37). Similar results were observed for jogging with C_{GR} *most likely* greater than both C_{ST} and NC_{ST} (ES = 1.17 ± 0.37 and 1.39 ± 0.37, respectively). Acceleration was also *likely* greater in C_{GR} compared to NC_{GR} during walking trials (ES = 0.52 ± 0.38). During the striding trials, C_{GR} was also *most likely* greater than C_{ST} (ES = 0.85 ± 0.28) and NC_{ST} (ES = 1.10 ± 0.39) while the effect was *possibly* greater compared to NC_{GR} (ES = 0.40 ± 0.54).

Speed into contact increased anterior-posterior acceleration for C_{GR} with *very likely* greater acceleration during striding trials compared to walking (ES = 0.92 ± 0.56) and *likely* greater compared to jogging (ES = 0.57 ± 0.56). For C_{ST} trials, acceleration in both jogging and striding were *most likely* greater than walking (ES = 1.21 ± 0.48 and 2.03 ± 0.69, respectively). Acceleration was also *likely* greater during striding than jogging for C_{ST} trials (ES = 0.82 ± 0.70). Striding was also greatest during NC_{GR} trials with *likely* greater acceleration compared to jogging (ES = 0.59 ± 0.46) and *most likely* greater compared walking (ES = 1.43 ± 0.57). Acceleration was also *very likely* greater when jogging compared to walking (ES = 0.70 ± 0.35). Striding resulted in *most likely* greater acceleration in NC_{ST} trials compared to jogging (ES = 5.42 ± 2.97) and walking

(ES = 24.24 ± 2.25). Jogging also resulted in *most likely* greater acceleration during NC_{ST} trials compared to walking (ES = 17.43 ± 2.98).

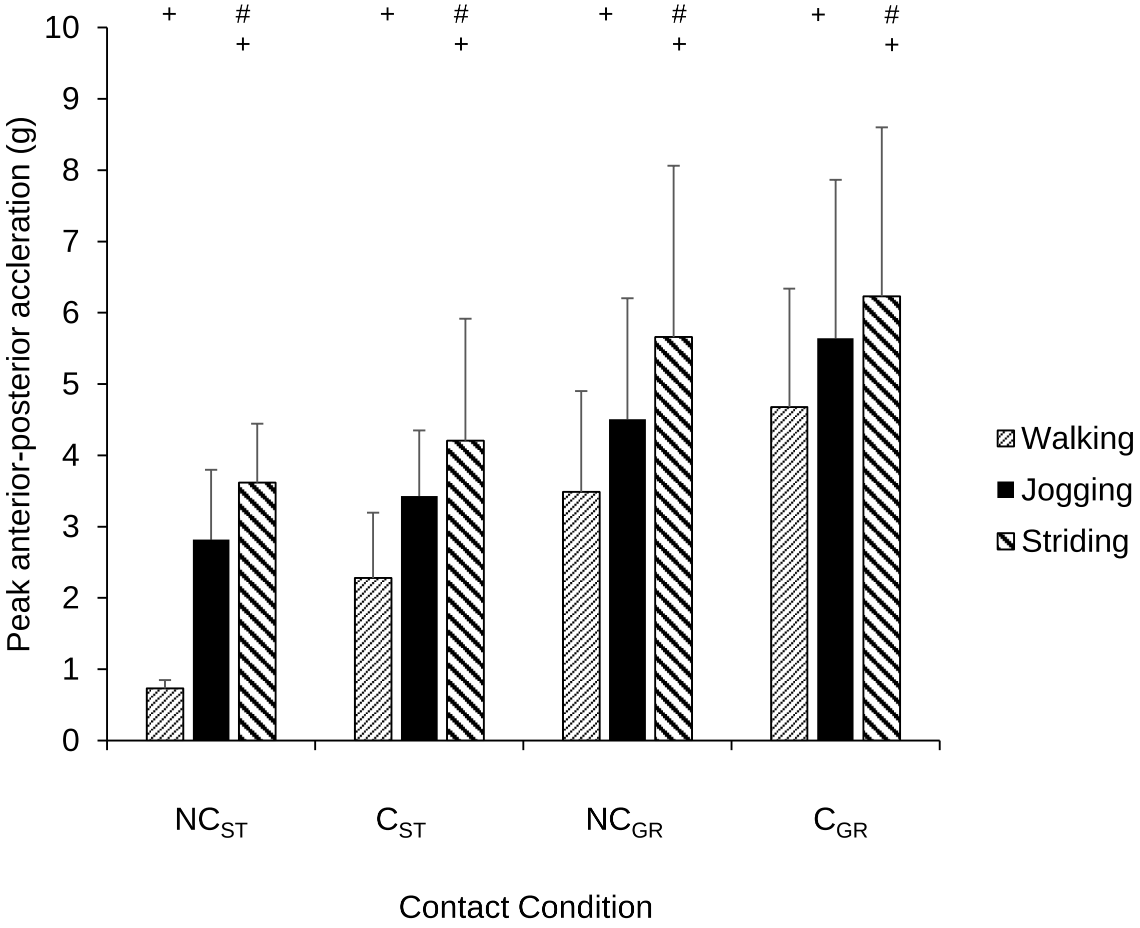


Figure 5. 7. Difference in peak anterior-posterior acceleration during C_{GR} and NC_{GR}, C_{ST} and NC_{ST} conditions at each speed. + denotes most likely greater effect compared to walking; # denotes most likely greater effect compared to jogging.
Abbreviations: NC_{ST}, no contact stand; C_{ST}, contact stand; NC_{GR}, no contact ground; C_{GR}, contact ground.

5.5 Discussion

The primary aim of this study was to investigate the influence of movement speed, contact and change of orientation on automatic tackle detection using a 10 Hz microtechnology device with 100 Hz accelerometer (Optimeye S5, Catapult Innovations, Melbourne, Australia). Log-linear analysis revealed that contact condition influenced tackle detection but not speed into contact. Accuracy, determined by the number of correctly detected trials, was 40-100% across the range of speeds and contact conditions investigated. Therefore, the use of automatic tackle detection to determine the frequency of physical contact efforts during the types of collision activities replicated in this study should be used with caution. Large differences in accumulated PlayerLoad^{TM} between speed and contact conditions indicate that the metric is sensitive to both locomotion and physical contact demands which could provide a useful indicator of total load in training and matches.

The present findings question the use of microtechnology devices to quantify the frequency of tackles during collision sports. Previous attempts to validate the use of automatic tackle detection have produced equivocal findings during training and matches (Gabbett et al., 2010; McLellen & Lovell, 2012), however an analysis of the algorithm with prescribed contact conditions has yet to be performed. In the current study, similar tackle detection accuracy was observed between NC_{GR} and C_{ST} conditions (one tackle observed in 41 and 43% of trials, respectively). This result indicates that either a spike in instantaneous PlayerLoad^{TM} from contact or a change of orientation from dropping to the ground will trigger automatic detection for ~40% of instances. Furthermore, the high percentage of occasions where no tackles were detected for NC_{GR} and C_{ST} (59 and 57%, respectively) during all speeds suggest that the ability of the device to detect tackles is impaired when one stimuli occurs independently. During rugby league matches there can be ~75 “missed tackles” where a physical collision occurs but the tackle is not completed (King, Hume & Clark, 2011). The present findings suggest that for collisions with a tackle bag, without change of orientation, will not be detected for ~50% of the occurrences, despite the associated physical collision that warrants detection. However, it is also apparent that if no spike in accelerometer load is present, then ~40% of independent changes in orientation will result in tackle detection when no discernible contact has occurred. C_{GR} combined both an instantaneous spike in PlayerLoad^{TM} and change of orientation by colliding with a tackle bag and going to ground. While C_{GR} resulted in the largest frequency of one tackle detected (62%), during 16% of trials two tackles were detected. It is likely that both the initial impact with the tackle bag could trigger a tackle in addition to the proceeding change of orientation when going to ground. It is relevant to include all body impacts when considering total load including contact with other players and the ground, for research purposes it is not appropriate to categorise the events as distinct tackles. Therefore, the current algorithm for automatic tackle detection frequencies derived from microtechnology in training and match play should be used with caution. However, attempts have been made to improve the accuracy and precision of tackle detection using pattern recognition techniques (Kelly et al., 2015) and different filtering rates (Wundersitz et al., 2015b). While this work is in the early stages, the use of machine learning improved tackle detection precision to 95.8%, which suggests the number of incorrect detections observed in the present study could be reduced with modification to the algorithm. For example, during C_{GR} 11 / 75 trials were incorrectly detected as two tackles, which might be reduced by introducing a longer "collision window" in the acceleration signal. This would stop the detection of another tackle within a set time frame based around the initial impact. Such a modification would stop a second tackle being detected when the player hits the ground.

Automatic tackle detection requires a pre-determined threshold for PlayerLoad^{TM} to be exceeded before contact, which is determined by movement speed (Barrett et al., 2014). However, the results in this study indicate that speed into contact from 1 – 4 $m \cdot s^{-1}$ does not influence automatic tackle detection. Log-linear analysis resulted in a model that did not include movement speed despite large increases in PlayerLoad^{TM} at faster speeds (*most likely* greater from walking to jogging and jogging to striding; Figure 3). Faster movement speed immediately before a tackle is also associated with larger accelerations during collisions (Wundersitz et al., 2015b). In agreement, peak forward acceleration was greater at faster speeds during C_{ST} (*most likely* greater from walking to jogging and jogging to striding) in this study. Furthermore, similar values for anterior-posterior acceleration (g) were observed compared to those during AFL matches (Gastin et al., 2014). Anterior-posterior acceleration values during contact have been reported between 1.4 and 7.3 g, which is comparable with the contact conditions in the present study (4.21 ± 1.71 and 6.23 ± 2.37 for C_{ST} and C_{GR}, respectively, when striding). However, automatic tackle detection was not influenced by increases in PlayerLoad^{TM} or acceleration at incrementally faster speeds. Further investigation into the role of vertical and lateral acceleration is required to understand the contribution to automatic tackle detection.

The present results demonstrate that PlayerLoad^{TM} is sensitive to changes in movement speed and the inclusion of physical contact (Table 4 and Figure 3). The tri-axial accelerometer within wearable microtechnology has previously been shown to produce reliable data for field sports athletes (Boyd et al., 2011), however an examination of PlayerLoad^{TM} with controlled collision events has yet to be performed. The results from the present study demonstrate that the metric can detect differences in movement speed, the inclusion of physical contact and changes in orientation during short bouts of activity designed to replicate typical training actions. While it is not currently possible to distinguish the contributing factors to PlayerLoad^{TM}, such a global metric could provide a simple indication of the total session load during collision-orientated activities. However, the data in this study is taken from 4 - 10 s of activity and caution is required when extrapolating results to more extended periods. Therefore, it is recommended that future research should investigate the utility of PlayerLoad^{TM} to quantify prolonged bouts of controlled intermittent running with physical contact.

This chapter is not without limitations including the sample size and study design. Individual tackle technique is likely to influence automatic tackle detection, so a large sample size with each participant performing fewer repetitions would minimise bias towards certain individuals. While it was not within the scope of this study, particular individual techniques (e.g. greater forward lean at impact) could result in improved tackle detection compared to others. Another limitation is the nature of the contact replication in this study. Speed before contact is less than that observed during high-intensity tackles (Gastin et al., 2014) and the use of a tackle bag does not fully replicate player on player body contact in matches. Such limitations impair the generalisability of the findings to competitive scenarios. However, the type of contact used is relevant for simulating match performance (Waldron et al., 2013b; Mullen et al., 2015) and is common in training practices (Johnston & Gabbett, 2011).

5.6 Conclusions

The results of this study demonstrate that automatic tackle detection algorithms in microtechnology devices should be interpreted with caution. Correct tackle frequency was attained for 40-100% of trials dependant on contact condition during discrete simulated collision events. The presence of physical contact and a change of device orientation influences automatic tackle detection, but movement speed before contact does not. Therefore, automatic tackle detection does not appear suitable for use in simulated match performance or to quantify collision frequency in training activities. However, due to limitations in this study, conclusions on tackle detection during matches are not currently possible. Alternatively, PlayerLoad^{TM} appears to be a useful metric that is sensitive to both increased speed into physical contact and change of orientation, although further research is required to determine the usability over extended bouts of controlled intermittent activity.

Chapter 6

The reliability of a modified rugby league match simulation protocol for interchange players.

6.1 Abstract

Background: Match simulations provide a useful tool to analyse specific match actions in rugby league. However, the absence of person-to-person physical contact in existing protocols means current simulations do not truly replicate the physiological load of competitive matches, as reported in Chapter 4. **Purpose:** Confirm the reliability of locomotive and physiological responses to modified physical contact during the RLMSP-i in the context of relevant analytical goals and provide comparison of these measurements to the previous simulation, training and match data. **Methods:** Nineteen rugby players performed two trials of a modified version of the RLMSP-i separated by one week. During the match simulation, participants' locomotion and tri-axial accelerometer load were recorded using a wearable micro-technology device (Optimeye S5, Catapult). Internal load was quantified with heart rate (%HR_{peak}) and rating of perceived exertion (RPE), measured throughout the simulation. **Results:** The coefficient of variation (%CV) for locomotive metrics ranged from 1.3 to 14.4%, with greatest variability observed for high-speed running distance (8.0 and 14.4% for Bouts 1 and 2, respectively). Accelerometer metrics %CV were 4.4 to 10.0%, while internal load markers were 4.8 to 13.7%. All variables presented a CV% less than the calculated moderate change during one or both bouts of the match simulation except from high-speed distance ($m \cdot min^{-1}$), %HR_{peak} and RPE (AU). **Conclusion:** The current rugby league match simulation with modified tackle replication provides a controlled model to investigate physical performance. Low variability in PlayerLoad^{TM} (CV% = 4.7-5.8%) and its derivatives permits further investigation to identify appropriate methods to quantify global-load in contact sports such as rugby league. Finally, total and high-speed running distance were reduced in the modified protocol and were closer to those reported from matches.

6.2 Introduction

Despite possessing acceptable validity and reliability for locomotive demands, previous attempts to simulate the match demands of rugby league have been limited by lower physiological responses relative to high-speed running compared to match play (Waldron et al., 2013b). The use of a soft tackle bag to replicate contact increased the overall running speed because of a faster approach to the collision and results in less neuromuscular fatigue when compared to a heavier tackle sled (Chapter 4). Therefore, further attempts to adequately replicate contact during the rugby league match simulation protocol, whilst maintaining the reliability of physiological, perceptual and performance responses, are required.

PlayerLoad^{TM} is positively correlated with treadmill running velocity (Barrett et al., 2014), total distance and collisions (Gabbett, 2015a) and has potential to distinguish between contact type (Chapter 5). Such markers appear able to quantify rugby league specific activities such as wrestling and grappling and have been shown to discriminate between positions during rugby league matches (Gabbett, 2015a). However, the reliability of such metrics during intermittent running interspersed with physical collisions is still unknown. Therefore, the aims of this study were to: a) confirm the reliability of these measurements in the context of relevant analytical goals and b) describe the locomotive and physiological responses to modified physical contact during the RLMSP-i and compare with previous protocols and match data.

6.3 Methods

6.3.1 Overview

Nineteen sub-elite rugby players (age: 17.9 ± 1.4 y, stature: 1.80 ± 0.08 m, mass: 87.9 ± 11.8 kg) performed two trials of a modified version of the previously described

RLMSP-i (Waldron et al., 2013b) separated by one week. The participants were asked to record their dietary intake in the 24 hours before the first trial, to be repeated in the 24 hours before their second trial. Both trials were performed at the same time of day (± 1 hour) on the same synthetic grass outdoor pitch in similar environmental conditions (14.4 ± 0.6°C). All participants provided written informed consent and were free from injury at the time of testing. The Faculty of Life Sciences Research Ethics Committee granted ethics approval for the study.

Participants were habituated to the simulation before each trial, comprising three cycles of the simulation that lasted approximately 6 minutes and given verbal instructions on the protocol requirements. During the match simulation, participants' locomotion, tri-axial accelerometer load, HR and RPE were measured.

6.3.2 Rugby league movement simulation protocol for interchange players

A full description of the protocol can be found in Chapter 3 (

3.1.2 Modified tackle using person-to-person contact (Chapters 6, 7 and 8).

Contact was modified from that described by Waldron and colleagues (2013) to involve a collision between two participants that were matched for body mass. The collision event comprised one participant performing a defensive tackle on their opponent holding a tackle shield. Participants performed 24 defensive and 24 offensive efforts over the duration of the simulation.

6.3.3 External load

The general method for micro-technology data collection can be found in Chapter 3 (3.2 External load measurement). In addition, total PlayerLoad^{TM}, two-dimensional PlayerLoad^{TM} (PlayerLoad^{TM} 2D) and PlayerLoad^{TM} slow were recorded and the ratio of PlayerLoad^{TM} slow to total PlayerLoad^{TM} (PlayerLoad^{TM} slow-ratio; %) was calculated for each bout of the simulation. All external load data was downloaded to a laptop and analysed using the manufacturer's software (Sprint, Version 5.1, Catapult Sports, Australia). These metrics were selected based on their appropriateness for quantifying the movements and activities of collision sports (Gabbett, 2015a).

6.3.4 Internal load

The method for HR and RPE measurement techniques can be found in Chapter 3 (3.3 Internal and perceptual load measurement).

6.3.5 Statistical analysis

Absolute reliability was assessed using Typical Error (TE), calculated as the standard deviation (SD) of the differences (diff) between trial 1 and trial 2 divided by √2. Relative reliability between trials was analysed using coefficient of variation (CV%) calculated as; (SD diff/√2) / (grand mean) x 100 (Hopkins, 2000). The smallest worthwhile change (SWC; 0.2 x between participant SD/grand mean), moderate change (MC; SWC x 3) and large change (LC; SWC x 6) were determined to provide an analytical goal for reliability (i.e. measurement error should be lower than these meaningful changes to have sufficient confidence that they are 'real'). All calculations were completed using a predesigned spreadsheet (Hopkins, 2006).

6.4 Results

No variable resulted in a CV% smaller than the SWC. All variables presented a CV% less than the calculated MC during one or both bouts of the match simulation except from high-speed distance ($m \cdot min^{-1}$) during bout 1 (8.0% c.f. 7.0%) and bout 2 (14.4% c.f. 10.3%), HR (%HR_{peak}) during bout 1 (4.8% c.f. 4.4%) and bout 2 (7.0% c.f. 5.8%) and RPE (AU) during bout 1 (13.7% c.f. 8.9%) and bout 2 (11.2% c.f. 6.7%). In all of these exceptions, the CV% was smaller than the LC. All data are presented in Table 6.1 and 6.2.

Table 6. 1. The reliability of internal and external load during bouts 1 and 2 over two trials of the modified rugby league movement simulation protocol for interchange players (RLMSP-i).

	Total distance ($m \cdot min^{-1}$)	High-speed ($m \cdot min^{-1}$)	Low-speed ($m \cdot min^{-1}$)	Peak speed ($km \cdot h^{-1}$)	$\%HR_{peak}$	RPE
Bout 1						
Trial 1 (± SD)	102.8 ± 2.4	25.0 ± 3.3	77.9 ± 3.8	24.3 ± 1.5	82.8 ± 6.6	14.4 ± 2.1
Trial 2 (± SD)	100.7 ± 3.1	24.1 ± 2.2	76.6 ± 2.6	23.7 ± 1.4	81.5 ± 5.1	12.7 ± 1.6
TE	1.4	2.0	1.7	0.9	3.9	1.9
CV%	1.3	8.0	2.2	3.7	4.8	13.7
SWC%	0.6	2.3	0.9	1.2	1.5	3.0
MC%	1.8	7.0	2.6	3.7	4.4	8.9
LC%	3.5	13.9	5.2	7.5	8.7	17.8
Bout 2						
Trial 1 (± SD)	100.3 ± 3.2	22.5 ± 3.3	78.6 ± 3.9	23.3 ± 1.9	80.8 ± 7.3	13.1 ± 1.8
Trial 2 (± SD)	100.7 ± 3.0	21.1 ± 4.0	79.6 ± 2.8	22.2 ± 2.6	78.9 ± 8.1	12.6 ± 0.9
TE	1.9	3.2	2.6	2.2	5.6	1.44
CV%	1.9	14.4	3.3	9.6	7.0	11.2
SWC%	0.6	3.4	0.9	2.0	1.9	2.2
MC%	1.9	10.3	2.6	6.1	5.8	6.7
LC%	3.7	20.5	5.2	12.2	11.7	13.5

SWC: Smallest worthwhile change
MC: Moderate change
LC: Large change

Table 6. 2. The reliability of PlayerLoad^{TM} variables during bouts 1 and 2 over two trials of the modified rugby league movement simulation protocol for interchange players (RLMSP-i).

	Total PlayerLoad^{TM} (AU·min^{-1})	PlayerLoad^{TM} slow (AU·min^{-1})	PlayerLoad^{TM} 2D (AU·min^{-1})	PlayerLoad^{TM} slow-ratio (%)	PlayerLoad^{TM} distance-ratio (AU·m^{-1})
Bout 1					
Trial 1 (± SD)	10.0 ±1.3	3.3 ± 0.7	6.1 ± 1.0	32.9 ± 4.5	9.4 ± 1.8
Trial 2 (± SD)	9.8 ± 1.4	3.1 ± 0.5	5.8 ± 0.7	31.9 ± 3.8	9.5 ± 1.6
TE	0.5	0.2	0.5	3.3	0.8
CV%	4.7	7.3	8.0	10.0	8.2
SWC%	2.7	3.8	3.0	2.6	3.6
MC%	8.0	11.4	8.9	7.8	10.9
LC%	16.0	22.7	17.9	15.5	21.8
Bout 2					
Trial 1 (± SD)	9.8 ± 1.2	3.3 ± 0.6	5.8 ± 0.7	33.7 ± 4.3	10.2 ± 1.8
Trial 2 (± SD)	9.6 ± 1.5	3.1 ± 0.6	5.6 ± 0.8	32.7 ± 3.9	10.8 ± 2.3
TE	0.6	0.2	0.3	1.9	1.9
CV%	5.8	7.5	5.2	5.6	18.2
SWC%	2.9	3.6	2.8	2.5	4.0
MC%	8.6	10.9	8.3	7.5	12.0
LC%	17.1	21.8	16.7	15.0	24.0

SWC: Smallest worthwhile change
MC: Moderate change
LC: Large change

6.5 Discussion

The primary aim of this study was to assess the reliability of internal and external load metrics during the RLMSP-i with a modified physical collision. Total and low-speed running distance, maximum sprint speed and PlayerLoad^{TM} metrics had a smaller CV% than the calculated moderate change (MC), but not SWC, between trials. Consequently, the match simulation provides a more controlled model than matches with sufficient reliability to accept moderate changes in performance as 'real' (i.e. due to an intervention and not the inherent variability of the test). Secondly, the study sought to describe the external load and examine if the addition of a more appropriate collision improved the simulation of match movement characteristics. High-speed running was less in comparison to the previous match simulation but greater than that observed during elite matches, while PlayerLoad^{TM} metrics provided comparable results with analysis of competitive rugby league. HR was also lower than that observed during competitive performance and the previous match simulation. As such, the current modified simulation provides a more accurate replication of external load compared to the previous version and could be used to analyse subtle changes in performance that cannot be detected using competitive performances.

The reliability of external load variables during this modified rugby league match simulation protocol are comparable with those presented originally by Waldron et al. (2013b) for total distance (CV% = 1.1 c.f. 1.3%), low-speed distance (CV% = 1.2 c.f. 2.2%) and peak speed (CV% = 2.0 c.f. 3.7%). The typical error for total distance (1.4 m·min^{-1} in Bout 1) is less than the observed difference between contact and non-contact match simulation trials (3-4 m·min^{-1}; Mullen et al., 2015) and the reduction reported during match play from quartile 1 to quartile 4 (~11 m·min^{-1}; Waldron et al., 2013a). However, the CV% for high-speed running distance is larger in the current study compared to Waldron and colleagues during Bout 1 (CV% = 8.0 c.f. 2.9%) and Bout 2 (CV% = 14.4 c.f. 5.5%). The greater variability during the modified protocol is likely due the modification to simulating physical contact. While the traditional tackle bag used by Waldron et al. (2013b) did not fully replicate physiological demands associated with competitive matches, the task is highly controlled and repeatable. In contrast, the tackle shield method in the present study is heavily reliant on participants' performance and can be influenced by individual variation in tackle technique. For example, effective tackles include contacting the opponent near their centre of gravity, effective use of the shoulder, well aligned body position to the opponent, leg drive upon contact, careful observation of the opponent's movements and effective weight transfer through the tackle (Gabbett, 2008). The greater number of variables when tackling an opponent is likely to increase variability compared to collisions with a tackle bag. Furthermore, as players fatigued during the protocol, it is also likely that tackle technique deteriorated (Gabbett, 2008), adding further to the variability of the modified collision. The type of contact has been shown to influence sprint behaviour (Chapter 4) and therefore variation in tackle performance is likely to result in greater variability in running performance compared to the previous match simulation. These issues notwithstanding, the variation between trials observed for the modified simulation protocol remains less than that between competitive matches for high-speed running above 15 $km \cdot h^{-1}$ during the first (CV% = 20.4%) and second half (CV% = 23.1%; Kempton et al., 2014). Furthermore, the variation between trials is less than changes in distance covered (7-20%) and high intensity running (10-32%) associated with adding contact to small-sided games (Johnston, Seibold & Jenkins, 2013), supplementing caffeine (Clarke et al., 2016) and manipulating pacing strategies (Highton et al., 2017). Consequently, this modified protocol is sufficiently reliable to detect previous observed changes in rugby performance and could be incorporated into future intervention studies.

PlayerLoad^{TM} metrics have been employed for quantifying match demands of outdoor team sports such as Australian football (Boyd et al., 2013), rugby union (Roe et al., 2016) and rugby league (Gabbett, 2015a). Positive correlations between collisions and PlayerLoad^{TM}

suggest that microtechnology can quantify external load for players that perform frequent tackles and hitups in addition to running demands (Gabbett, 2015a). There are also clear differences in total and relative PlayerLoad^{TM} between positional groups that likely occur from different collision demands during matches. For example, PlayerLoad^{TM} is greater in hookers (10.4 ± 1.1 AU·min^{-1}) compared to adjustables (8.7 ± 1.3 AU·min^{-1}) and outside backs (7.2 ± 0.8 AU·min^{-1}; Gabbett, 2015a). However, the reliability of many of these metrics during controlled exercise involving collisions is yet to be established. The TE for relative PlayerLoad^{TM} in the present study was 0.47 AU·min^{-1} and 0.56 AU·min^{-1} for the first and second bout, respectively. The present results indicate that PlayerLoad^{TM} can be used to determine differences in match demands between positional groups as the TE is less than the observed effect. It has been suggested that PlayerLoad^{TM} 2D (i.e. all non-longitudinal acceleration) and PlayerLoad^{TM} slow (all accelerations that occur at < 2 m·s^{-1}) could provide metrics to quantify load attributed to physical contact (Gabbett, 2015a). Present findings indicate that these metrics are sufficiently reliability to detect moderate changes in performance (CV% = 5.2-8.0%). Furthermore, PlayerLoad^{TM} slow-ratio, which determines the relative contribution of low-speed accelerations to total PlayerLoad^{TM} for each player, could provide a metric to compensate for individual variation in total PLayerLoad^{TM} from differences in gait (Barrett et al., 2014). PlayerLoad^{TM} slow-ratio appears adequately reliable to detect moderate to large differences in performance (CV% = 5.6–10.0%). The present results demonstrate that this modified rugby league match simulation protocol produces reliable measures of accelerometer-based metrics that can detect moderate changes in performance. However, further research is needed to determine the sensitivity of PlayerLoad^{TM} metrics to variation in collisions.

Heart rate (%HR$_{peak}$) and RPE resulted in CV% greater than the calculated moderate change, which suggests that internal load markers during the simulation are not as reliable as external load metrics. As mentioned previously, variation in tackle technique is likely to influence running performance and could also affect cardiovascular responses. Furthermore, the absolute results are lower than those previously reported for simulated rugby league performance but still within the range observed during competitive performance (~80-90 %HR_{peak}; Waldron et al., 2013a). RPE in the present chapter is ~3 AU lower (~13 c.f. ~16) while %HR_{peak} is ~6% less (81% c.f. 87%). Lower running loads observed during the simulation with modified physical contact could explain such results. Previously only amateur rugby players were recruited to analyse the reliability and validity of the match simulation protocol (Waldron et al., 2013b) whereas academy players made up ~47% of the participants in the current study. Such players participate in more frequent strength and conditioning sessions in addition to rugby training that results in greater aerobic capacity and sprint performance compared to non-elite players (Johnston et al., 2014). Therefore, it is to be expected that professional players would exhibit lower physiological and perceptual responses to similar external demands compared to amateur players.

Total distance and high-speed running were reduced in the modified protocol compared to the previous version described by Waldron and colleagues (2013). It is likely that the modified physical contact influenced running behaviour in a similar manner to that demonstrated in Chapter 4, with participants managing their effort to maintain performance during physiologically demanding collisions (Johnston & Gabbett, 2011; Mullen et al., 2015). As high-speed running is largely self-regulated during the match simulation, participants can down-regulate this without the consequence of losing a match to avoid excessive fatigue (Waldron & Highton, 2014). Total and high-speed running distance with the modified contact is less than that previously observed during simulated performance (100 c.f. 105 $m \cdot min^{-1}$ and 23 c.f. 27 $m \cdot min^{-1}$, respectively Waldron et al., 2013b) and closer to those reported from matches (80-105 $m \cdot min^{-1}$; Johnston et al., 2014). Total PlayerLoad™ (~10 c.f. 8-10 $AU \cdot min^{-1}$), PlayerLoad™ slow (~3 c.f. 3-5 $AU \cdot min^{-1}$), and PlayerLoad™ 2D (~6 c.f. 4-6 $AU \cdot min^{-1}$) indicate that the collision load during the modified simulation is also similar to that in matches

(Gabbett, 2015a). Taken in combination, the modified contact likely increased tackle intensity and therefore reduced running distance.

While the modified physical contact has appeared to reduce physiological load compared to the previous match simulation, the influence of this modified contact on changes to running performance during the simulation and post-match responses are unknown. Further investigation of pacing during and neuromuscular and biochemical responses after the simulation would reveal the influence of the modified contact compared to previous methods to replicate tackles.

6.6 Conclusions

The current rugby league match simulation with modified tackle replication provides a controlled model to detect decreases in physical performance from fatigue or pacing strategies and potential differences between positional groups. Furthermore, the variation observed in commonly used performance variables such as high-speed running was lower in the simulation protocol (8-14%) compared to competitive matches (~20%). Accordingly, the modified simulation protocol provides a more controlled model with which to investigate subtle influences of physical contact on running performance. The low variability in PlayerLoad^{TM} (CV% = 4.7-5.8%) and its derivatives would permit further investigation to identify appropriate and valid methods to quantify global-load, including the frequency, intensity and nature of collisions, in sports such as rugby league.

Chapter 7

The influence of physical contact type on accelerometer load during simulated rugby league match performance

7.1 Abstract

Background: Micro-technology devices have been validated for measuring acceleration during isolated physical contact tasks (Wundersitz et al., 2015) and appear to be sensitive to changes in orientation during different contact events (see Chapter 5). PlayerLoad^{TM} metrics also provide a reliable indicator of global load during simulated rugby league activity (Chapter 6). However, it is not clear whether PlayerLoad^{TM} metrics can distinguish between contact types and determine differences in demands between playing positions. **Purpose:** Investigate the influence of different contact types during a rugby league match simulation protocol on accelerometer load measured using wearable microtechnology devices. **Methods:** Twenty-seven rugby players performed one trial of the rugby league match simulation protocol for interchange players with either a tackle shield (n=10), tackle bag (n=7) or no-contact (n=10) to replicate tackle performance. Total PlayerLoad^{TM}, PlayerLoad^{TM} 2D (AU), PlayerLoad^{TM} slow (AU) and PlayerLoad^{TM} slow-ratio (%) were analysed from the accelerometer in addition to high- and low-speed running, sprint speed. HR and RPE were also measured during the first and second bout of the simulation protocol. **Results:** Total PlayerLoad^{TM} was *likely lower* for the bag group compared to the run group (498 cf. 460 AU, ES = 0.85 ± 0.92) however there were no clear differences between the other groups. During the shield trial (167 ± 26 AU) PlayerLoad^{TM} slow was *very likely greater* than both the bag (133 ± 11 AU; ES = 2.02 ± 1.16) and run trials (128 ± 20 AU; ES = 1.44 ± 0.79) but no clear difference was found between the bag and run groups. No differences were observed in PlayerLoad^{TM} 2D between any trials. **Conclusion:** Total PlayerLoad^{TM} is not sensitive to contact type but does reflect greater high-speed running distance during a rugby league match simulation. However, PlayerLoad^{TM} slow can detect the types of contact and therefore could be preferred for quantifying match and training loads associated with physical contact.

7.2 Introduction

Collectively, the PlayerLoad^{TM} metric and its derivatives are thought to provide an indication of collision load during sports that combine running and physical contact (Gabbett, 2015a; Chapter 5 & 6). However, given the large variation in movement characteristics between matches and positional groups (Kempton et al., 2014; Austin & Kelly, 2014), further investigation is required using a more controlled model to determine the sensitivity of PlayerLoad^{TM} metrics to quantify running and collision load.

Microtechnology devices have been validated for measuring acceleration during isolated physical contact tasks (Wundersitz et al., 2015b) and appear to be sensitive to changes in orientation during different contact events (Chapter 5). However, these results are based on acute, well controlled contact events that are not indicative of the more prolonged activities associated with rugby league training or match-play. It is also unclear what influence fatigue or pacing could have on PlayerLoad^{TM} metrics. The purpose of this study was to investigate the suitability of PlayerLoad^{TM} and its derivatives to detect differences in external load during prolonged bouts of intermittent running with and without physical contact.

7.3 Methods

7.3.1 Overview

This study was part of a larger, independent groups design project evaluating differences in recovery after simulated rugby league performance (Chapter 8). In this study, 27 rugby players performed one trial of the RLMSP-i (Waldron et al., 2013b) on an outdoor synthetic grass pitch (3G all-weather surface). Full details of the match simulation can be found in Chapter 3 (

3.1.2 Modified tackle using person-to-person contact (Chapters 6, 7 and 8), page 63). During the match simulation, the participant performed contact using either a tackle shield held by an opponent (Shield; n = 10), a tackle bag (Bag; n = 7; Gilbert Rugby, East Sussex, England;

mass = 23 kg) or no contact (Run; n = 10). The participants in the Shield group performed the match simulation in pairs, so to minimize the influence of competition on sprint performance, the participants ran in opposite directions so direct comparison could not be made. Participants were randomly assigned to each group using an online number generator set to give a result between one and three. All participants gave written informed consent and successfully completed a health questionnaire before participating in the study. The Faculty of Life Sciences Research Ethics Committee granted ethics approval for the study.

Each participant's stature and body mass were recorded along with 10 m sprints and the Yo-Yo intermittent recovery test level 1 (IRTL1) 3-7 days before performing the match simulation protocol. These were followed by a single habituation session to the match simulation protocol 20-30 minutes after the fitness tests. Participants performed six cycles of the match simulation protocol, which included the nominated contact replication. During the match simulation, participants' locomotion, tri-axial accelerometer load, HR, blood lactate concentration and RPE were measured. Full details of internal and external load measurements can be found in Chapter 3 (3.2 External load measurement and 3.3 Internal and perceptual load measurement, page 67). All trials were performed at similar times of the day (11:00 ± 2 h) and environmental conditions (14.7 ± 0.6 °C).

7.3.2 Fitness tests

Intermittent running performance was assessed using the Yo-Yo IRTL1 (Krustrup et al., 2003) where participants ran 2 x 20 m shuttles back and forth between a start, turn and finish point at increasing speeds, controlled by a series of audio signals. The test was performed indoors (sports hall). Each 40 m run was followed by a 10 s active recovery, comprising 2 x 5 m of jogging/walking. The test begins at 10 $km \cdot h^{-1}$ with 1 $km \cdot h^{-1}$ increments per shuttle to 13 $km \cdot h^{-1}$ followed by seven shuttles at 13.5–14 $km \cdot h^{-1}$. Thereafter, speed increases by 0.5 $km \cdot h^{-1}$ every eight shuttles. The test was terminated when participants reached volitional exhaustion or were unable to complete the 40 m shuttle in the allotted time on two consecutive occasions, as determined by the researcher. Total running distance (m) was recorded for each participant and maximal HR was determined immediately on completion using a HR monitor (Polar Electro, Oy, Finland). This test provides a good measure of intermittent running ability in rugby league players (Gabbett & Seibold, 2013) with a coefficient of variation (CV%) of 4.9% (Krustrup et al., 2003).

Sprint performance was assessed on an outdoor synthetic running track wearing standard running shoes. Participants performed three 10 m sprints interspersed with a 2 min rest period. Time to 10 m was measured using timing gates (Brower Timing System, Utah, USA). All participants started with their front foot 0.5 m behind the first gate and were given verbal encouragement to sprint with maximal effort.

7.3.3 Statistical analyses

Internal and external load metrics were quantified in total (24 cycles of the match simulation) and in periods (8 periods of 3 cycles). Between trial differences and within trial differences between periods for internal and external load were determined using magnitude-based inferences based on effect sizes and 90% confidence intervals (ES ± 90% confidence interval). Effect sizes were calculated as the difference between trial means divided by the pooled standard deviation and supplemented with qualitative descriptor of the mechanistic effect. Threshold probabilities for a mechanistic effect based on 90% confidence intervals were: <0.5% most unlikely, 0.5–5% very unlikely, 5–25% unlikely, 25–75% possibly, 75–95% likely, 95–99% very likely and >99.5% most likely. Effects with confidence limits across a likely small positive or negative change were classified as unclear. All calculations were completed using a predesigned spreadsheet (Hopkins, 2006).

7.4 Results

7.4.1 Fitness qualities

Body mass of the Shield group was *likely* greater than the Run group (ES = 1.15 ± 1.25) but *unclear* between the other groups. Stature (ES = 0.11–0.58), 10 m sprint time (ES = 0.01–0.27) and intermittent running performance (ES = 0.03–0.27) differences were *unclear* between groups. Physical and physiological characteristics can be found in Table 7. 1.

Table 7. 1. Physical and physiological characteristics of the independent groups.

Group	Body mass (kg)	Stature (m)	Yo-Yo IRL1 (m)	10 m sprint (s)
Shield (n = 7)	82.1 ± 5.0	1.79 ± 0.03	1137 ± 245	1.82 ± 0.11
Bag (n = 10)	89.1 ± 10.9	1.82 ± 0.07	1200 ± 397	1.86 ± 0.25
Run (n = 10)	89.7 ± 10.4	1.80 ± 0.08	1146 ± 342	1.86 ± 0.15

Yo-Yo IRL1: Yo-Yo intermittent recovery test level 1

7.4.2 External running demands

High-speed running distance for the Shield group was *likely* lower compared to the Bag group (ES = 0.89 ± 0.7) and *very likely* lower compared to the Run group (ES = 1.01 ± 0.64). Low-speed running distance was *likely* greater for the Shield group compared to the Bag group (ES = 0.70 ± 0.67) and *most likely* greater compared to the Run group (ES = 1.78 ± 0.92). No differences were observed between the Bag and Run groups for either high- or low-speed running distance. Mean sprint A speed was fastest for the Run group, with mean speed *very likely* lower compared the Shield group (ES = 1.73 ± 1.03) and *likely* lower during the Bag group. Furthermore, relative mean sprint A (%peak) was *likely* lower for the Shield compared to the Run group (ES = 1.05 ± 0.98). Sprint to contact speed was fastest for the Bag group, with speed *most likely* lower compared to the Shield group (ES = 2.20 ± 1.00) and *most likely* greater compared to the Run group (ES = 1.63 ± 0.75). Running distances and sprint data are presented in Table 7. 2.

Table 7. 2. Mean ± SD high- and low-speed running distance, sprint A and sprint to contact speed and fatigue index for Shield, Bag and Run groups. Data are effect size ± 90% confidence interval and qualitative descriptor for between group differences.

	Shield (n = 10)	Bag (n = 7)	Run (n = 10)	Shield c.f. Bag	Shield c.f. Run	Bag c.f. Run
High-speed distance (m)	1056 ± 128	1326 ± 245	1317 ± 175	0.89 ± 0.73 *Likely* lower	1.01 ± 0.64 *Very likely* lower	0.03 ± 0.69 *Unclear*
Low-speed distance (m)	3562 ± 92	3421 ± 161	3374 ± 139	0.70 ± 0.67 *Likely* greater	1.78 ± 0.92 *Most likely* greater	0.24 ± 0.72 *Unclear*
Sprint A (km·h^{-1})	21.4 ± 2.1	22.4 ± 1.4	23.7 ± 1.3	0.63 ± 0.92 *Unclear*	1.73 ± 1.03 *Very likely* lower	0.93 ± 0.83 *Likely* lower
Sprint A (%peak speed)	88 ± 5	89 ± 4	92 ± 3	0.23 ± 0.85 *Unclear*	1.05 ± 0.98 *Likely* lower	0.73 ± 0.95 *Unclear*
Sprint to contact (km·h^{-1})	11.7 ± 1.7	14.5 ± 1.0	12.4 ± 1.0	2.20 ± 1.00 *Most likely* lower	0.36 ± 0.59 *Unclear*	1.63 ± 0.75 *Most likely* greater

High-speed distance: ≥ 14 km·h^{-1}

Low-speed distance: < 14 km·h^{-1}

7.4.3 PlayerLoad^{TM}

Total PlayerLoad^{TM} was greatest for the Run group compared to both the Shield and Run groups (498, 482 and 460 AU, respectively) with *likely* lower PlayerLoad^{TM} observed for the Bag group compared to the Run group (ES = 0.85 ± 0.92). No clear differences were observed between the other groups. PlayerLoad^{TM} slow was 167 AU during the Shield group compared to 133 and 128 AU for Bag and Run groups, respectively. For the Shield group, PlayerLoad^{TM} slow was *very likely* greater than both Bag (ES = 2.02 ± 1.16) and Run groups (ES = 1.44 ± 0.79), with no clear differences observed between the other groups. PlayerLoad^{TM} slow-ratio was also largest for the Shield group (34.5%) compared to Bag (29.7%; ES = 1.41 ± 0.81, *very likely* lower) and Run groups (26.3%; ES = 2.50 ± 0.77, *most likely* lower). The Run group also had a lower PlayerLoad^{TM} slow-ratio compared to the Bag group (ES = 1.03 ± 0.79, *very likely* lower). No differences were observed between the groups for PlayerLoad^{TM} 2D.

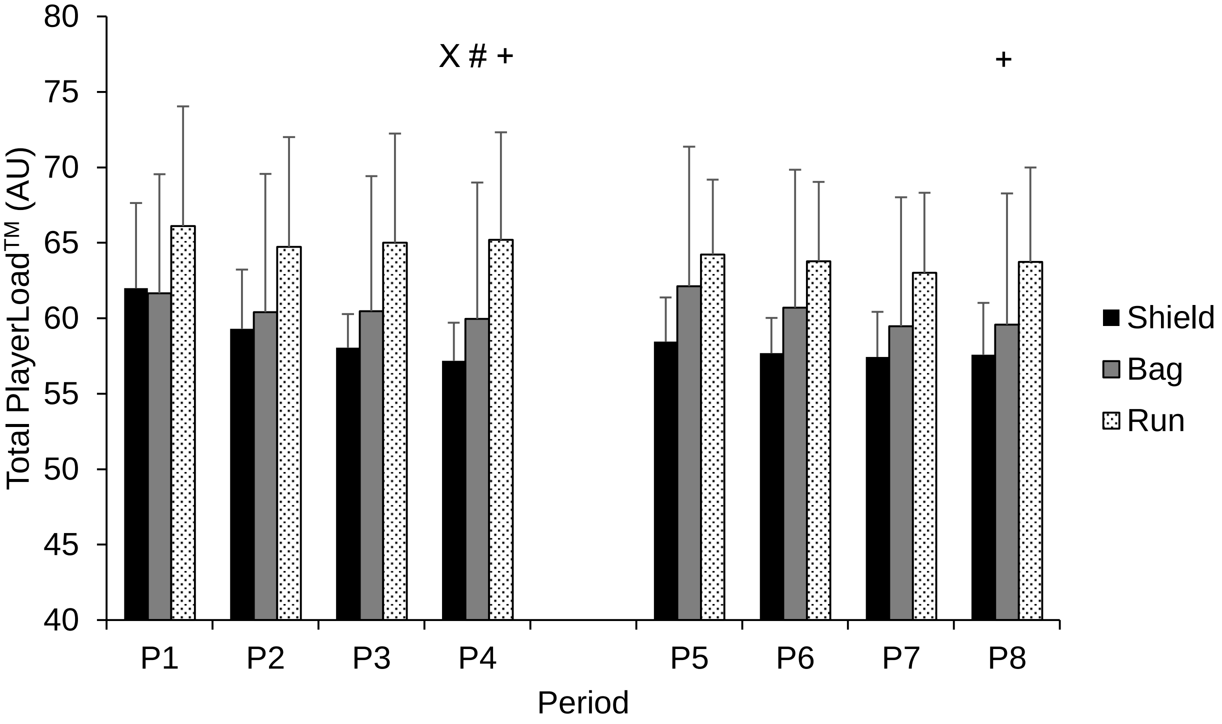


Figure 7. 1. Change in total PlayerLoad^{TM} by period during the first and second bouts of the simulation. Values are mean with ES; ±90 CI and qualitative descriptor between trials included. # denotes a *likely* difference across periods in the Bag group. X denotes a *likely* difference across periods in the Shield group. + denotes a *likely* difference across periods in the Run group.

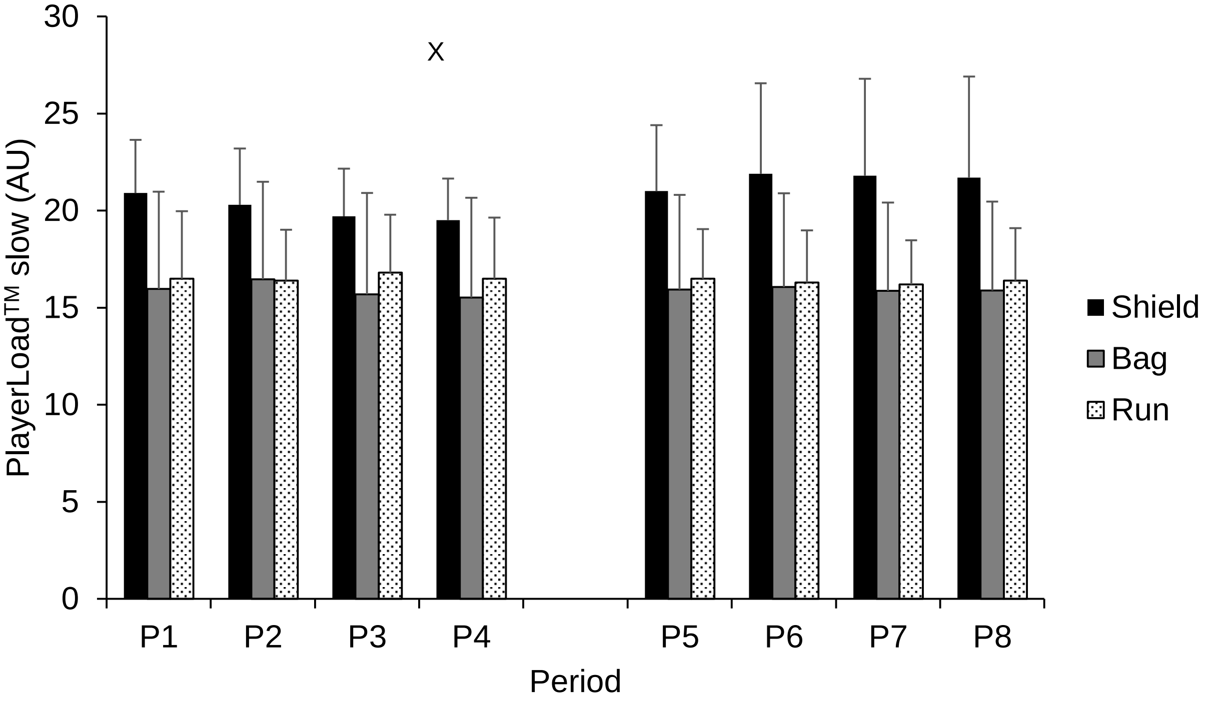


Figure 7. 2. Change in PlayerLoad^{TM} slow by period during the first and second bouts of simulation. Values are mean with ES; ±90 CI and qualitative descriptor between trials included. X denotes a *likely* difference across periods in the Shield group.

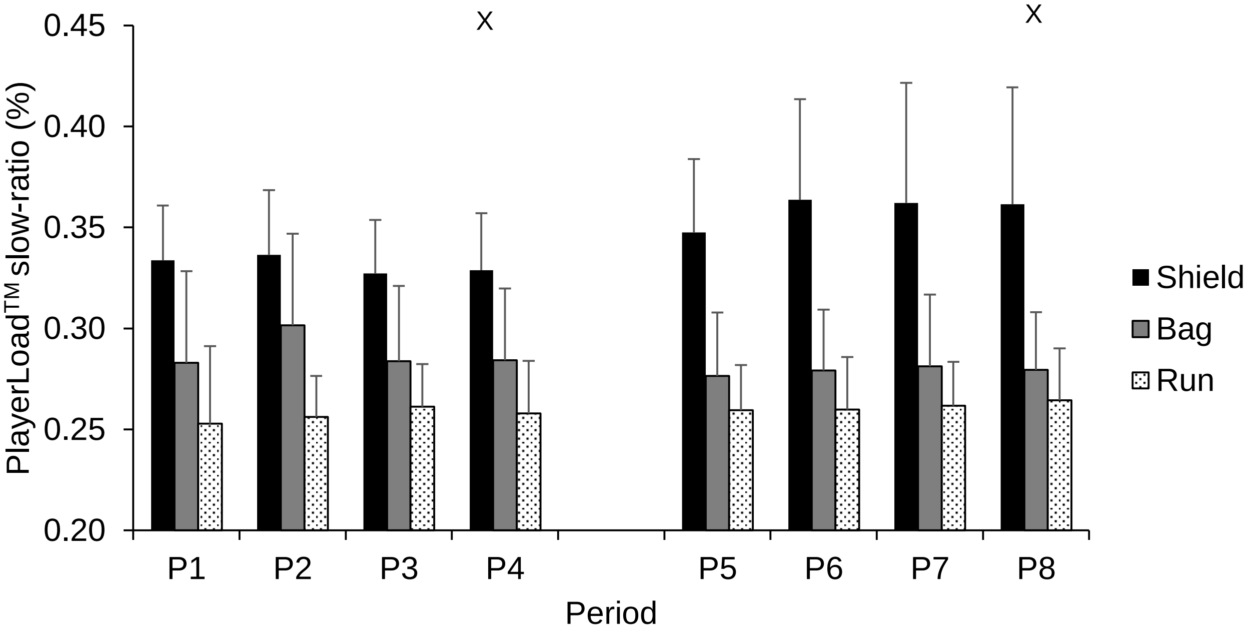


Figure 7. 3. Change in PlayerLoad^{TM} slow-ratio by period during the first and second bouts of simulation. Values are mean with ES; ±90 CI. X denotes a likely difference between period 1 and 4 and between period 5 and 8 in the Shield group.

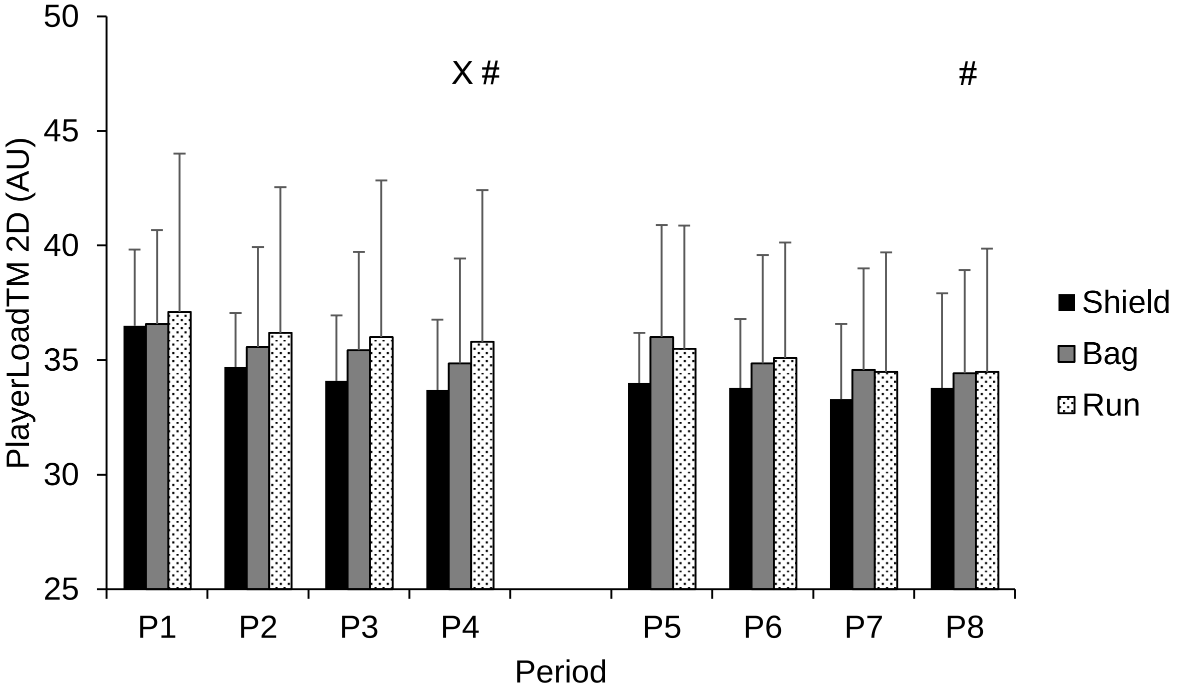


Figure 7. 4. Change in PlayerLoad^{TM} 2D by period during the first and second bouts of simulation. Values are mean ±SD. X denotes a *likely* difference between period 1 and 4 in the Shield group. # denotes a *likely* difference between period 1 and 4 and period 5 and 8 in the Bag group.

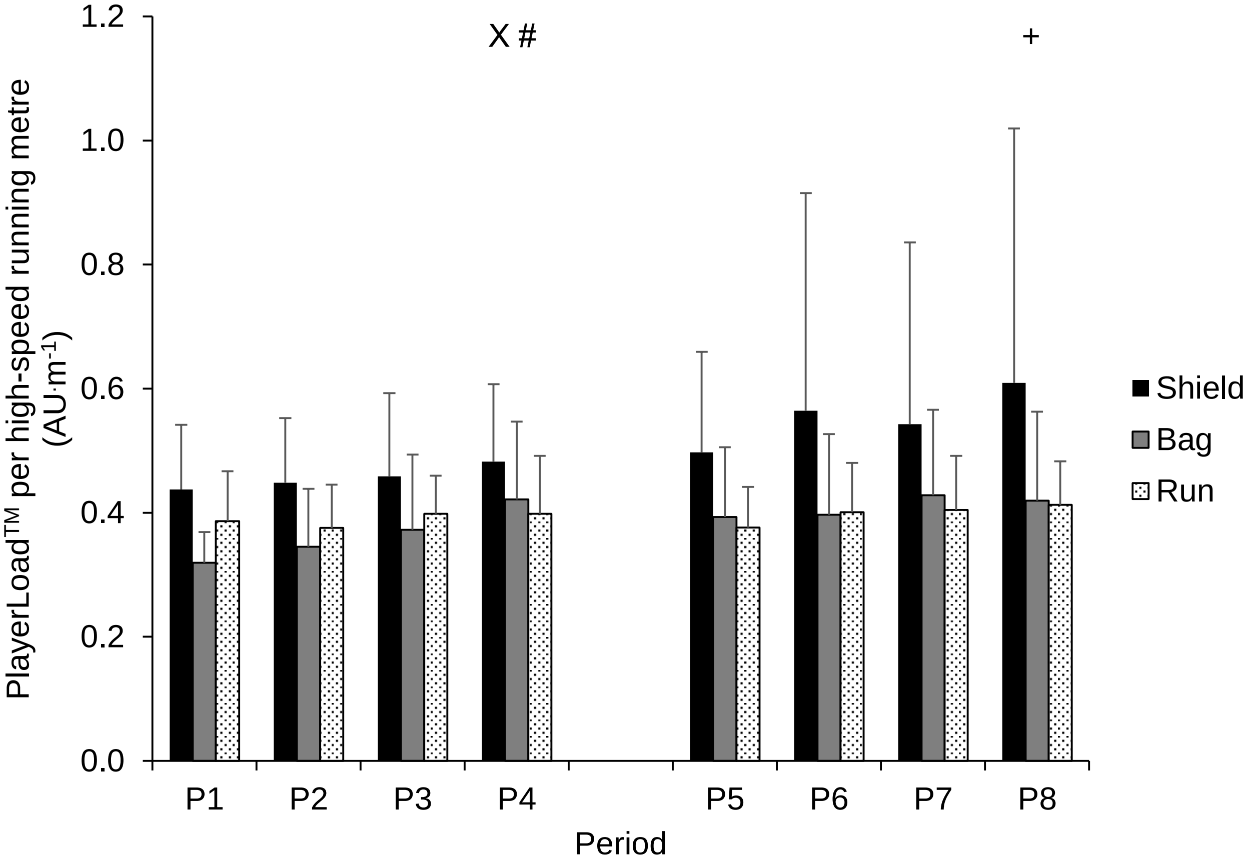


Figure 7. 5. Change in PlayerLoad^{TM} distance-ratio by period during the first and second bouts of simulation. Values are mean ±SD. X denotes a *likely* difference between period 1 and 4 in the Shield group. # denotes a *likely* difference between period 1 and 4 in the Bag group. + denotes a *likely* difference between period 5 and 8 in the Run group.

Total PlayerLoad^{TM} was *likely* lower in period 4 compared to 1 for the Shield (ES = -0.49 ± 0.52) and Bag groups (ES = 0.49 ± 0.52) and *unclear* from period 5 to 8 for the Shield (ES = 0.08 ± 0.29) and Bag groups (ES = 0.08 ± 0.29). The Run group displayed *possible* decreases in period 4 compared to 1 and 8 compared to 5 (ES = 0.18 ± 0.15 and 0.19 ± 0.26, respectively). The Shield group *likely* decreased PlayerLoad^{TM} slow from period 1 to 4 (ES = 0.44 ± 0.31) while the change was *unclear* from 5 to 8 (ES = 0.22 ± 0.53). Differences in period were *unclear* in both the Bag and Run group for PlayerLoad^{TM} slow. PlayerLoad^{TM} slow-ratio decreased during bout 1 in the Shield group with *possibly* lower ratio in period 4 compared to 1 (ES = 0.16 ± 0.36) and then increased in bout 2 with *likely* greater ratio in period 8 compared to 5 (ES = 0.44 ± 0.63). Responses in the Bag and Run groups were *unclear*. PlayerLoad^{TM} 2D *likely* decreased from period 1 to 4 (ES = 0.73 ± 0.62) in the Shield group. The Bag group displayed *likely* decreases from period 1 to 4 (ES = 0.34 ± 0.25) and 5 to 8 (ES = 0.31 ± 0.23). Changes in PlayerLoad^{TM} 2D for the Run group were *unclear* in bout 1 and 2. PlayerLoad^{TM} distance-ratio *likely* increased from period 1 to 4 in the Shield group (ES = 0.37 ± 0.22) and Bag group (ES = 1.66 ± 1.06) and from period 5 to 8 in the Run group (ES = 0.39 ± 0.37). All other differences in PlayerLoad^{TM} distance-ratio were *unclear*.

Table 7. 3. Mean ± SD total PlayerLoad^{TM}, PlayerLoad^{TM} slow, PlayerLoad^{TM} slow-ratio, PlayerLoad^{TM} 2D and PlayerLoad^{TM} distance-ratio for Shield, Bag and Run groups. Data are effect size ± 90% confidence interval and qualitative descriptor for between group differences.

	Shield (n = 10)	Bag (n = 7)	Run (n = 10)	Shield c.f. Bag	Shield c.f. Run	Bag c.f. Run
Total PlayerLoad^{TM} (AU·min^{-1})	10.5 ± 0.9	10.0 ± 1.0	10.8 ± 0.8	0.47 ± 0.91 *Unclear*	0.36 ± 0.70 *Unclear*	0.85 ± 0.92 *Likely lower*
PlayerLoad^{TM} slow (AU·min^{-1})	3.6 ± 0.6	2.9 ± 0.2	2.8 ± 0.4	2.02 ± 1.16 *Very likely* greater	1.44 ± 0.79 *Very likely* greater	0.17 ± 0.62 *Unclear*
PlayerLoad^{TM} slow-ratio (%)	34.5 ± 3.3	29.7 ± 2.8	26.3 ± 2.9	1.41 ± 0.81 *Very likely* greater	2.50 ± 0.77 *Most likely* greater	1.03 ± 0.79 *Very likely* greater
PlayerLoad^{TM} 2D (AU·min^{-1})	5.9 ± 0.5	6.1 ± 0.8	6.2 ± 1.0	0.19 ± 0.68 *Unclear*	0.20 ± 0.57 *Unclear*	0.05 ± 0.70 *Unclear*
PlayerLoad^{TM} distance-ratio (AU·m^{-1})	0.49 ± 0.16	0.38 ± 0.10	0.39 ± 0.07	0.57 ± 0.65 *Likely* greater	0.52 ± 0.56 *Likely* greater	0.13 ± 1.14 *Unclear*

7.4.4 Physiological and perceptual responses

Mean RPE was not different between the Shield (14.7 AU), Bag (14.3 AU) and Run groups (14.6 AU). Mean $\%HR_{peak}$ was *likely* lower during the Run compared to the Shield group (84 ± 6% c.f. 88 ± 5%; ES = 0.78 ± 0.80). HR responses during the Bag group (86 ± 4%) resulted in *unclear* differences compared to both Run and Shield groups.

Table 7. 4. Mean ± SD HR (%HR_{peak}), RPE and blood lactate concentration (mmol·l^{-1}) for Shield, Bag and Run groups. Data are effect size ± 90% confidence interval and qualitative descriptor for between group differences.

	Shield (n = 10)	Bag (n = 7)	Run (n = 10)	Shield c.f. Bag	Shield c.f. Run	Bag c.f. Run
HR (%HR_{peak})	88 ± 5	86 ± 4	84 ± 6	0.33 ± 0.79 *Unclear*	0.78 ± 0.80 *Likely* greater	0.38 ± 0.84 *Unclear*
RPE	14.8 ± 1.9	14.3 ± 1.6	14.6 ± 1.5	0.24 ± 0.81 *Unclear*	0.06 ± 0.64 *Unclear*	0.24 ± 0.81 *Unclear*
Blood lactate (mmol·l^{-1})	4.9 ± 3.0	4.2 ± 1.0	4.6 ± 2.4	0.64 ± 1.68 *Unlikely*	0.08 ± 0.64 *Unlikely*	0.41 ± 1.38 *Unlikely*

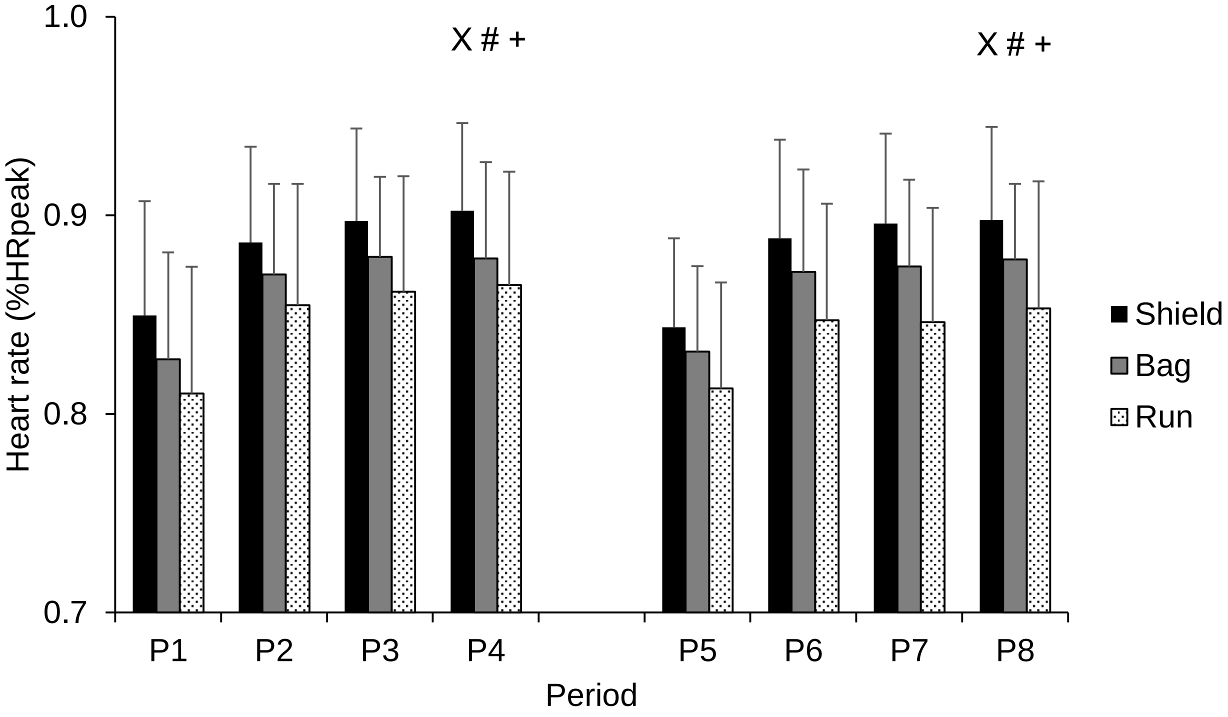


Figure 7. 6. Change in heart rate (%HR$_{peak}$) by period during the first and second bouts of simulation. Values are mean ±SD. X denotes a *likely* difference between period 1 and 4 and period 5 and 8 in the Shield group. # denotes a *likely* difference between period 1 and 4 and period 5 and 8 in the Bag group. + denotes a *likely* difference between period 1 and 4 and period 5 and 8 in the Run group.

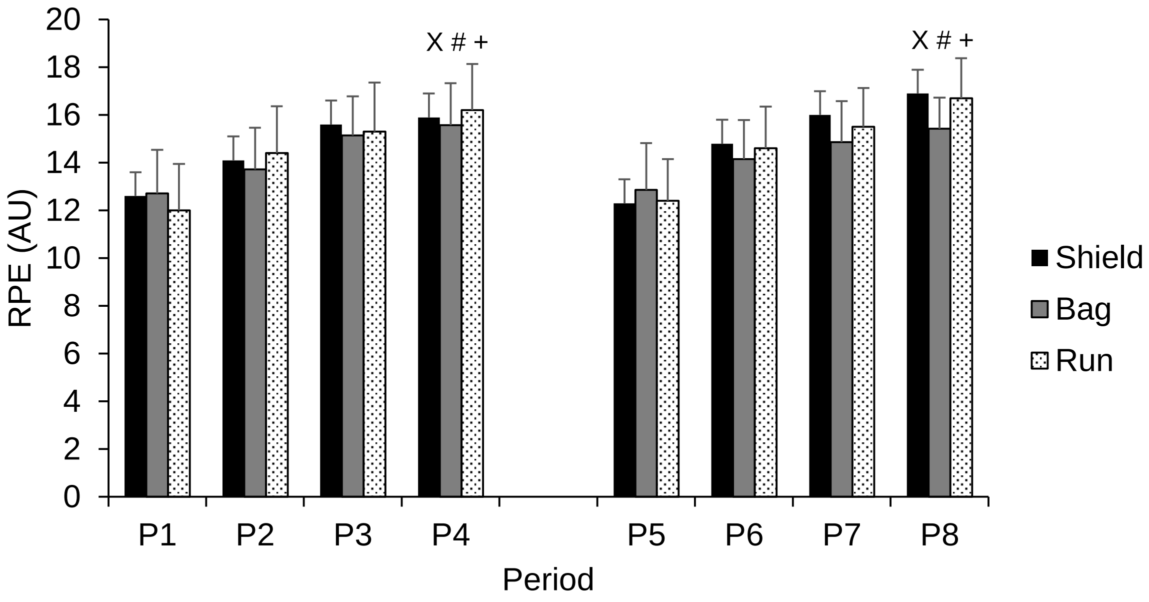


Figure 7. 7. Change in rating of perceived exertion (RPE) by period during the first and second bouts of simulation. Values are mean ±SD. X denotes a *likely* difference between period 1 and 4 and period 5 and 8 in the Shield group. # denotes a *likely* difference between period 1 and 4 and period 5 and 8 in the Bag group. + denotes a *likely* difference between period 1 and 4 and period 5 and 8 in the Run group.

7.5 Discussion

The aim of this study was to investigate the suitability of PlayerLoad^{TM} and its derivatives to quantify prolonged intermittent running, interspersed with physical contact. PlayerLoad^{TM} slow, PlayerLoad^{TM} slow-ratio and PlayerLoad^{TM} distance-ratio were greater during the tackle shield group compared to the tackle bag and running groups, however total PlayerLoad^{TM} was largest during the running group. High-speed running distance mean sprint A speed and relative sprint performance were greater during the running group compared to the Shield group. These results indicate clear differences in external load as a consequence of additional physical contact. Internal load is similar between groups except heart rate responses which were likely greater for the Shield group compared to Run. Therefore, total PlayerLoad^{TM} might not be suitable to quantify training or match load specifically associated with physical contact, instead derivatives of PlayerLoad^{TM} appear to be more sensitive to collision demands and better reflect internal load.

Total PlayerLoad^{TM} was greatest during the Run group (498 AU) compared to the Shield (481 AU) and Bag (460 AU) groups, respectively. This finding is despite the Run group performing no replication of physical contact and similar (~1300 m) total high-speed running distance compared to the Bag and Run groups. Greater PlayerLoad^{TM} for those without contact probably reflects the influence of a faster sprint A speed observed during the Run group. Furthermore, the Run group maintained faster relative sprint A speeds throughout the simulation compared to the Shield group. Faster running speeds are positively associated with greater overall PlayerLoad^{TM} during treadmill running because of large vertical accelerations (Barrett et al., 2014). Total PlayerLoad^{TM} is a combined, three-dimension acceleration metric that is strongly correlated with running distance (Scott et al., 2013). The large vertical contribution might be attributed to upper body movement from arm swing or greater displacement from trunk flexion (Barrett et al., 2014). The present findings suggest that total PlayerLoad^{TM} does not reflect specific collision demands but rather high-speed running and sprinting.

Previously PlayerLoad^{TM} 2D, which excludes the vertical contribution to total PlayerLoad^{TM}, has been suggested to provide an indicator of collision load by reducing the influence of running on PlayerLoad^{TM} during rugby league matches (Gabbett, 2015a). The present findings contradict those from match play as each group had very similar PlayerLoad^{TM} 2D (5.9 ± 0.5, 6.1 ± 0.8 and 6.2 ± 1.0 $AU{\cdot}min^{-1}$ for the Shield, Bag and Run groups, respectively) despite considerable differences in physical contact type and frequency. Match play has comparable PlayerLoad^{TM} 2D results for forwards and hookers in semi-professional rugby league to those observed in the present study (6.1 ± 1.4 and 6.4 ± 0.7 $AU \cdot min^{-1}$, respectively; Gabbett, 2015a). While PlayerLoad^{TM} 2D is similar, high-speed running demands were greater in the simulation compared to matches (3.8–5.8 $m \cdot min^{-1}$ c.f. 11.7–14.5 $m \cdot min^{-1}$). As antero-posterior acceleration increases in a linear fashion with movement speed (Barrett et al., 2014), it is possible that greater high-speed running masks differences in PlayerLoad^{TM} 2D from collisions. As with the observation for total PlayerLoad^{TM}, the results from this study suggest that PlayerLoad^{TM} 2D is not sensitive to detect the load imposed by physical contact during prolonged intermittent running. Accordingly, both metrics are not suitable to quantify collision load in training and matches.

PlayerLoad^{TM} slow provides a measure of accelerations from the internal accelerometer that occur at speeds < 2 $m \cdot s^{-1}$. As rugby league players perform numerous bouts of wrestling or grappling during physical contact, PlayerLoad^{TM} slow might provide a useful indicator of load for collision athletes that cannot be ascertained from GPS data. For example, PlayerLoad^{TM} slow has been correlated with the number of collisions performed by rugby league forwards during a match (Gabbett, 2015a). In the present study, PlayerLoad^{TM} slow was *very likely* greater for the Shield group (3.6 ± 0.6 $AU \cdot min^{-1}$) compared to both Bag (2.9 ± 0.2 $AU \cdot min^{-1}$; ES = 2.02 ± 1.16) and Run groups (2.8 ± 0.4 $AU \cdot min^{-1}$; ES 1.44 ± 0.79). The PlayerLoad^{TM} slow values in the present study (2.8–3.6 $AU \cdot min^{-1}$) are lower than those reported for forward players (4.4–4.7 $AU \cdot min^{-1}$) but similar to backs (3.1–3.6 $AU \cdot min^{-1}$; Gabbett, 2015a). There were more collisions in the match simulation compared to competitive performance (48 c.f. 22–29), but this was not reflected by greater PlayerLoad^{TM} slow. Despite the greater number of tackles, the results demonstrate that the modified contact replication does not fully reflect the demands of collisions in matches. This is likely as a result of less intense wrestling that is fundamental to success in competitive performance. PlayerLoad^{TM} slow-ratio, calculated by dividing total PlayerLoad^{TM} by PlayerLoad^{TM} slow, was *most likely* greater for the Shield group compared to the Run group (34.5 ± 3.3% c.f. 26.3 ± 2.9%; ES = 2.50 ± 0.77) and *very likely* greater than the Bag group (34.5 ± 3.3% c.f. 29.7 ± 2.8%; ES = 1.41 ± 0.81). In contrast with total PlayerLoad^{TM} slow, PlayerLoad^{TM} slow-ratio appears to be sensitive to the differences between the tackle bag and the running group. PlayerLoad^{TM} slow-ratio was *very likely* lower for the Run group compared the Bag group (ES = 1.03 ± 0.79), suggesting that the metric can detect the inclusion of physical contact. These results demonstrate that PlayerLoad^{TM} slow-ratio can quantify activities such as tackling and wrestling in addition to intermittent running.

Higher HR and reduced sprint and high-speed running performance have been observed with the inclusion of physical contact to intermittent sprints (Johnston and Gabbett, 2011), small-sided games (Johnston et al., 2014c) and simulated match performance (Mullen et al., 2015). Attempts to investigate the role of physical contact during match simulation protocols have, however, been limited by the method of tackle replication (Waldron et al., 2013b; Mullen et al., 2015). Rugby league match simulations have resulted in greater high-speed running compared to elite match performance, despite similar HR values (Waldron et al., 2013b). In the present study, the limitations of the tackle bag to replicate physical contact are evident as high-speed running, HR and PlayerLoad^{TM} slow were not different between the Bag and Run groups. In contrast, the Run group had *likely lower* %HR$_{peak}$ (84 ± 6% c.f. 88 ± 5%; ES = 0.78 ± 0.80) and *very likely* lower PlayerLoad^{TM} slow (ES = 1.44 ± 0.79) compared to the Shield group. Furthermore, high-speed running was *very likely* lower for the Shield group compared to the Run group (1056 ± 225 m c.f. 1318 ± 175 m; ES = 1.01

± 0.64). These findings reaffirm that a traditional tackle bag does not adequately replicate internal or external load during a match simulation compared to competitive matches. The tackle shield provides an improved method to simulate collision compared to the tackle bag and could be used to further investigate the role of physical contact on fatigue responses after a match simulation.

Total PlayerLoad^{TM} and PlayerLoad^{TM} 2D decreased during each bout of the simulation. These responses could be indicative of fatigue whereby the participant is unable to maintain the same running intensity throughout the simulation. Despite the movement demands being controlled by an audible signal, sprint speed is a self-regulated “maximum effort”. Therefore, pacing strategies can be adopted to optimize performance during certain aspects of the simulation and preserve energy for later periods (Waldron & Highton, 2014). Both total PlayerLoad^{TM} and PlayerLoad^{TM} 2D appear to decay in a similar manner to high-speed running during competitive matches (Waldron et al., 2013a). However, PlayerLoad^{TM} distance-ratio increases during the first bout in the Bag and Shield groups and during the second bout for the Run group. Similar results have been observed during simulated soccer performance and have been attributed to altered movement strategies or compromised efficiency (Barrett et al., 2016). Increased PlayerLoad^{TM} distance-ratio supports the concept of altered movement strategies and could be indicative of changes to lower limb stiffness (Cormack et al., 2013). However, further research is required to investigate whether acute changes in PlayerLoad^{TM} are indicative of reduced efficiency and neuromuscular fatigue.

The current chapter is not without a number of limitations. The use of an independent group design is susceptible to between participant variation that can influence results. Furthermore, large individual variation in PlayerLoad^{TM} can occur due to differences in running kinematics such as stride rate and upper body movement (Barrett et al., 2014). The use of PlayerLoad^{TM} slow-ratio provides a measure of contact load relative to total accelerometer load that reduces the influence of individual variation. Furthermore, while intermittent running ability, sprint speed and body mass were not different between groups, individual responses to the match simulation could influence effects between groups. The modified collision in the present chapter appears to have improved the validity of the match simulation by reducing high-speed running distance and producing similar PlayerLoad^{TM} results to elite match-play (Gabbett, 2015a). However, the use of a tackle shield blunts and direct trauma to soft tissue, which likely reduces the magnitude of muscle damage compared to match-play. The physical collision also lacks multiple player tackles. During elite rugby league match-play tackles are often completed by > 2 players from the defending team which likely increases internal and external load for the attacking player (King et al., 2010). Multiple defenders in one tackle will contact the ball-carrier's upper and lower-body increasing the potential for muscle damage caused by blunt force trauma and the accelerometer load experienced by the player.

7.6 Conclusions

This study provides evidence to support the use of PlayerLoad^{TM} slow to quantify physical contact demands of rugby league training and competition. PlayerLoad^{TM} slow appears sensitive to both the addition of physical contact to intermittent running and the type of contact performed, with clear differences between the tackle shield, tackle bag and run groups. That total PlayerLoad^{TM} and PlayerLoad^{TM} 2D were not different between groups suggests that these metrics are not suitable to quantify external load associated with physical contact in rugby league activities. Finally, the use of a tackle shield can provide more realistic internal and external load during a match simulation compared to a tackle bag. The modified tackle shield simulation provides an improved model to further investigate the influence of physical contact on fatigue responses during and after rugby league performance.

Chapter 8

The influence of physical contact type on neuromuscular, biochemical and perceptual responses after simulated rugby league match performance

8.1 Abstract

Background: Physical collisions combined with running can increase markers of EIMD more than just running alone (Johnston, Gabbett, Seibold & Jenkins, 2014), however to date no research has sought to systematically manipulate match demands to determine their contribution to EIMD. Previously, the RLMSP-i did not adequately replicate match demands to investigate the contribution of physical contact on EIMD. However, the modified protocol better reflects competitive match demands (Chapter 6 and 7) and can be performed in a controlled environment to enable more invasive measures linked to EIMD. **Purpose:** Investigate the influence of contact type on changes in neuromuscular, perceptual and biochemical parameters associated with EIMD. **Methods:** 20 recreational rugby players performed one trial of the RLMSP-i with either a tackle shield held by an opponent matched for body mass (n = 6; Shield), a tackle bag (n = 7; Bag; Gilbert Rugby, East Sussex, England; mass = 23 kg) or no contact (n = 7; Run). Measures of venous blood, muscle function and soreness were repeated immediately (+0, +24 and +72 hours after the match simulation. **Results:** Peak knee flexion torque decreased more in the Shield group +0 and +72 hours after the match simulation compared to both the Bag (ES = 1.01 ± 1.15 and 1.11 ± 0.98 at +0 and +72 hours, respectively) and Run groups (ES = 0.88 ± 1.04 and 1.00 ± 0.86, at +0 and +72 hours, respectively). Peak upper body pushing force decreased more in the Shield group compared to both Run (ES = 0.73 ± 0.61) and Bag (ES = 0.44 ± 0.48) groups +0 hours after the match simulation compared to baseline. All between group differences for IL-6 and IL-10 were unclear. **Conclusion:** The Shield and Run group had larger decrements in upper body and lower body muscle function, respectively. However, commonly used biochemical markers of inflammatory processes appear unable to distinguish between clear differences in physical demands. Il-6, IL-10 and WBC concentration increased for all groups despite differences in external load and were not associated with the prolonged (up to 72 h) reductions in muscle function or perceived soreness.

8.2 Introduction

Rugby league training and matches result in EIMD in the hours and days after. This EIMD is associated with increased myofibrillar proteins in blood plasma (Oxendale et al., 2016; McLean et al., 2010; McLellan et al., 2010;), increased perception of muscle soreness (Twist et al., 2012) and decreased neuromuscular function (Johnston et al., 2015b). Such changes are related to a combination of high intensity running distance, total collisions and repeated high-intensity efforts (RHIE) performed by players (Oxendale et al., 2016; Johnston et al., 2014c; Twist et al., 2012; Gabbett et al., 2011). While physical collisions combined with running can increase markers of EIMD more than just running alone (Johnston et al., 2014c), collision frequency can vary considerably between individual players during matches (Twist et al., 2012; Gabbett et al., 2011). To date no research has sought to systematically manipulate match demands to determine their contribution to EIMD.

The influence of including physical contact on fatigue responses during prolonged intermittent running remains unclear. Greater running demands during simulated performance compared to matches likely results from greater sprint to contact speed associated with using a tackle bag to simulate collisions (Chapter 4). Notably, Chapter 4 also revealed that faster sprint to contact speeds were observed during simulations with a tackle bag than a custom-built tackle sled. Slower speeds into contact with the tackle sled were likely to ensure successful skill execution and reduce any discomfort associated with colliding into a larger and heavier object. While overall high-speed running was greater during a tackle bag condition compared to a non-contact condition (Mullen et al., 2015), Chapter 7 revealed slower peak speeds in the tackle bag group compared to the run group to maintain high sprint to contact speeds. These results agree with previous findings that players compromise running speed and distance to maintain tackle performance (Gabbett, 2013b; Waldron et al, 2012). Given the potential issues surrounding the use of tackle bags, work is needed to examine the influence of more appropriate replications of collision on running performance and post-session fatigue responses, i.e. physical contact with a partner holding a tackle shield.

Indirect measures of EIMD commonly used in rugby league research include muscle soreness, blood myofibre proteins and muscle function (Twist & Highton, 2013). An increase in circulating creatine kinase (CK) is positively correlated with the number of physical collisions during a match, indicating the role of blunt force trauma on muscle damage responses (Twist et al., 2012; Oxendale et al., 2016). However, increased CK concentration is also correlated with total time on the pitch during a match (Oxendale et al., 2016), which suggests that it cannot discriminate between mechanical eccentric damage and that from blunt trauma. Furthermore, a poor temporal relationship with neuromuscular function (Margaritis et al., 1999) suggests that CK might not be a suitable marker to measure the time course of recovery after matches or training. Measures of muscle function are suggested to provide the most valid and reliable indirect assessment of muscle-damaging exercise (Warren, Lowe & Armstrong, 1999; Damas et al., 2016). In rugby, assessing both upper and lower body muscle function is deemed necessary given decrements to both occur because of sport-specific actions, i.e. collisions, wrestling, running (Oxendale et al., 2016; Johnston et al., 2014c; Johnston et al., 2015; Roe et al., 2017). Decrements in neuromuscular performance can occur simultaneously with an inflammatory response after an initial bout of muscle damaging activity (Peake et al., 2005), however few studies have compared responses between measures of neuromuscular function and inflammation (Paulsen et al., 2012). Elevated cytokine concentration (IL-6) and leukocytosis has been observed after elite rugby union (Cunniffe et al., 2010), although limited data was presented on the specific match actions performed by the players. There are also compensatory anti-inflammatory responses after strenuous exercise including elevated IL-10 that blunt production of further pro-inflammatory cytokines and return the system to homeostasis (Zaldivar et al., 2006). Investigation of these cytokine and leukocyte responses to simulated rugby league activity with different contact types, alongside other indirect markers, could develop the current understanding of the mechanisms that underpin exercise-induced muscle damage and recovery in response to specific match actions such as tackles and ball-carries. Therefore, the purpose of this study was to investigate the influence of contact type on changes in neuromuscular, perceptual and biochemical parameters associated with EIMD.

8.3 Methods

8.3.1 Overview

In this independent groups design study, 20 recreational rugby players were recruited from a larger sample (n = 27) as described in Chapter 7. All participants were rugby players with > 6 months experience of rugby union or league competition and training. Participants were randomly allocated to a group that, during a simulated rugby league match, performed contact using either a tackle shield held by an opponent matched for body mass (n = 6; Shield), a tackle bag (n = 7; Bag; Gilbert Rugby, East Sussex, England; mass = 23 kg) or no contact (n = 7; Run). Participants were asked to refrain from intense physical activity and recovery strategies for the duration of the study whilst maintaining normal dietary habits. All participants gave written informed consent and successfully completed a health questionnaire before participating in the study. The Faculty of Life Science Research Ethics Committee granted ethics approval for the study.

On the initial visit to the laboratory, the participant’s stature and body mass were recorded along with 10 m sprints and the Yo-Yo intermittent recovery test level 1 (IRTL1). Participants were then habituated to the match simulation protocol 20-30 minutes after, comprising six cycles of the protocol and the nominated contact replication. After 3-7 days, participants returned to the laboratory and provided a venous blood sample. This was followed by measures of upper and lower body muscle function, including plyometric push-ups, counter-movement jumps, isokinetic strength of knee extensors, knee flexors and upper body. Participants were also asked to rate their perceived muscle soreness in the upper and lower body. Thereafter, participants performed the RLMSP-i (Waldron et al., 2013b) on an outdoor synthetic grass pitch (3G all-weather surface) using their allocated contact condition. Measures of venous blood, muscle function and soreness were repeated immediately (+0), +24 and +72 hours after the match simulation.

8.3.2 Assessment of physical qualities

Participants completed measurements of 10 m sprint performance and a Yo-Yo intermittent recovery test level 1 (IRTL1). Full details of the procedures for physical profiling tests are outlined in Chapter 7 (7.3.2 Fitness tests, page 120).

8.3.3 Plyometric push-up and counter-movement jump measurements

Upper and lower body neuromuscular function was assessed using a plyometric push-up and counter-movement jump (CMJ), respectively. All measures were recorded on a force platform (FP8, HUR Labs, Finland) connected to a laptop using software supplied by the manufacturer (Jump Test for Windows 8, HUR Labs, Finland). After a standardised warm-up consisting of 5 minutes static cycling at 100 W and 3 practice repetitions of CMJ and plyometric push-up, participants performed three maximal trials of each test with ~2 min between each. During CMJ measurements, participants were instructed to keep their hands-on-hips and jump as high as possible with no restriction on depth of counter-movement. For the plyometric push-up, participants started in a push-up position with their hands at a self-selected width on the force platform. The participants then rapidly flexed their elbows to approximately 90° before maximally exploding off the platform and landing with their arms fully extended (Oxendale et al., 2016). For both CMJ and plyometric push-up, peak power (W) from the three trials was recorded for analysis. In-house reliability (CV%) was 2.6 and 15.3% for CMJ and plyometric push-up peak power, respectively.

8.3.4 Isokinetic strength measurements

An isokinetic dynamometer (Biodex 3, Biodex Medical Systems, Shirley, NY) was used to measure peak torque of the knee extensors and flexors (dominant limb) at $60°\cdot s^{-1}$ and upper body pushing and pulling (dominant limb) at $90°\cdot s^{-1}$. During peak torque assessment, the participant was fitted to the dynamometer per the manufacturer's guidelines and the mass of the limb was recorded for knee-torque assessment to enable gravitational correction. Visual feedback, displaying real-time torque, was used to encourage maximal efforts while participants were consistently encouraged to exceed target values based on those achieved during habituation. In house reliability (CV%) was 4.8 and 8.0% for peak torque during knee extension and flexion and 5.4 and 6.3% for peak force during upper pushing and pulling, respectively.

8.3.5 Perception of muscle soreness

Participants were asked to rate the soreness of the upper and lower body using a visual analogue scale (Twist & Eston, 2005). The scale used qualitative cues ranging from "no muscle soreness" to "muscle too sore to move" that corresponded to numerical ratings of 0 to 10, respectively. Soreness of the upper body was quantified during a single press up with elbows flexed to 90°. To rate lower body soreness, participants performed a body weight squat with depth so that the centre of the hip joint was approximately level with the centre of the knee joint.

8.3.6 Venous blood sampling

Venous blood was obtained by venipuncture from an antecubital vein and collected into two vacutainer tubes (Becton Dickinson, Oxford, UK). Participants were either seated or in a supine position dependent on individual preference, which was then replicated during follow-up visits. Blood was collected into 6 ml K_2EDTA vacutainer tubes. Samples were kept at room temperature and analysed for full blood count including total number of leukocytes (white blood cells [WBC], red blood cells (RBC), haemoglobin (HGB), haematocrit (HCT) and platelets (PLT) within 3 hours using a Coulter MicroDiff analyser (Beckman Coulter, UK). The EDTA tube was then centrifuged at 1500 *g* for 10 minutes and plasma was removed and stored at -30°C. Serum cytokine concentrations of IL-6 and IL-10 were measured with commercially available ELISA kits (Quantikine HS, R&D Systems, USA) according to manufacturer's instructions. A standard curve was derived from each set of samples that resulted in a correlation coefficient > 0.99. The concentration of each substance was calculated for every sample by comparison with the standard curve.

8.3.7 Match simulation

Participants performed the rugby league match simulation protocol during which measures of high- and low-speed distance, sprint performance, PlayerLoad^{TM} slow, HR, blood lactate and RPE were recorded. Full details of the procedures for the simulation and measures of external and internal load are outlined in Chapter 3 (

3.1.2 Modified tackle using person-to-person contact (Chapters 6, 7 and 8), page 63).

8.3.8 Statistical analysis

Between group differences in match simulation data were determined using magnitude-based inferences based on effect sizes and 90% confidence intervals (ES ± 90% confidence interval). Effect sizes were calculated as the difference between trial means divided by the pooled standard deviation and supplemented with qualitative descriptor of the mechanistic effect. Threshold probabilities for a mechanistic effect based on 90% confidence intervals were: <0.5% most unlikely, 0.5–5% very unlikely, 5–25% unlikely, 25–75% possibly, 75–95% likely, 95–99% very likely and >99.5% most likely. Effects with confidence limits across a likely small positive or negative change were classified as unclear. All calculations were completed using a predesigned spreadsheet (Hopkins, 2006). Between group differences in neuromuscular function, perceived muscle soreness and biochemical markers of inflammation were determined by comparing the size of the effect at +0, +24 and +72 hours compared to baseline results. Differences in ES were analyzed using a predesigned spreadsheet (Hopkins, 2006).

8.4 Results

8.4.1 Physical qualities

Body mass was *likely* greater in the Bag group compared to both the Run (ES = 0.67 ± 0.84) and Shield group (ES = 0.51 ± 0.68) but differences between the Shield and Run groups were *unclear* (ES = 0.16 ± 0.68). Stature, 10 m sprint time and Yo-Yo IRL1 distance were *unclear* between groups (ES < 0.30). Physical and physiological characteristics can be found in

.

Table 8. 1. Physical qualities of the independent groups.

Group	Body mass (kg)	Stature (cm)	10 m sprint (s)	Yo-Yo IRL1 (m)
Bag (n = 7)	89.1 ± 11.9	181.5 ± 7.0	1.83 ± 0.20	1205 ± 429
Run (n = 7)	79.9 ± 11.9	180.4 ± 7.6	1.84 ± 0.17	1057 ± 333
Shield (n = 6)	82.1 ± 5.5	179.4 ± 3.1	1.82 ± 0.11	1246 ± 327

Yo-Yo IRL1: Yo-Yo intermittent recovery test level 1

8.4.2 External and internal and load

High-speed running distance during the Shield group was *likely* lower compared to the Bag group (ES = 0.89 ± 0.73) and the Run group (ES = 0.76 ± 0.91). Low-speed running distance was *likely* greater during the Shield group compared to the Bag group (ES = 0.77 ± 0.74) and *most likely* greater compared to the Run group (ES = 1.78 ± 0.92). Differences between the Bag and Run groups for both high- and low-speed running distance were *unclear*. Peak sprint A speed was *unclear* between the groups, but mean sprint A speed was faster in the Run group compared to Shield with mean speed *very likely* lower (ES = 1.65 ± 1.44). Sprint to contact speed was fastest in the Bag group with speed *likely* lower in the Shield group (ES = 1.47 ± 1.30) and *most likely* greater compared to the Run group (ES = 1.88 ± 0.68). Finally, PlayerLoad^{TM} slow was greatest in the Shield group compared to both the Bag (ES = 1.23 ± 1.10, *likely*) and Run groups (1.02 ± 0.77, *very likely*) and *unclear* between the Bag and Run groups. External load data are presented in **Error! Reference source not found.**. Internal load measures of mean HR (%HR$_{peak}$), RPE and blood lactate resulted in *unclear* differences between groups.

Table 8. 2. Mean ± SD high- and low-speed running distance, sprint A and sprint to contact speed and fatigue index for Shield, Bag and Run groups. Data are effect size ± 90% confidence interval and qualitative descriptor for between group differences.

	Shield (n = 6)	Bag (n = 7)	Run (n = 7)	Shield c.f. Bag	Shield c.f. Run	Bag c.f. Run
High-speed distance (m·min^{-1})	25.5 ± 4.0	28.8 ± 5.8	29.2 ± 4.6	0.89 ± 0.73 *Likely* less	0.76 ± 0.91 *Likely* less	0.06 ± 0.76 *Unclear*
Low-speed distance (m·min^{-1})	77.7 ± 2.5	74.3 ± 3.8	72.4 ± 3.4	0.77 ± 0.74 *Likely* greater	1.78 ± 0.92 *Most likely* greater	0.45 ± 0.80 *Unclear*
Mean Sprint A (km·h^{-1})	21.1 ± 2.6	22.4 ± 1.4	23.7 ± 1.3	0.79 ± 1.40 *Unclear*	1.65 ± 1.44 *Very likely* less	0.65 ± 0.85 *Unclear*
Max Sprint A (km·h^{-1})	24.8 ± 1.4	25.0 ± 1.8	25.7 ± 2.2	0.38 ± 0.74 *Unclear*	0.11 ± 0.80 *Unclear*	0.29 ± 0.76 *Unclear*
Sprint to contact (km·h^{-1})	12.6 ± 1.9	14.5 ± 1.1	12.1 ± 0.6	1.47 ± 1.30 *Likely* less	0.23 ± 0.72 *Unclear*	1.88 ± 0.68 *Most likely* greater
PlayerLoad^{TM} slow (AU·min^{-1})	3.36 ± 0.40	2.95 ± 0.29	2.75 ± 0.52	1.23 ± 1.10 *Likely* greater	1.02 ± 0.77 *Very likely* greater	0.34 ± 0.69 *Unclear*
Mean heart rate (%HR$_{peak}$)	87.1 ± 5.9	86.1 ± 5.4	84.2 ± 6.3	0.13 ± 1.00 *Unclear*	0.24 ± 0.89 *Unclear*	0.17 ± 1.00 *Unclear*
Mean RPE (AU)	15.6 ± 2.0	14.3 ± 1.7	15.0 ± 1.8	0.65 ± 0.95 *Unclear*	0.26 ± 0.81 *Unclear*	0.34 ± 0.85 *Unclear*
Blood lactate (mmol·l^{-1})	4.6 ± 2.0	4.2 ± 1.0	4.7 ± 2.9	0.35 ± 1.63 *Unclear*	0.07 ± 1.02 *Unclear*	0.50 ± 1.99 *Unclear*

High-speed distance: ≥ 14 km·h^{-1}
Low-speed distance: < 14 km·h^{-1}

8.4.3 Neuromuscular responses

8.4.3.1 Plyometric push-up and counter-movement jump measurements

Within group decreases in plyometric push-up peak power were observed +0 hours after the simulation in the Shield (ES = 0.27 ± 0.19, *likely*), Bag (ES = 0.26 ± 0.35, *possibly*) and Run groups (ES = 0.43 ± 0.45, *likely*). *Unclear* differences in effect between groups were observed for peak power in plyometric push-up +0 and +24 hours after the match simulation. Peak power output in the plyometric push-up *likely* increased in the Shield group +72 hours after the match simulation compared to the Bag (ES = 0.99 ± 1.09) and Run groups (ES = 0.87 ± 0.98).

Within group time effects during the CMJ were evident in the Run group +0 hours after the match simulation where peak power was *possibly* less compared to baseline (ES = 0.24 ± 0.25). All other within group differences were *unclear*. Differences in effect between groups were apparent between the Run and Shield group for CMJ power, with a *likely* larger negative effect in the Run group at +0 (ES = 0.44 ± 0.53) and *possibly* larger negative effect +72 hours (ES = 0.32 ± 0.45) after the simulation. Differences in CMJ performance were *unclear* between groups at all other time points.

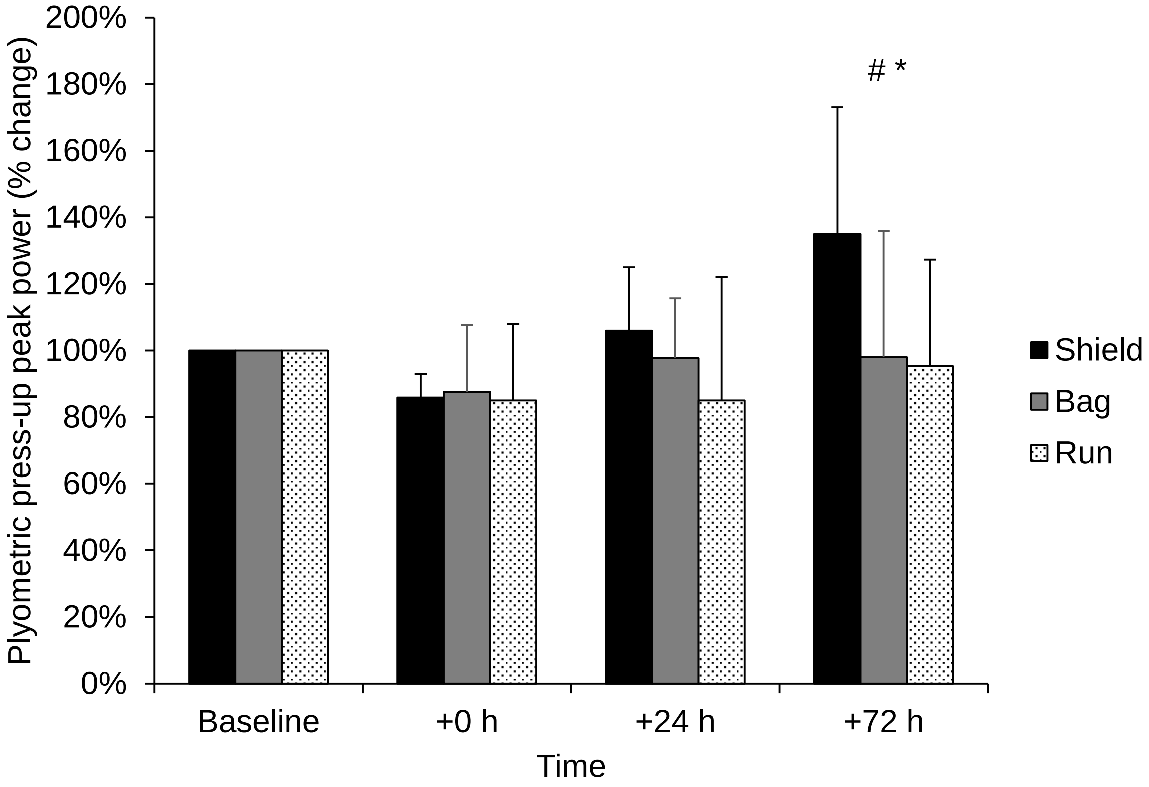


Figure 8. 1. Percentage change from baseline for peak power in plyometric press-up for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups. Data are means ± SD. * denotes *likely* difference in effect from baseline between Shield and Run groups. # denotes *likely* difference in effect from baseline between Shield and Bag groups.

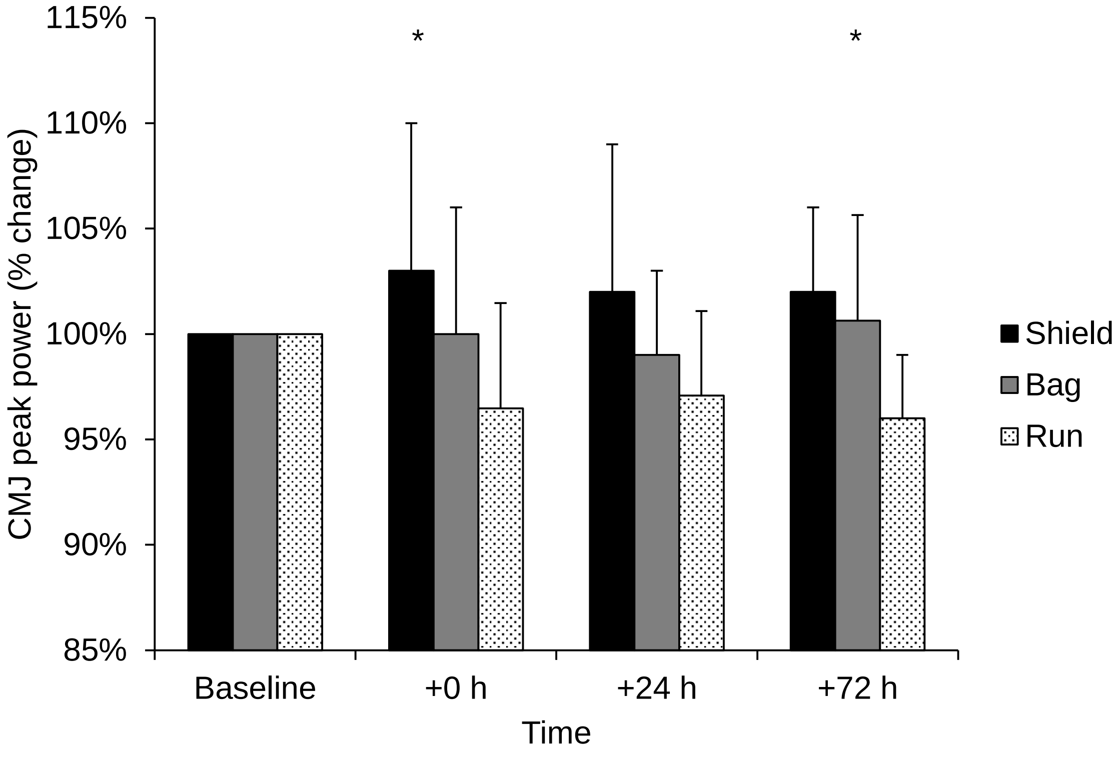


Figure 8. 2. Percentage change from baseline for peak power in counter-movement (CMJ) for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups. Data are means ± SD. * denotes *likely* difference in effect from baseline between Shield and Run group.

Table 8. 3. Plyometric push-up and counter-movement jump (CMJ) data for the Shield (n = 6), Bag (n = 7) and Run (n = 7) group.

		Baseline	+0 h	+24 h	+72 h
Plyometric push-up peak power (W)	Shield	1710 ± 282	1470 ± 220	1785 ± 362	2228 ± 362
	Bag	2364 ± 904	2071 ± 999	2310 ± 955	2167 ± 822
	Run	1924 ± 719	1537 ± 590	1653 ± 914	1834 ± 1072
CMJ peak power (W)	Shield	4012 ± 482	4102 ± 320	4068 ± 287	4063 ± 383
	Bag	4516 ± 594	4542 ± 443	4443 ± 542	4545 ± 472
	Run	4037 ± 487	3895 ± 557	3920 ± 541	3921 ± 410

Table 8. 4. Isokinetic strength data for the Shield (n = 6), Bag (n = 7) and Run (n = 7) group.

		Baseline	+0 h	+24 h	+72 h
Knee extension peak toque (Nm)	Shield	261 ±36	253 ± 32^{+}	250 ± 20	265 ± 29
	Bag	274 ± 21	268 ± 30	270 ± 23	268 ± 27
	Run	245 ± 46	231 ± 57^{+}	237 ± 46^{+}	243 ± 44
Knee flexion peak torque (Nm)	Shield	142 ± 18	123 ± 14^{+}	134 ± 20	128 ± 7^{+}
	Bag	146 ± 13	143 ± 15	149 ± 14	150 ± 14
	Run	130 ± 18	128 ± 31	127 ± 23	135 ± 22
Upper body pushing peak torque (Nm)	Shield	601 ± 95	515 ± 107^{+}	559 ± 99^{+}	532 ± 82^{+}
	Bag	602 ± 86	557 ± 101^{+}	536 ± 99^{+}	540 ± 84^{+}
	Run	521 ± 89	510 ± 70	505 ± 70	529 ± 82
Upper body pulling peak torque (Nm)	Shield	417 ± 37	389 ± 62	395 ± 54	380 ± 66
	Bag	422 ± 66	415 ± 66	421 ± 68	421 ± 69
	Run	377 ± 61	394 ± 69^{+}	384 ± 49	391 ± 70^{+}

$^{+}$ Denotes *likely* difference compared to baseline.

8.4.3.2 Isokinetic peak torque

Within group, time effects for peak knee flexion torque were *unclear* in the Bag and Run groups, but were *likely* less +0 (ES = 0.81 ± 0.75) and +72 hours (ES = 0.61 ± 0.74) after the simulation in the Shield group. Furthermore, peak knee flexion torque *likely* decreased more in the Shield group +0 and +72 hours after the match simulation compared to both the Bag (ES = 1.01 ± 1.15 and 1.11 ± 0.98 at +0 and +72 hours, respectively) and Run groups (ES = 0.88 ± 1.04 and 1.00 ± 0.86, at +0 and +72 hours, respectively).

Between group differences in peak knee extension torque were apparent +0 hours after the simulation with *possibly* greater reduction in torque in the Run compared to Shield group (ES = 0.13 ± 0.33). All other time points after the simulation were *unclear*. Within group time effects were observed in the Run and Shield group with *possible* decreases observed +0 hours after the simulation (Shield ES = 0.17 ± 0.27; Run ES = 0.26 ± 0.30). Peak knee extension torque was also *possibly* less +24 hours after the match simulation in the Run group (ES = 0.15 ± 0.17).

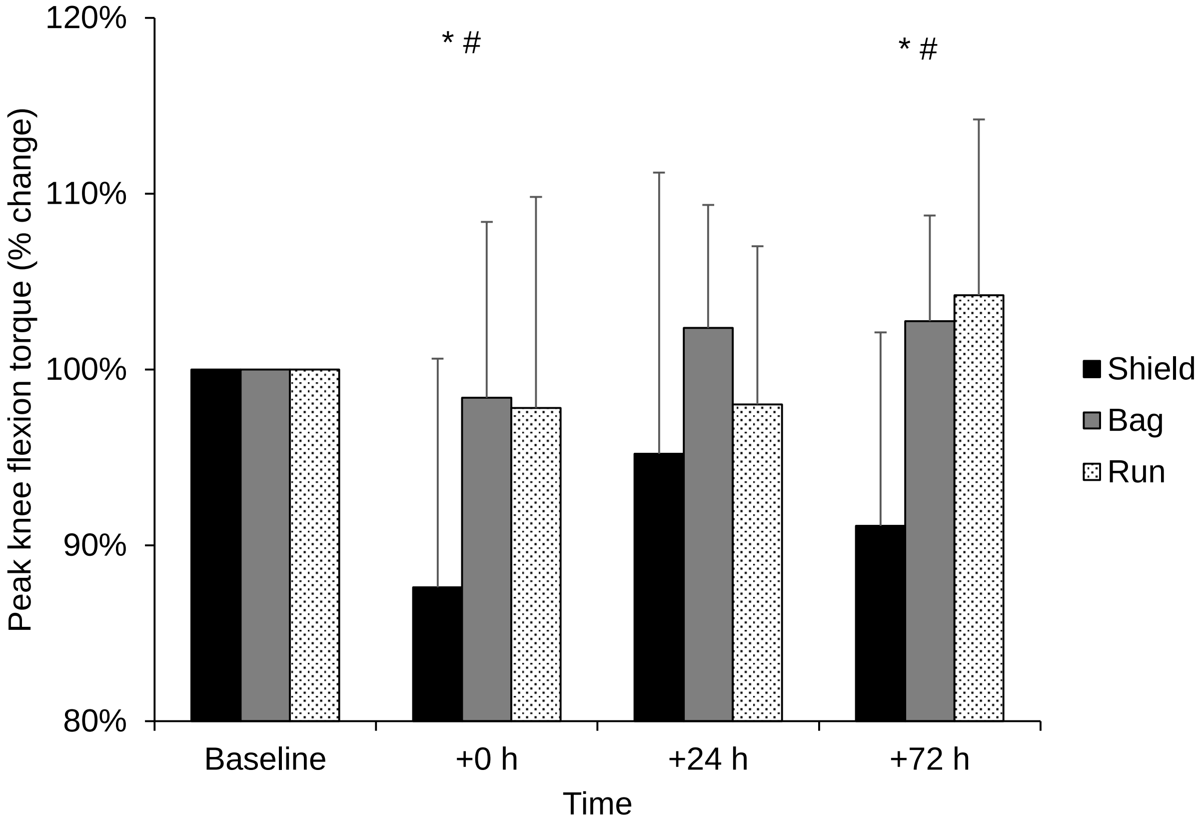


Figure 8. 3. Percentage change from baseline for peak knee flexion torque at 60°·s^{-1} for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups. Data are means ± SD. * denotes meaningful difference in effect from baseline between Shield and Run group. # denotes meaningful difference in effect from baseline between Shield and Bag group.

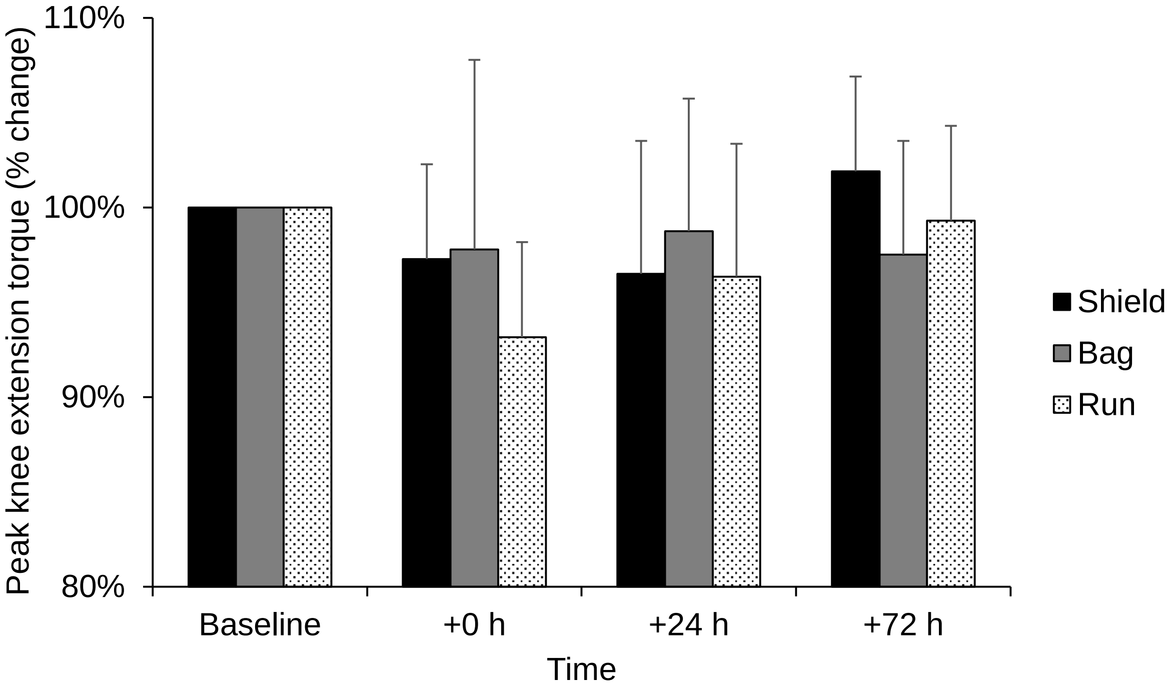


Figure 8. 4. Percentage change from baseline for peak knee extension torque at 60°·s^{-1} for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups.

Peak upper body pushing force *likely* decreased more in the Shield group compared to both Run (ES = 0.73 ± 0.61) and Bag (ES = 0.44 ± 0.48) groups +0 hours after the match simulation compared to baseline. Peak upper body pushing force was *likely* lower +24 (ES = 0.81 ± 1.09) and +72 hours (ES = 0.70 ± 0.66) after the simulation in the Bag group compared to the Run group, while the Shield group *likely* decreased more compared to Run at +72 hours only (ES = 0.86 ± 0.69). Within group time effects were also found in the Shield group with a *very likely* decrease +0 (ES = 0.70 ± 0.25) and *likely* decreases +24 (ES = 0.34 ± 0.33) and +72 (ES = 0.56 ± 0.41) hours after the simulation. Peak force was *likely* less at all time points compared to baseline within the Bag group (+0 hours, ES = 0.42 ± 0.36; +24 hours, ES = 0.91 ± 0.96; +72 hours, ES = 0.57 ± 0.43) but differences were *unclear* in the Run group. There were also *unclear* between groups differences for Shield and Bag in upper body pulling peak force at all time points, whilst Shield (ES = 0.60 ± 0.67) and Bag (ES = 0.36 ± 0.42) groups *likely* decreased greater +0 hours after the simulation compared to the Run group. Further *unclear* results were observed +24 and +72 hours after the simulation between groups. The within group results were *unclear* for the Shield group and *likely* trivial for the Bag group. Peak upper body pulling force *possibly* increased in the Run group +0 (ES = 0.23 ± 0.30) and +72 (ES = 0.18 ± 0.34) hours after the match simulation.

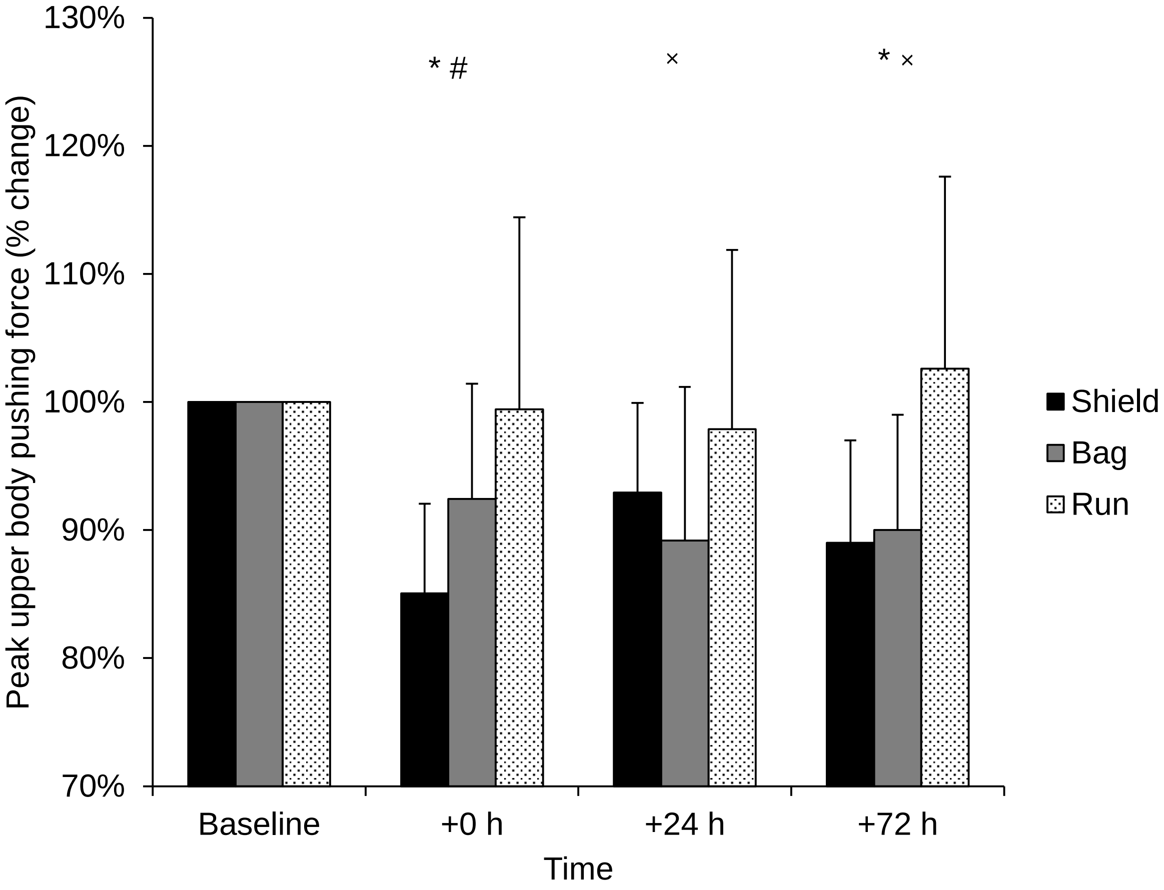


Figure 8. 5. Percentage change from baseline for peak upper body pushing torque at 90°·s^{-1} for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups. Data are means ± SD. * denotes meaningful difference in effect from baseline between Shield and Run group. # denotes meaningful difference in effect from baseline between Shield and Bag group. × denotes meaningful difference in effect from baseline between Bag and Run group.

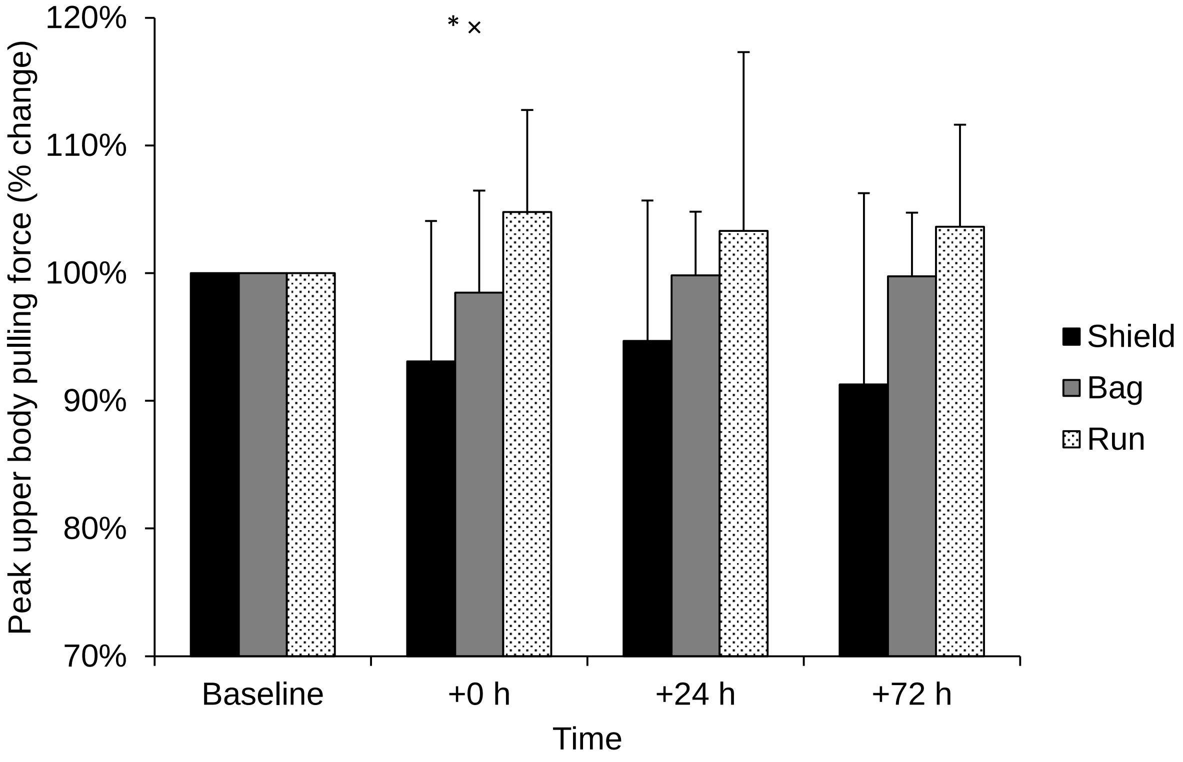


Figure 8. 6. Percentage change from baseline for peak upper body pulling torque at 90°·s^{-1} for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups. Data are means ± SD. * denotes meaningful difference in effect from baseline between Shield and Run group. × denotes meaningful difference in effect from baseline between Bag and Run group.

8.4.4 Perceptual responses

The perceived quadriceps muscle soreness effect was *likely* greater in the Run group compared to the Bag group +72 hours after the match simulation (ES = 0.67 ± 0.54). There were *likely* greater effects in the Run group compared to Shield at +0 (ES = 0.49 ± 0.53), +24 (ES = 0.69 ± 0.51) and +72 hours after the simulation (ES = 0.35 ± 0.73). All differences in effect between the Shield and Bag group were *unclear*. Both Bag (ES = 3.54 ± 3.02) and Run groups (ES = 4.35 ± 2.57) perceived quadriceps soreness *very likely* increased +0 hours after the match simulation while the change in the Shield group was *unclear*. Shield and Bag groups were *very likely* greater and the Run group was *most likely* greater +24 hours after the match simulation (ES = 0.58 ± 0.37, 5.92 ± 5.19, 5.59 ± 2.56, respectively).

Between group differences in perceived hamstring soreness were *unclear* at all time points, while there were *likely* within-group increases +0 and +24 hours after the simulation in the Shield group (ES = 0.56 ± 0.40 and 0.78 ± 0.83, respectively). There were also *very likely* increases in hamstring soreness at +0 and +24 hours in the Bag group (ES = 2.07 ± 1.38 and 4.12 ± 3.87, respectively) and at +0 and +72 hours in the Run group (ES = 14.20 ± 8.78 and 5.88 ± 5.15). A *most likely* increase in hamstring soreness was also evident +24 hours after the match simulation in the Run group (ES = 21.09 ± 10.60).

The perceived upper body muscle soreness effect size was *likely* greater in the Bag group compared to the Run group +72 hours after the simulation (ES = 1.37 ± 1.53). All other between group effect differences were *unclear*. Within group time effects were evident at +0 for the Bag group (ES = 5.24 ± 3.50, *most likely*) and across all groups +24 hours after the simulation with a *very likely* increase for the Shield (ES = 0.58 ± 0.37), Bag (ES = 5.92 ± 5.19) and Run groups (ES = 1.96 ± 0.97). +72 hours after the simulation, all within group differences were *unclear*.

Table 8. 5. Perceived muscle soreness at Baseline and +0, +24 and +72 hours after the match simulation for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups.

		Baseline	+0 hours	+24 hours	+72 hours
Quadriceps soreness	Shield	2.7 ± 2.8	4.6 ± 2.8$^{!}$	5.0 ± 2.4$^{+!}$	3.6 ± 2.9!
	Bag	0.4 ± 0.3	1.2 ± 0.9^{+}	2.7 ± 2.4^{+}	0.7 ± 0.4$^{!}$
	Run	0.3 ± 0.5	3.1 ± 2.0$^{+\#}$	3.8 ± 2.0$^{+\#}$	1.6 ± 1.2$^{+*\#}$
Hamstring soreness	Shield	2.7 ± 2.9	4.9 ± 2.4^{+}	5.8 ± 1.9^{+}	4.0 ± 2.3
	Bag	0.5 ± 0.5	1.8 ± 1.3^{+}	3.0 ± 2.9^{+}	1.5 ± 2.1
	Run	0.1 ± 0.2	2.9 ± 2.1^{+}	4.3 ± 2.6^{+}	1.3 ± 1.1^{+}
Upper-body soreness	Shield	3.2 ± 3.2	4.6 ± 2.1	6.9 ± 0.5$^{+!}$	5.2 ± 2.7$^{!}$
	Bag	0.2 ± 0.3	2.1 ± 1.5$^{+!}$	2.6 ± 2.1^{+}	2.8 ± 3.1$^{!}$
	Run	0.4 ± 0.7	1.0 ± 1.7*	1.5 ± 1.1$^{+\#}$	0.4 ± 0.4$^{\#*}$

$^{+}$ Denotes *likely* difference compared to baseline.

$^{\#}$ Denotes *likely* difference in effect from baseline compared to Shield.

* Denotes *likely* difference in effect from baseline compared to Bag.

$^{!}$ Denotes *likely* difference in effect from baseline compared to Run.

8.4.5 Biochemical responses

Full blood count and cytokine concentration data can be found in Table 8. 6. The size of the effect compared to baseline for WBC concentration was *likely* greater +0 hours after the match simulation in the Shield group compared to the Bag group (ES = 0.36 ± 0.39). Further differences in effect were apparent +72 hours after the match simulation with *likely* greater increase in the Run group compared to the Shield (ES = 0.44 ± 0.39). All other between group effects were *unclear*. Within group time effects were *most likely* greater for WBC concentration +0 hours after the simulation in the Shield (ES = 3.56 ± 1.27) and Run groups (ES = 1.81 ± 0.79) and *very likely* greater concentration +0 hours after the simulation for the Bag group (ES = 1.79 ± 1.63). WBC concentration was also *possibly* greater +24 hours (ES = 0.21 ± 0.34) and *likely* greater +72 hours (ES = 0.29 ± 0.14) after the simulation for the Run group. The Bag group time effect was *unclear* +24 hours after and *possibly* less than baseline +72 hours after the simulation (ES = 0.29 ± 0.33).

Between group differences were *unclear* at all time points for IL-6 concentration. *Very likely* increases in IL-6 were apparent +0 hours after the simulation for the Shield group (ES = 7.05 ± 4.51) and *most likely* increases in both Bag (ES = 6.02 ± 1.52) and Run (ES = 8.28 ± 1.99) groups. Within the Run group there was also a *likely* increase compared to baseline +72 hours after the simulation (ES = 0.70 ± 0.85).

All between group differences in effect were *unclear* for IL-10 concentration. In the Shield and Bag groups, there were *most likely* increases +0 hours after the simulation (ES = 1.85 ± 1.02 and 3.61 ± 1.78, respectively) whilst the Run group exhibited *very likely* increases at the same time point (ES = 2.54 ± 1.25). All other within group time effects were *unclear*.

Table 8. 6. Concentration of white blood cells (WBC), IL-6 and IL-10 at Baseline and +0, +24 and +72 hours after the match simulation for the Shield (n = 6), Bag (n = 7) and Run (n = 7) groups.

		Baseline	+0	+24	+72
WBC ($10^9 \cdot L^{-1}$)	Shield	6.5 ± 0.9	$10.4 \pm 1.7^{+*}$	6.5 ± 1.2	$5.9 \pm 0.5^{!}$
	Bag	6.0 ± 1.3	$8.9 \pm 4.3^{+\#}$	6.1 ± 1.5	5.5 ± 1.2
	Run	6.4 ± 1.7	$10.3 \pm 2.4^{+}$	6.8 ± 1.8	$7.0 \pm 1.9^{+\#}$
IL-6 (pg·ml^{-1})	Shield	2.2 ± 1.4	$15.2 \pm 9.2^{+}$	2.4 ± 1.6	2.3 ± 2.7
	Bag	1.5 ± 1.8	$10.3 \pm 3.2^{+}$	2.7 ± 2.6	1.9 ± 2.1
	Run	0.9 ± 0.8	$8.8 \pm 2.6^{+}$	1.0 ± 0.4	1.6 ± 1.1
IL-10 (pg·ml^{-1})	Shield	8.6 ± 5.1	$20.9 \pm 8.9^{+}$	6.8 ± 3.2	8.5 ± 6.2
	Bag	8.6 ± 2.9	$21.6 \pm 7.7^{+}$	6.7 ± 2.7	9.4 ± 4.0
	Run	7.7 ± 3.4	$18.6 \pm 8.3^{+}$	10.7 ± 6.5	9.5 ± 4.8

$^{+}$ Denotes *likely* difference compared to baseline.

$^{\#}$ Denotes *likely* difference in effect from baseline compared to Shield.

* Denotes *likely* difference in effect from baseline compared to Bag.

$^{!}$ Denotes *likely* difference in effect from baseline compared to Run.

8.5 Discussion

To understand the influence of collision on player fatigue and recovery, this study investigated changes in neuromuscular, perceptual and biochemical markers after a rugby league match simulation protocol performed with either contact with a tackle bag, contact with an opponent or without contact (i.e. running only). Internal and external loads during the simulation were similar to that observed in Chapter 7. No clear differences were apparent for internal load between the three groups, yet high-speed running was *likely* lower in the Shield group compared to both Bag and Run groups. Similarly, mean sprint A speed (i.e. during the longest sprint) was *very likely* lower for the Shield group compared to the Run. Concurrently, PlayerLoad^{TM} slow was greater in the Shield group compared to both Bag and Run groups, which indicates the modified competitive contact was more demanding for the participants.

Furthermore, upper body neuromuscular performance decreased in the Shield group +0 and +72 hours after the simulation compared to the other groups. The Run group demonstrated a *likely* greater loss in CMJ peak power immediately after the match simulation compared to the Shield group, which could be due to greater running demands. All three groups demonstrated a clear increase in cytokines IL-6 and IL-10 immediately after the match simulation, but differences between the groups were *unclear* and values returned to baseline +24 hours after the simulation. Neuromuscular responses after the match simulation indicate subtle differences in the mechanisms of fatigue between those performing greater high-speed running distance compared to players who were involved in physical collisions. However, the cytokine and leukocyte response did not differentiate between high running demands and high contact demands.

While lower-body neuromuscular performance has been extensively examined after rugby league matches (Twist et al., 2012; McLean et al., 2010; McLellan & Lovell, 2012; Duffield et al., 2012; Johnston et al., 2015b), limited research has explored the upper-body response. Plyometric push-up peak power decreased at only +0 hours after the match simulation in all groups but differences between the groups were *unclear*. These findings are in contrast to Oxendale and colleagues (2016), who identified small decrements in performance of a repeated plyometric push-up test, 12 and 36 hours after an elite, competitive rugby league match, which were also negatively correlated with collision frequency. The changes in plyometric push-up after the simulation were also in contrast to the immediate and prolonged reductions observed in upper body isokinetic peak pushing and pulling force for the Shield and Bag groups. Isokinetic force data confirmed the expected preservation of upper body force in the group that performed only running, while the Shield group had the greatest and most extended loss in upper body function. These data suggest that the plyometric push-up exercise seems to possess insufficient sensitivity to identify small differences in functional impairment between groups compared to isokinetic dynamometry. This is confirmed by the in-house reliability of the tests indicating CV% of 15.3 and 5.4% for the plyometric push-up and isokinetic test, respectively. While it is impractical to suggest isokinetic dynamometry should be used to identify upper-body neuromuscular fatigue in elite sport settings, caution is warranted when interpreting data derived from a plyometric push-up. Given running with contact impairs upper body muscle function that might have implications for training in the days after, further research is warranted to identify a robust, field test for upper body neuromuscular function in contact team sport athletes.

While only small differences were apparent between groups for knee extension (Shield c.f. Run; ES = 0.13 ± 0.33), there were *likely* greater decrements in knee flexion torque at +0 and +72 hours after the simulation for the Shield compared to Bag and Run groups. To execute effective tackles, players must recruit the lower limbs to drive opponents backwards. Knee flexion torque was lower after the simulation in the Shield group, suggesting a crucial role for the hamstrings during competitive physical contacts and wrestling. The same decrement was not observed in knee extensors; therefore, improved hamstring strength could be particularly important for players to improve tackle performance and recovery after matches. The response of isokinetic hamstring torque resembles the biomodal pattern of recovery observed after exhaustive stretch-shortening cycle activity (Nicol et al., 2006). This response has not been observed after competitive rugby league performance, but has been reported in rugby union players after maximum speed training sessions (Johnston et al., 2015). Johnston and colleagues (2015) attributed the immediate decrements in force to metabolic disturbances and later decreases associated with the inflammatory response. However, the biochemical data in the present study do not indicate a prolonged inflammatory response with IL-6 and IL-10 returning to baseline concentrations +24 hours after the simulation in the Shield group. It is well documented that IL-6 does not correspond with impaired muscle function over longer periods of time (Peake et al., 2005; Toft et al., 2002). Decrements in performance could be associated with perceived muscle soreness that had not fully recovered after 72 hours, although it is unclear what mechanism is responsible for these findings. “Mild” muscle damage (<20% decrement in function; Paulsen et al., 2012) is usually associated with rapid recovery within 48 hours of the activity. As the Shield group were the only group to exhibit more prolonged symptoms of muscle damage, it is probable that blunt trauma to the muscle is responsible for the observed results. The current study was unable to identify a mechanism to differentiate between mechanical and blunt trauma muscle damage, therefore further investigation is required to clarify the influence of physical contact on recovery. The contradictory findings in CMJ peak power measured +0 hours after the match simulations are of interest. The change in peak power was greater in the Run group (-4 ± 5%) compared to the Shield (3 ± 7%) and Bag (0 ± 6%) groups. These results are more aligned with the knee extension torque changes where a small difference in effect was found in the Run group (-7 ± 9%) compared to the Shield (-3 ± 5%; ES = 0.13 ± 0.33) but not Bag (-2 ± 10%) groups. Taken together, these findings suggest a larger force decrement in the knee extensors after high-speed running and larger decrement to the knee flexors when more physical collisions are included. The importance of decrements in peak torque after intermittent exercise means practitioners should consider the exercise content when selecting the measurement tool to monitor athletes’ fatigue status and recovery.

Upper body muscle soreness increases were similar in the Bag and Shield groups, both of which were *likely* greater compared to the Run group +24 and +72 hours after the match simulation. These findings are likely explained by the addition of physical contact to the upper body and associated blunt force trauma. Perceived quadriceps muscle soreness was *likely* greater +0, +24 and +72 hours after the simulation in the Run group compared to the Shield group. Within all three groups there was a *likely* increase in quadriceps soreness +24 hours after the simulation. Such responses are consistent with observations of muscle soreness after competitive and simulated rugby league performance (Twist et al., 2012; McLean et al., 2010; Oxendale et al., 2016; Mullen et al., 2015). Repeated exposure to faster sprints could result in greater changes in metabolic activity and muscle damage from higher deceleration loads that in turn would increase sensations of muscle soreness after the Run simulation (Howatson & Malik, 2009). While differences in mean sprint speed and high-speed running were *unclear* between Bag and Run groups, the Shield group performed *likely* less high speed running and *very likely* lower mean sprint speed compared to the Run group. These results reaffirm that external running load could result in specific lower body fatigue responses, regardless of physical contact (Chapter 3; Mullen et al., 2015; Twist et al., 2012). Similarly, specific tissue damage from blunt trauma to the upper body after physical collisions could influence perceptions of upper body soreness for the Shield group compared to the Run group. These results are relevant for monitoring physical fatigue and recovery in rugby players as different positional groups perform diverse match actions with forward players more often involved in physical collisions and backs more high-speed running and sprinting (Twist et al., 2012; Oxendale et al., 2016). The current results demonstrate the requirement for monitoring upper body recovery, as fatigue responses can be present independent of lower body changes.

After the simulation IL-6 concentration was greater compared to that in rugby union players (3.7 cf. 8.8-15.2 pg·ml^{-1}; Cunniffe et al., 2010), but similar to increases observed immediately after soccer (~12 pg·ml^{-1}; Mohr et al., 2015) and futsal (~11 pg·ml^{-}1; Andersson et al., 2010), with comparable decreases 24 hours after. While precise mechanisms for IL-6 increases are unknown, it is thought that increases in reactive oxygen species associated with cellular stress augments transcription (Kramer & Goodyear, 2007). Furthermore, the type of activity as well as the duration and intensity appear to influence the magnitude of change (Pedersen & Hoffman-Goetz, 2000). No clear differences in cytokine response were apparent between the groups in the present study, despite variation in physical contact type and site-specific decrements in muscle function. It has been argued that increased IL-6 concentration is not related to exercise-induced muscle damage because a rise in IL-6 does not correspond with delayed and prolonged indicators such as impaired muscle function and elevated concentrations of myofibre proteins (Peake et al., 2005; Toft et al., 2002). This was evident in the present study with prolonged decrements to upper-body force and knee flexion torque despite IL-6 concentration returning to baseline. As the current muscle function results indicate ‘mild’ muscle damage (i.e. < 20% loss in function), it is not surprising that systemic increases in IL-6 were short lived (Paulsen et al., 2012). However, the prolonged decrement in muscle function is contradictory with mild muscle damage which is normally fully recovered within two days of the activity (Malm et al., 2004). This could be indicative of “collision-specific” muscle damage that has a different time-course to mechanical damage. Only the Shield group exhibited prolonged decrements in muscle function. Despite differences in muscle function, *unclear* differences between groups suggests that IL-6 concentration is indicative of total physical load rather than specific collision- or running induced, muscle damage.

Future research is required to confirm the hypothesis of a longer recovery period after collision specific muscle damage, despite relatively small changes in function.

Large increases in WBC and IL-10 occurred immediately after the match simulation, which is also indicative of an acute response to initiate tissue repair after exercise (Gleeson, 2007). IL-6 has previously been shown to mediate leukocytosis and signal the start of an anti-inflammatory response; therefore the concurrent increase in both cytokine markers and WBC is to be expected (Steensberg et al., 2003). The values of WBC are lower than those reported after elite rugby union (Cunniffe et al., 2010) and elite soccer (Mohr et al., 2015), but could be explained by the shorter duration of activity performed using the simulation (Gleeson, 2007). The current modified physical collision is also still not truly representative of body-on-body contact experienced during competitive rugby that could lead to a greater inflammatory response. In the present study, the match simulation was ~46 minutes in duration compared to ~80 minutes for rugby union and ~90 minutes for soccer. It is apparent in the present study that IL-6, IL-10 and WBC respond to both high running load without physical contact and high contact load with less running demands. Therefore, these blood markers may not be appropriate to quantify specific fatigue and recovery responses to intense physical contact associated with rugby league performance. However, the current results do provide further insight into the mechanisms that underpin match related fatigue after rugby league performance. While site-specific muscle function responses are present dependant on physical contact type, there are unclear differences in systemic blood markers that indicate total match demands such as time in play, total distance and mean HR are key determinants of fatigue. Future research should investigate the differences in parameters such as time-in-play and total running distance on the inflammatory response to better understand positional differences in recovery.

8.6 Conclusions

Modification to physical contact type during a rugby league match simulation results in clear differences in external load, primarily to high-speed running and mean sprint speed. As in Chapter 7, there was greater PlayerLoad^{TM} slow in the Shield group, which is a surrogate measure for physical contact load. Such differences in external load appear to result in specific responses of neuromuscular and perceptual markers of fatigue and recovery. The Shield and Run group had larger decrements in upper body and lower body muscle function, respectively. However, commonly used biochemical markers of inflammatory processes appear unable to distinguish between clear differences in physical demands. Il-6, IL-10 and WBC concentration increased for all groups despite differences in external load and were not associated with the prolonged (up to 72 h) reductions in muscle function or perceived soreness. Furthermore, the plyometric push-up does not reflect changes in upper body isokinetic peak torque over 72 hours of recovery after a match simulation. Also, CMJ testing did not correspond with decreased knee flexion torque in the Shield group after the match simulation. It is possible that competitive physical contact including wrestling requires fatiguing hamstring recruitment that cannot be detected using the CMJ test. Therefore, future examinations of match related fatigue after rugby league should incorporate muscle specific tests.

Chapter 9

Practical Applications and Conclusions

9.1 Practical applications

Automatic tackle detection should be used with caution, particularly in training sessions that replicate physical contact using tackle bags or shields. Instead, accelerometer-derived metrics could be used to quantify load associated with physical contact during rugby league training. These metrics possess acceptable reliability (CV% < moderate change) and are sensitive to differences in physical contact. PlayerLoad^{TM} slow is able to distinguish between contact and no-contact match simulations; however, the present data is based on training style physical contact and should not be generalised to match play. Rugby league coaches and sport scientists could use PlayerLoad^{TM} slow as a surrogate measure for physical contact to monitor training intensity and prescribe session load but further research is required to determine the practicality for quantifying matches.

Rugby league coaches and sport scientists should be aware of the influence the type of contact has on running performance, internal load and neuromuscular fatigue when planning the purpose of a training session. Previous literature suggests that a soft tackle cylinder provides an additional metabolic challenge to running alone, but it does not appear to adequately challenge the cardiovascular or neuromuscular system to prepare players for physical contact. Therefore, for training sessions designed to improve tolerance to physical contact, tackle shields or body-on-body contacts are recommended.

The results in the final study reaffirm the challenges associated with quantifying physical contact specific fatigue. However, site-specific muscle function tests can provide an indication of physical performance and readiness to train after contact sessions. Upper body neuromuscular function tests could be used to monitor responses to training and matches to optimise training schedules. Use of biochemical testing is not recommended due to the lack of sensitivity to varied external load, financial implications, the invasive nature of the sample collection and the time-consuming analysis.

9.2 Quantifying the collision in rugby

Attempts to validate automatic tackle detection from microtechnology during training and matches have produced equivocal findings (Gabbett et al., 2010; McLellen & Lovell, 2012; Hulin et al., 2017; Reardon et al., 2017). In Chapter 4, an analysis of automatic tackle detection, using controlled tackle scenarios, revealed that either a spike in instantaneous PlayerLoad^{TM} from contact or a change of orientation from dropping to the ground will register as a tackle in ~40% of instances. The combination of contact and going to ground improved correct tackle detection frequency to 62%; however, during 16% of trials, two tackles were detected. The initial impact with the tackle bag and the subsequent change of orientation when going to ground likely registered as independent collisions in these 16% of cases. This detailed analysis of the tackle detection algorithm explains the observation in Chapter 3 that automatic tackle detection varied compared to the actual frequency of tackles during the rugby league match simulation protocol. During the tackle Sled and Bag trials, ~59 and ~53 tackles were detected respectively, compared to 48 that were included in the match simulation (CV% = 11.9 and 10.9%, respectively). Tackle replication in Chapter 3 included going to ground after impact which likely inflated the total number of detected tackles by registering the initial impact and the change of orientation. The results from this thesis suggest that the current automatic tackle detection metric should be used with caution, particularly in training sessions.

The tri-axial accelerometer within wearable microtechnology has previously been shown to produce reliable data for field sports athletes (Boyd et al., 2011); however, an examination of PlayerLoad^{TM} with controlled collision events had yet to be performed. Chapter 4 demonstrated that PlayerLoad^{TM} can detect differences in movement speed, the inclusion of physical contact and changes in orientation during short bouts of activity designed to replicate typical collision training actions. PlayerLoad^{TM} was greatest in the condition that combined physical contact with going to ground and there were also positive associations between increases in PlayerLoad^{TM} and the approach speed into contact. This reaffirms the influence of movement speed on accelerometer-derived metrics (Barrett et al., 2014).

Chapter 6 extended these findings to identify the utility of PlayerLoad^{TM} metrics for quantifying types of physical contact in combination with intermittent running. In contrast with Chapter 4, total PlayerLoad^{TM} was not influenced by physical contact combined with running, with similar values reported when participants ran without contact, ran with the inclusion of tackling a tackle bag or ran along with completing person-on-person collisions (10.0 ± 1.0, 10.8 ± 0.8 and 10.5 ± 0.9 AU, respectively). While movement speed into contact was carefully controlled in Chapter 4, sprint to contact speed was self-regulated in Chapter 6. Sprint to contact speed was fastest in the Bag group which likely increased PlayerLoad^{TM} so that there were no clear differences between groups despite lower contact intensity. However, analysis of PlayerLoad^{TM} derivatives indicated that PlayerLoad^{TM} slow, PlayerLoad^{TM} slow-ratio and PlayerLoad^{TM} distance-ratio can quantify the load associated with physical contact independent of running demands. Larger values of these PlayerLoad^{TM} derivatives were observed in the Shield group compared to both Run and Bag groups, indicative of the more intense collision and wrestle. Chapter 6 also demonstrated that changes in PlayerLoad^{TM} derivatives could be indicative of acute fatigue during the match simulation. That is, PlayerLoad^{TM} decreased from period 1 to 4 in all groups, which reflects the decrease in high-speed running distance and sprint speed as perception of fatigue increased (RPE). Collectively, Chapters 4 and 6 confirm the potential utility in accelerometer-derived metrics to determine global load (total PlayerLoad^{TM}) and load specifically associated with physical contact during rugby training and match play (PlayerLoad^{TM} slow). While improvements in automatic tackle detection are required before researchers and sport scientists can be truely confident in the data, PlayerLoad^{TM} and associated derivatives from the embedded accelerometer provide a useful measure of contact specific load during training and competitive matches. Specifically, PlayerLoad^{TM} slow appears sensitive to collisions, evidenced by greater load in the Shield group while total PlayerLoad^{TM} provides an indication of total load combining high-speed running and collisions.

9.3 Influence of physical contact on external load during rugby-related movement

Previous studies have reported lower external load during running with contact compared to non-contact (Johnston & Gabbett, 2011; Johnston et al., 2013). These findings contrast with those of Mullen et al. (2015), who reported more high-speed running when a simulated rugby league match was performed with compared to without contact. Chapters 3, 5 and 6 demonstrated that physical contact influenced external load by modifying a participant’s running strategy during simulated match performance. Sprint to contact speed was ~9% faster when a tackle bag was used to simulate physical contact compared to a heavier tackle sled (Chapter 3). Greater sprint speed into contact with the tackle bag led participants to employ a pacing strategy that reduced total high-speed running throughout the rest of the simulation to maintain sprint to contact performance. This is supported by Chapter 6, where similar running demands were observed between the tackle bag and no-contact groups, indicating that sprint performance was prioritised over tackle performance when using a tackle bag. Contact with the tackle sled is likely to have required greater technical proficiency compared to the tackle bag and provided more resistance due to the size and mass of the tackle arm and steel frame. Consequently, the participants reduced sprint to contact speed to ensure successful execution of skill performance and to reduce any discomfort associated with the physical collision. Similarly, in Chapter 6 sprint to contact speed was ~19% slower in the Shield group compared to the Bag group. However, the group that performed the modified shield contact also performed less high-speed distance and slower self-regulated sprints compared to the Bag group. These differences in external load were independent of internal load as HR, RPE and blood lactate responses were similar between the tackle shield and tackle bag groups. The consequence of this altered movement strategy was that the modified match simulation presented in Chapters 5 and 6 more closely resembled match play than the version presented by Waldron et al. (2013b). That is, total and high-speed running distance with the modified contact is lower than that previously observed during simulated performance (100 c.f. 105 $m \cdot min^{-1}$ and 23 c.f. 27 $m \cdot min^{-1}$, respectively; Waldron et al., 2013a) and closer to those reported from matches (80-105 $m \cdot min^{-1}$; Waldron et al., 2011; Waldron et al., 2013a; Johnston, Gabbett & Jenkins, 2014).

These differences in running load are again attributed to the modified tackle shield contact and are supported by total PlayerLoad^{TM} (~10 c.f. 8-10 AU·min^{-1}), PlayerLoad^{TM} slow (~3 c.f. 3-5 AU·min^{-1}), and PlayerLoad^{TM} 2D (~6 c.f. 4-6 AU·min^{-1}) results (Chapter 6) that indicate that the collision load during the modified simulation is similar to that in matches (Gabbett, 2015a). PlayerLoad^{TM} slow was also greater for the Shield group than both the Bag and Run groups (Chapter 6), providing support for increased physical contact load during this form of collision. The modified physical contact did also not adversely affect the reliability of the match simulation protocol with comparable between trial variation to the previous version for total, high- and low-speed distance (CV% = 1-4%; Waldron et al., 2013b). Furthermore, PlayerLoad^{TM} metrics were adequately reliable to detect moderate changes in performance (CV% = 5.2-8.0%), for example differences in positional demands (Gabbett, 2015a). Collectively, the results from Chapters 3, 5 and 6 of the thesis confirm that physical contact decreases running load and encourages participants to down-regulate their high-speed activity to maintain performance and to avoid excessive fatigue. Moreover, a tackle shield is more appropriate than a traditional tackle bag to better replicate the movements before and physical load during a rugby collision. Careful consideration of the contact type used is therefore required to replicate competitive physical collisions observed during training and matches. These findings have important implications for coaches and researchers who wish to replicate the collision with rugby players.

9.4 Influence of physical contact on post-simulation fatigue responses

Previously, simulated rugby league has not resulted in the same magnitude of neuromuscular function impairment, despite a greater external load being performed compared to athletes in elite competition (Mullen et al., 2015). Chapter 3 reaffirmed these findings, showing that there is no clear change in CMJ flight time after a simulated rugby league match using a traditional tackle bag to replicate physical contact (~2.6%). However, this study did show that CMJ flight time decreased after physical contact with a heavy tackle sled (~5.9%), suggesting that the magnitude of any observed neuromuscular function impairment measured via a CMJ is likely influenced by the type and intensity of collision employed. To further explore this, neuromuscular function was also measured in Chapter 8 for the Run, Bag and Shield groups. The results contradicted Chapter 4, with a *possible* decrease in peak power for the Run group, while the Shield and Bag groups change was *unclear* immediately after the match simulation. Further measurements indicated site-specific fatigue as the Run group exhibited reduced knee extension peak torque compared to impaired knee flexion in the Shield group. These results partly explain differences in CMJ power between groups, whilst supporting the notion that neuromuscular fatigue is dependent on the contact type. The increased physical load from contact in Chapter 7 was also reaffirmed in Chapter 8 that reported superior reductions in upper body isokinetic muscle function for the Shield group compared to both Run and Bag groups. The poor sensitivity of a plyometric push-up (Chapter 8) to detect meaningful losses in muscle function and impracticalities of isokinetic dynamometry require further examination of suitable upper body assessment strategies.

Regardless of contact type, Chapter 8 also reported large increases (~700%) in IL-6 concentration after simulated rugby league performance with a return to basal values 24 hours after. Similarly, large increases in WBC and IL-10 occurred immediately after the match simulation, indicative of an acute response to initiate tissue repair after exercise (Gleeson, 2007). *Unclear* differences between the groups suggests that an increased concentration of inflammatory cytokines is indicative of intense physical activity rather than specific collision-induced, muscle damage. The absence of a prolonged inflammatory response is also concomitant with the aforementioned “mild” losses in neuromuscular function (< 20% reduction in force or power) over the same time period. Therefore, while the modified contact improved the external validity of the simulation and was reliable (Chapter 6), Chapter 8 confirms the challenges of replicating the collision associated with rugby league match-play.

In an applied context, practitioners should appropriately prepare players to cope with the physical demands imposed on them by their respective collision loads. This will enable players to resist fatigue that might impact on running performance, skill and increase their susceptibility to injury. Monitoring systemic markers of inflammation might provide an indication of an athlete’s responses to overall workload such as total distance or time on the field, but are not recommended in a practical setting. However, to understand fatigue responses and manage training stimuli, site-specific muscle function tests are necessary to monitor recovery after training sessions and matches.

9.5 Potential limitations

9.5.1 Simulated physical contact

While this body of work has clearly extended knowledge on physical contact, its quantification and influence on fatigue, replicating the intensity of collision to that observed in match play remains a challenge. For example, tackles during matches will frequently involve more than two players with direct trauma inflicted on the muscle body. The controlled, non-competitive nature of simulated collisions is also likely to reduce the intensity and technical elements of these actions compared to matches.

Therefore, the additive physical and cognitive loads that would be associated with a more intense collision are not accounted for in the data presented and should be considered when interpreting the reported responses. These factors not withstanding, the methods used within this body of work still enable a reliable and representitive replication of collision that can be used by practitioners and researchers working to improve rugby performance.

9.5.2 Participant characteristics

Given the challenges of recruiting professional athletes because of the undesirable interference of research outcomes and involvement on training practices and competition, the participants recruited for the studies in this thesis were predominantly university-standard rugby players. While all participants were familiar with the movements and demands of rugby and possessed physical qualties similar to professional players (e.g. $\dot{V}O_{2\max}$, high intensity intermittent running performance, sprint speed), these tended to be commensuate with sub-elite rather than elite players. For example YoYo IR1 in Chapters 6 and 7 (~1200 m) was similar to sub-elite (~1010 m; Gabbett and Seibold, 2013) compared to professional (1600 m; Atkins, 2006). Other physical characteristics, such as body mass, were also typically lower (~5-10 kg) than those reported in professional players but similar to those of non-elite players (Johnston et al., 2014a). Greater body mass would influence physical contact characteristics, with greater momentum into contact at the same speed (Waldron et al., 2014). Superior upper and lower body strength in professional compared to university standard players (Baker, 2001) might also evoke a protective effect on fatigue responses after rugby league matches (Johnston et al., 2014c; 2015b) that influences the interpretation of data considering player recovery (e.g. Chapter 7).

Finally, differences in age and playing experience are likely to influence tackling ability that differentiates between playing standards (Gabbett et al., 2011a).

9.5.3 Small sample size

Small sample sizes can result in bias from a lack of variability within the group and can also be suscepltible to Type II error using null hypothesis significance testing. In Chapter 4, the use of five participants does not reflect wide variations in tackle technique (Gabbett & Ryan, 2009) that could influence automatic tackle detection. However, the use of magnitude-based inferences combats these issues by providing an indication of the liklihood that the effect is meaningful compared to between individual variation. These statistics are not susceptible to bias from small sample sizes and as such the results presented in thesis can be appropriately interpreted. Furthermore, sample sizes were estimated *a priori* using the anticipated magnitude of effect. Therefore, while the participant numbers are low in all chapters, the sample sizes are large enough to detect meangingful changes in a variety of physiological and GPS based measurements.

9.5.4 Study design

The use of an independent group design (Chapter 6 and 7) is susceptible to between participant variation. Between individual comparisions of PlayerLoad^{TM} are not recommended due to large individual variation in PlayerLoad^{TM} from differences in running kinematics (Barrett et al., 2014). The use of PlayerLoad^{TM} slow-ratio provides a measure of contact load relative to individual accelerometer load that attempts to account for variation in total PlayerLoad^{TM} and isolate collision specific external load. Furthermore, the use of magnitude based inferences to interpret differences between groups accounts for between participant variation. Large variation due to individual gait characteristics are encorporated into the calculation of smallest worthwhile change and therefore influence whether differences between groups are “meaningful”. Relative PlayerLoad^{TM} metrics and magnitude based statistics limit the impact of individual variability inherent within an independent groups design.

9.6 Future directions

9.6.1 Automatic tackle detection

The current algorithm for automatic tackle detection frequencies derived from microtechnology in training and match play should be used with caution. However, attempts have been made to improve the accuracy and precision of tackle detection using pattern recognition techniques (Kelly et al., 2012) and different filtering rates (Wundersitz et al., 2015b). While this work is in the early stages, the use of machine learning improved tackle detection precision to 95.8%.

Should automatic tackle detection be improved to provide accurate frequency data, then further analysis of tackle intensity and tackle load could be derived from these events. While the use of PlayerLoad^{TM} derivatives appears to provide a surrogate measure for physical contact load, being able to quantify accelerometer load that occurs during “tackle windows” would add to the current understanding of contact specific load. Analyses of both match and training tackle data could underpin training strategies and develop periodisation models for contact loading. This is useful for applied sport scientists and coaches to understand how to best prepare players for the rigours of physical contact during competition.

9.6.2 Upper body neuromuscular measurement

While measurement of lower-body neuromuscular function has received considerable attention, consideration for upper-body performance has been more limited. Oxendale and colleagues (2016) identified decreased performance using a plyometric press-up test after competitive performance. However, in Chapter 6 of this thesis peak power during a single plyometric press-up did not appear sensitive to physical contact (CV% = 15.3%) whilst isokinetic dynamometry and perceptual feelings of soreness were different between contact and non-contact. Further research is required to determine the validity and reliability of field-based, upper-body neuromuscular tests after contact team sports.

9.6.3 Periodisation of collision training

Physical collision accounts for the highest proportion of player injury in rugby league (Fitzpatrick et al., 2017) and rugby union (Williams et al., 2013), with higher incidence of injury reported at the start of the playing season and in the final quarter of matches (Fitzpatrick et al., 2017). Collision-specific conditioning to ensure players are able to tolerate the loads and resist fatigue are therefore warranted. However, that coaches are anecdotally reluctant to engage in collision training because of the increased risk of injury to players and the prolonged symptoms of muscle soreness reported in players (Fletcher et al., 2016) makes the prescription of collision-based training difficult. The valuable information provided within this thesis on the training responses to varying activities and how to monitor them might therefore be employed in the conditioning of rugby players. In particular, the internal and external responses to intermittent running with and without common types of physical collision could be used to prescribe and periodise appropriate training drills to improve match-specific conditioning. Future studies should therefore examine the utility of these findings to improve player conditioning that improves performance and reduces injury risk.

9.6.4 Influence of physical qualities on recovery after rugby league activity

The influence of physical qualities on recovery has been investigated in elite players after competitive matches (Johnston et al. 2015b). However, there are inherent limitations in using competitive performances to identify fatigue responses, including high between match variability and high between player variability in external load (Kempton et al., 2014; Johnston et al., 2015b). Furthermore, well-developed physical qualities are positively associated with number of tackles and high-speed running distance (Johnston et al., 2015b). In Chapter 8 there were unclear differences in neuromuscular function between groups with different collision loads, reaffirming the influence of match demands on fatigue and recovery. Controlled external load, such as a match simulation, should be used to identify the influence of physical qualities on the magnitude of fatigue and the time course of recovery. Such investigation could provide support for the findings in Chapter 4 where lower HR responses correlated with greater high-speed running.

References

Abt, G., & Lovell, R. (2009). The use of individualized speed and intensity thresholds for determining the distance run at high-intensity in professional soccer. *Journal of Sports Sciences*, *27*(9), 893-898.

Andersson, H., Bøhn, S. K., Raastad, T., Paulsen, G., Blomhoff, R., & Kadi, F. (2010). Differences in the inflammatory plasma cytokine response following two elite female soccer games separated by a 72-h recovery. *Scandinavian Journal of Medicine and Science in Sports*, *20*(5), 740-747.

Ascensão, A., Rebelo, A., Oliveira, E., Marques, F., Pereira, L., & Magalhães, J. (2008). Biochemical impact of a soccer match - analysis of oxidative stress and muscle damage markers throughout recovery. *Clinical Biochemistry, 41*(10-11), 841-851.

Austin, D. J., Gabbett, T. J., & Jenkins, D. G. (2013). Reliability and sensitivity of a repeated high-intensity exercise performance test for rugby league and rugby union. *Journal of Strength and Conditioning Research, 27*(4), 1128-1135.

Austin, D. J., Gabbett, T. J., & Jenkins, D. J. (2011a). Repeated high-intensity exercise in a professional rugby league. *Journal of Strength and Conditioning Research*, *25*(7), 1898-1904.

Austin, D. J, Gabbett, T., & Jenkins, D. (2011b). Tackling in a professional rugby league. *Journal of Strength and Conditioning Research*, *25*(6), 1659-1663.

Austin, D. J., & Kelly, S. J. (2013). Positional differences in professional rugby league match play through the use of global positioning systems. *Journal of Strength and Conditioning Research, 27,*14–19.

Austin, D. J., & Kelly, S. J. (2014). Professional rugby league positional match-play analysis through the use of global positioning system. *Journal of Strength and Conditioning Research, 28*(1), 187-193.

Baker, D. G. (2001). A series of studies on the training of high-intensity muscle power in rugby league football players. *Journal of Strength and Conditioning Research, 15*(2), 198–209.

Baker, D. G. (2002). Differences in strength and power among junior-high, senior-high, college-aged, and elite professional rugby league players. *The Journal of Strength and Conditioning Research*, *16*(4), 581-585.

Baker, D. G. (2009). Ability and validity of three different methods of assessing upper-body strength-endurance to distinguish playing rank in professional rugby league players. *The Journal of Strength & Conditioning Research*, *23*(5), 1578-1582.

Baker, D. G., & Newton, R. U. (2007). Change in power output across a high-repetition set of bench throws and jump squats in highly trained athletes. *The Journal of Strength and Conditioning Research*, *21*(4), 1007.

Baker, D. G., & Newton, R. U. (2008). Comparison of lower body strength, power, acceleration, speed, agility, and sprint momentum to describe and compare playing rank among professional rugby league players. *Journal of Strength and Conditioning Research*, *22*(1), 153-158.

Baker, D. G., & Nance, S. (1999). The relation between running speed and measures of strength and power in professional rugby league players. *Journal of Strength and Conditioning Research*, *13*(3), 230-235.

Bangsbo, J., Iaia, F. M., & Krustrup, P. (2008). The Yo-Yo intermittent recovery test. *Sports Medicine*, *38*(1), 37-51.

Bangsbo, J., Krustrup, P., González-Alonso, J., & Saltin, B. (2001). ATP production and efficiency of human skeletal muscle during intense exercise: effect of previous exercise. *American Journal of Physiology-Endocrinology and Metabolism*, *280*(6), E956-E964.

Barrett, S., Midgley, A., & Lovell, R. (2014). PlayerLoad^{TM}: Reliability, convergent validity, and influence of unit position during treadmill running. *International Journal of Sports Physiology and Performance, 9*(6), 945-952.

Barrett, S., Midgley, A.W., Towlson, C., Garrett, A., Portas, M., & Lovell, R. (2016). Within-match PlayerLoad^{TM} patterns during a simulated soccer match: potential implications for unit positioning and fatigue management. *International Journal of Sports Physiology and Performance*, *11*(1), 135-140.

Bishop, N. C., Gleeson, M., Nicholas, C. W., & Ali, A. (2002). Influence of carbohydrate supplementation on plasma cytokine and neutrophil degranulation responses to high intensity intermittent exercise. *International Journal of Sport Nutrition and Exercise Metabolism*, *12*(2), 145-156.

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. *Journal of Strength and Conditioning Research, 28*(6), 1507-1516.

Booth, M., & Orr, R. (2017). Time-loss injuries in sub-elite and emerging rugby league players. *Journal of Sports Science and Medicine*, *16(2)*, 295-301.

Borg, G. (1998). The Borg RPE scale. In *Borg's perceived exertion and pain scales* (pp. 29-38). Champaign, IL: Human Kinetics.

Borg, G., Ljunggren, G., & Ceci, R. (1985). The increase of perceived exertion, aches and pain in the legs, heart rate and blood lactate during exercise on a bicycle ergometer. *European Journal of Applied Physiology and Occupational Physiology*, *54*(4), 343-349.

Boyd, L. J., Ball, K., & Aughey, R. J. (2011). The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *International Journal of Sports Physiology and Performance*, *6*(3), 311-321.

Boyd, L. J., Ball, K., & Aughey, R. J. (2013). Quantifying external load in Australian football matches and training using accelerometers. *International Journal of Sports Physiology and Performance*, *8*(1), 44-51.

Boyd, L.J., Gallagher, E.L., Ball, K., Stepto, N.K., & Aughey, R.J. (2010). Practical application of accelerometers in Australian football. *Journal of Science and Medicine in Sport*, 13: e14–e15.

Bradley, W. J., Hannon, M. P., Benford, V., Morehen, J. C., Twist, C., Shepherd, S., ... & Close, G. L. (2017). Metabolic demands and replenishment of muscle glycogen after a rugby league match simulation protocol. *Journal of Science and Medicine in Sport*, *20*(9), 878-883.

Bradley, W., Morehen, J. C., Haigh, J., Clarke, J., Donovan, T. F., Twist, C., … & Close, G. L. (2016). Muscle glycogen utilisation during Rugby match play: Effects of pre-game carbohydrate. *Journal of Science and Medicine in Sport*, *19*, 1033-1038.

Bruunsgaard, H., Galbo, H., Halkjaer-Kristensen, J., Johansen, T. L., MacLean, D. A., & Pedersen, B. K. (1997). Exercise-induced increase in serum interleukin-6 in humans is related to muscle damage. *Journal of Physiology*, *499*(3), 833-841.

Byrne, C., Twist, C., & Eston, R. (2004). Neuromuscular function after exercise-induced muscle damage. *Sports Medicine*, *34*(1), 49-69.

Byrne, C., & Eston, R. (2002). Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions. *Journal of Sports Sciences*, *20*(12), 951-959.

Carling, C. (2013). Interpreting physical performance in professional soccer match-play: Should we be more pragmatic in our approach? *Sports Medicine, 43*(8), 655-663.

Castellano, J., Casamichana, D., Calleja-González, J., San Román, J., & Ostojic, S. M. (2011). Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. *Journal of Sports Science and Medicine*, *10*(1), 233.

Cheung, K., Hume, P. A., & Maxwell, L. (2003). Delayed onset muscle soreness. *Sports Medicine*, *33*(2), 145-164.

Clarke, J. S., Highton, J., Close, G. L., & Twist, C. (2016). Carbohydrate and caffeine improves high intensity running of elite rugby league interchange players during simulated match play. *Journal of Strength and Conditioning Research,* Epub ahead of print.

Comfort, P., Graham-Smith, P., Matthews, M. J., & Bamber, C. (2011). Strength and power characteristics in English elite rugby league players. *Journal of Strength and Conditioning Research*, *25*(5), 1374-1384.

Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*, *3*(2), 131-144.

Cormack, S. J., Mooney, M. G., Morgan, W., & McGuigan, M. R. (2013). Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. *International Journal of Sports Physiology and Performance, 8*(4), 373-378.

Coutts, A.J., Reaburn, P. & Abt, G., (2003). Heart rate, blood lactate concentration and estimated energy expenditure in a semi-professional rugby league team during a match: a case study. *Journal of Sports Sciences, 21,* 97–103.

Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of Science and Medicine in Sport*, *13*(1), 133-135.

Cummins, C., & Orr, R. (2015). Analysis of physical collisions in elite national rugby league match play. *International Journal of Sports Physiology and Performance*, *10*(6), 732-739.

Cummins, C., Gray, A., Shorter, K., Halaki, M., & Orr, R. (2016). Energetic and metabolic power demands of national rugby league match-play. *International Journal of Sports Medicine*, *37*(07), 552-558.

Cummins, C., Orr, R., O’Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Medicine*, *43*(10), 1025-1042.

Cunniffe, B., Hore, A. J., Whitcombe, D. M., Jones, K. P., Baker, J. S., & Davies, B. (2010). Time course of changes in immuneoendocrine markers following an international rugby game. *European Journal of Applied Physiology*, *108*(1), 113-122.

Dalen, T., Jørgen, I., Gertjan, E., Geir Havard, H., & Ulrik, W. (2016). Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. *Journal of Strength and Conditioning Research*, *30*(2), 351-359.

Damas, F., Nosaka, K., Libardi, C. A., Chen, T. C., & Ugrinowitsch, C. (2016). Susceptibility to exercise-induced muscle damage: a cluster analysis with a large sample. *International Journal of Sports Medicine, 37*(8), 633-640.

De Lacey, J., Brughelli, M.E., McGuigan, M.R., & Hansen, K.T. (2014). Strength, speed and power characteristics of elite rugby league players. *Journal of Strength and Conditioning Research, 28*(8), 2372-2375.

de Moura, N. R., Cury-Boaventura, M. F., Santos, V. C., Levada-Pires, A. C., Bortolon, J., Fiamoncini, J., ... & Hatanaka, E. (2012). Inflammatory response and neutrophil functions in players after a futsal match. *Journal of Strength and Conditioning Research*, *26*(9), 2507-2514.

De Pauw, K., Roelands, B., Marusic, U., Tellez, H. F., Knaepen, K., & Meeusen, R. (2013). Brain mapping after prolonged cycling and during recovery in the heat. *Journal of Appied Physiology*, *115*, 1324–1331.

Delaney, J. A., Duthie, G. M., Thornton, H. R., Scott, T. J., Gay, D., & Dascombe, B. J. (2016a). Acceleration-based running intensities of professional rugby league match play. *International Journal of Sports Physiology and Performance*, *11*(6), 802-809.

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. *International Journal of Sports Physiology and Performance, 10*(6), 725-731.

Delaney, J. A., Thornton, H. R., Duthie, G. M., & Dascombe, B. J. (2016b). Factors that influence running intensity in interchange players in professional rugby league. *International Journal of Sports Physiology and Performance, 11*(8), 1047-1052.

Dempsey, G. M., Gibson, N. V., Sykes, D., Pryjmachuk, B., & Turner, A. P. (2017). Match demands of senior and junior players during international rugby league. *Journal of Strength and Conditioning Research*. Epub ahead of print.

di Prampero, P.E., Fusi, S., Sepulcri, L., Morin, J., Belli, A., & Antonutto, G. (2008). Sprint running: a new energetic approach. *Journal of Experimental Biology*, *208*(14), 2809–2816.

Duffield, R., & Coutts, A. J. (2011). Fatigue and the regulation of exercise intensity during team sport matches. In: *Regulation of Fatigue in Exercise*, F. Marino (Ed.), New York, NY: Nova Science Publishers, Inc, pp. 117–136.

Duffield, R., Murphy, A., Snape, A., Minett, G. M., & Skein, M. (2012). Post-match changes in neuromuscular function and the relationship to match demands in amateur rugby league matches. *Journal of Science and Medicine in Sport, 15*(3), 238-243.

Edwards, A. M., & Noakes, T. D. (2009). Dehydration: Cause of fatigue or sign of pacing in elite soccer? *Sports Medicine, 39*(1), 1-13.

Edwards, S. (1993). The heart rate monitor book. Sacremento, CA: Fleet Feet Press.

Falvo, M. J., & Bloomer, R. J. (2006). Review of exercise-induced muscle injury: relevance for athletic populations. *Research in Sports Medicine*, *14*(1), 65-82.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*, 1149-1160.

Fitzpatrick, A. C., Naylor, A. S., Myler, P., Robertson, C. (2017). A three-year epidemiological prospective cohort study of rugby league match injuries from the european super league. *Journal of Science and Medicine in Sport*, Epub ahead of print.

Fletcher, B. D., Twist, C., Haigh, J. D., Brewer, C., Morton, J. P., & Close, G. L. (2016). Season-long increases in perceived muscle soreness in professional rugby league players: role of player position, match characteristics and playing surface. *Journal of Sports Sciences, 34*(11), 1067-1072.

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., ... & Dodge, C. (2001). A new approach to monitoring exercise training*. Journal of Strength and Conditioning Research, 15*(1), 109-115.

Froyd, C., Millet, G. Y., & Noakes, T. D. (2013). The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. *Journal of Physiology, 591*(5), 1339–1346.

Gabbett, T. J. (2013a). Quantifying the physical demands of collision sports: does microsensor technology measure what it claims to measure? *Journal of Strength and Conditioning Research*, *27*(8), 2319-2322.

Gabbett, T. J. (2014a). Effects of physical, technical, and tactical factors on final ladder position in semiprofessional rugby league. *International Journal of Sports Physiology and Performance, 9*(4), 680-688.

Gabbett, T. J. (2015a). Relationship between accelerometer load, collisions, and repeated high-intensity effort activity in rugby league players. *Journal of Strength and Conditioning Research*, *29*(12), 3424-3431.

Gabbett, T. J. (2015b). Use of relative speed zones increases the high-speed running performed in team sport match play. *Journal of Strength and Conditioning Research*, *29*(12), 3353-3359.

Gabbett, T. J., & Jenkins, D. G. (2011). Relationship between training load and injury in professional rugby league players. *Journal of Science and Medicine in Sport, 14*(3), 204-209.

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. *Journal of Science and Medicine in Sport*, *17*(5), 556-561.

Gabbett, T. J., & Mulvey, M.J. (2008). Time-motion analysis of small-sided training games and competition in elite women soccer players. *Journal of Strength and Conditioning Research, 22,* 543-553.

Gabbett, T. J., & Ryan, P. (2009) Tackling technique, injury risk, and playing performance in high-performance collision sport athletes. *International Journal of Sports Science and Coaching, 4(4)*, 521-533.

Gabbett, T. J. (2008). Influence of fatigue on tackling technique in rugby league players. *Journal of Strength and Conditioning Research, 22*(2), 625-632.

Gabbett, T. J. (2013). Influence of playing standard on the physical demands of professional rugby league. *Journal of Sports Sciences, 31,* 1125-1138.

Gabbett, T. J. (2015). Influence of ball-in-play time on the activity profiles of rugby league match-play. *Journal of Strength and Conditioning Research, 15*(29), 716–721.

Gabbett, T. J. (2013d). Activity and recovery cycles of National Rugby League matches involving higher and lower ranked teams. *Journal of Strength & Conditioning Research*, *27*(6), 1623-1628.

Gabbett, T. J. (2013). Influence of the opposing team on the physical demands of elite rugby league match play. *Journal of Strength and Conditioning Research, 27,* 1629–1635

Gabbett, T. J., Abernethy, B., Jenkins, D. G. (2011a). Correlates of tackling ability in high-performance rugby league players. *Journal of Strength and Conditioning Research*, *25*, 72-79.

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2011b). Physical collisions and injury in professional rugby league match-play. *Journal of Science and Medicine in Sport, 14,* 210–215.

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2011c) Relationships between physiological, anthropometric, and skill qualities and playing performance in professional rugby league players. *Journal of Sports Sciences, 29,* 1655–1664.

Gabbett, T. J., Jenkins, D. G. & Abernethy, B. (2012). Physical demands of professional rugby league training and competition using microtechnology. *Journal of Science and Medicine in Sport, 15,* 80–86.

Gabbett, T. J., Jenkins, D. G., & Abernethy, B. (2010). Physical collisions and injury during professional rugby league skills training. *Journal of Science and Medicine in Sport*, *13*(6), 578-583.

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

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews, 81*(4), 1725-1789.

Gastin, P. B., McLean, O. C., Breed, R. V. P., & Spittle, M. (2014). Tackle and impact detection in elite Australian football suing wearable microsensor technology. *Journal of Sports Sciences*, *32*(10), 947-953.

Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology and Performance*, *10*(1), 84-92.

Gejl, K. D., Hvid, L. G., Frandsen, U., Jensen, K., Sahlin, K., & Ørtenblad, N. (2014). Muscle glycogen content modifies SR Ca^{2+} release rate in elite endurance athletes. *Medicine and Science in Sports & Exercise, 46*(3), 496–505.

Gissane, C., White, J., Kerr, K., & Jennings, D. (2001). An operational model to investigate contact sports injuries. *Medicine and Science in Sports and Exercise*, *33*(12), 1999-2003.

Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability—Part I. *Sports Medicine*, *41*(8), 673-694.

Glatthorn, J. F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F. M., & Maffiuletti, N. A. (2011). Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *Journal of Strength and Conditioning Research*, *25*(2), 556-560.

Gleeson, M. (2007). Immune function in sport and exercise. *Journal of Applied Physiology*, *103*(2), 693-699.

Gregson, W., Drust, B., Atkinson, G., & Salvo, V. D. (2010). Match-to-match variability of high-speed activities in Premier League soccer. *International Journal of Sports Medicine*, *31*(4), 237-242.

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Medicine*, *44*(2), 139-147.

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 Medicine*, *46*(4), 559-588.

Hendricks, S., Karpul, D., & Lambert, M. (2014). Momentum and kinetic energy before the tackle in rugby union. *Journal of Sports Science and Medicine*, *13*(3), 557.

Hendricks, S., O'Connor, S., Lambert, M., Brown, J., Burger, N., Mc Fie, S., ... & Viljoen, W. (2015). Contact technique and concussions in the South African under-18 Coca-Cola Craven week Rugby tournament. *European Journal of Sport Science, 15*(6), 557-564.

Highton, J., Mullen, T., & Twist, C. (2017). Knowledge of task end-point influences pacing and performance during simulated rugby league match-play. *International Journal of Sports Physiology and Performance*, Epub ahead of print.

Hoffman, J. R., Nusse, V., & Kang, J. (2003). The effect of an intercollegiate soccer game on maximal power performance. *Canadian Journal of Applied Physiology*, *28*(6), 807-817.

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3.

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

Hopkins, W.G. A New View of Statistics. [Web page] 2000 [cited Feb 2007]; Available from: http://www.sportsci.org/resource/stats/procmixed.html/#indif.

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

Hulin, B. T., Gabbett, T. J., Johnston, R. D., & Jenkins, D. G. (2017). Wearable microtechnology can accurately identify collision events during professional rugby league match-play. *Journal of Science and Medicine in Sport, 20(7),* 638.

Hulin, B. T., Gabbett, T.J., Kearney, S., & Corvo, A. (2015). Physical demands of match play in successful and less-successful elite rugby league teams. *International Journal of Sports Physiology and Performance*, *10*(6), 703-710.

Hulin, B. T., & Gabbett, T. J. (2015). Activity profiles of successful and less-successful semi-elite rugby league teams. *International Journal of Sports Medicine, 36*(6), 485-489.

Ispirlidis, I., Fatouros, I. G., Jamurtas, A. Z., Nikolaidis, M. G., Michailidis, I., Douroudos, I., ... & Alexiou, V. (2008). Time-course of changes in inflammatory and performance responses following a soccer game. *Clinical Journal of Sport Medicine*, *18*(5), 423-431.

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. *International Journal of Sports Physiology and Performance*, *5*(3), 328-341.

Jennings, C. L., Viljoen, W., Durandt, J., & Lambert, M. I. (2005). The reliability of the FitroDyne as a measure of muscle power. *Journal of Strength and Conditioning Research*, *19*(4), 859-863.

Johnston, R. D., Gabbett, T. J., & Jenkins, D. G. (2014a). Applied sport science of rugby league. *Sports Medicine*, *44*(8), 1087-1100.

Johnston, R. D., Gabbett, T. J., & Jenkins, D. G. (2015a). Influence of playing standard and physical fitness on activity profiles and post-match fatigue during intensified junior rugby league competition. *Sports Medicine-Open*, *1*(1), 18.

Johnston, R. D., Gabbett, T. J., Jenkins, D. G., & Hulin, B. T. (2015b). Influence of physical qualities on post-match fatigue in rugby league players. *Journal of Science and Medicine in Sport, 18*(2), 209-213.

Johnston, R. D., Gabbett, T. J., Jenkins, D. G., & Speranza, M. J. (2016). Effect of different repeated-high-intensity-effort bouts on subsequent running, skill performance, and neuromuscular function. *International Journal of Sports Physiology and Performance*, *11*(3), 311-318.

Johnston, R. D., Gabbett, T. J., Seibold, A. J., & Jenkins, D. G. (2014b). Influence of physical contact on pacing strategies during game-based activities. *International Journal of Sports Physiology and Performance*, *9*(5), 811-816.

Johnston, R. D., Gabbett, T. J., Seibold, A. J., & Jenkins, D. G. (2014c). Influence of physical contact on neuromuscular fatigue and markers of muscle damage following small-sided games. *Journal of Science and Medicine in Sport*, *17*(5), 535-540.

Johnston, R. D., Gibson, N. V., Twist, C., Gabbett, T. J., MacNay, S. A., & MacFarlane, N. G. (2013). Physiological responses to an intensified period of rugby league competition. *Journal of Strength and Conditioning Research, 27*(3), 643-654.

Johnston, R. D., & Gabbett, T. J. (2011). Repeated-sprint and effort ability in rugby league players. *Journal of Strength and Conditioning Research, 25*, 2789–95.

Johnston, R. D., Watsford, M. L., Kelly, S. J., Pine, M. J., & Spurrs, R. W., (2014d). Validity and interunit reliability of 10 HZ and 15 Hz GPS units for assessing athlete movement demands. *Journal of Strength and Conditioning Research, 28(6).*1649-55.

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. *Journal of Strength and Conditioning Research, 26*, 758–765.

Jones, M. R., West, D. J., Harrington, B. J., Cook, C. J., Bracken, R. M., Shearer, D. A. & Kilduff, L. P. (2014). Match play performance characteristics that predict post-match creatine kinase responses in professional rugby union players.

BMC Sports Science, Medicine, and Rehabilitation, *6*(38), doi: 10.1186/2052-1847-6-38.

Kelly, S. J., Murphy, A. J., Watsford, M. L., Austin, D., & Rennie, M. (2015). Reliability and validity of sports accelerometers during static and dynamic testing. *International Journal of Sports Physiology and Performance*, *10*(1), 106-111.

Kempton, T., & Coutts, A. J. (2016). Factors affecting exercise intensity in professional rugby league match-play. *Journal of Science and Medicine in Sport*, *19*(6), 504-508.

Kempton, T., Sirotic, A. C., & Coutts, A. J. (2014). Between match variation in professional rugby league competition. *Journal of Science and Medicine in Sport*, *17*(4), 404-407.

Kempton, T., Sirotic, A. C., & Coutts, A. J. (2015). An integrated analysis of match-related fatigue in professional rugby league. *Journal of Sports Sciences*, *33*(1), 39-47.

Kempton, T., Sirotic, A. C., & Coutts, A. J. (2017). A comparison of physical and technical performance profiles between successful and less-successful professional rugby league teams. *International Journal of Sports Physiology and Performance*, *12*(4), 520-526.

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. *Journal of Sports Sciences*, *31*(16), 1770-1780.

King, T., Jenkins, D., & Gabbett, T. (2009). A time–motion analysis of professional rugby league match-play. *Journal of Sports Sciences*, *27*(3), 213-219.

King, D. A., Hume, P. A., Milburn, P. D., & Guttenbeil, D. (2010). Match and training injuries in rugby league. *Sports Medicine*, *40*(2), 163-178.

Komi, P. V. (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *Journal of Biomechanics*, *33*, 1197-1206.

Kramer, H. F., & Goodyear, L. J. (2007). Exercise, MAPK, and NF-κB signaling in skeletal muscle. *Journal of Applied Physiology*, *103*(1), 388–395.

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., Pedersen, P. K., & Bangsbo, J. (2003). The Yo-Yo intermittent recovery test: physiological response, reliability and validity. *Medicine and Science in Sports and Exercise*, *35*(4), 697-705.

Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjær, M., & Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. *Medicine and Science in Sports and Exercise*, *38*(6), 1165-1174.

Krustrup, P., Ørtenblad, N., Nielsen, J., Nybo, L., Gunnarsson, T. P., Iaia, F. M., ... & Bangsbo, J. (2011). Maximal voluntary contraction force, SR function and glycogen resynthesis during the first 72 h after a high-level competitive soccer game. *European Journal of Applied Physiology*, *111*(12), 2987-2995.

Leger, L., & Gadoury, C. (1989). Validity of the 20 m shuttle run test with 1 min stages to predict VO2max in adults. *Canadian Journal of Sport Sciences*, *14*(1), 21-26.

Lovell, T. W., Sirotic, A. C., Impellizzeri, F. M., & Coutts, A. J. (2013). Factors affecting perception of effort (session rating of perceived exertion) during rugby league training. *International Journal of Sports Physiology and Performance, 8*(1), 62-69.

Malm, C., Sjodin, T. L., Sjoberg, B., Lenkei, R., Renstrom, P., Lundberg, I. E., & Ekblom, B. (2004). Leukocytes, cytokines, growth factors and hormones in human skeletal muscle and blood after uphill or downhill running. *Journal of Physiology, 556*(3), 983-1000.

Margaritis, I., Tessier, F., Verdera, F., Bermon, S., & Marconnet P. (1999). Muscle enzyme release does not predict muscle function impairment after triathlon. *Journal of Sports Medicine and Physical Fitness*, *39*(2),133–139.

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. *International Journal of Sports Physiology and Performance*, *5*(3), 367-383.

McLellan, C. P., & Lovell, D. I. (2012). Neuromuscular responses to impact and collision during elite rugby league match play. *Journal of Strength and Conditioning Research*, *26*(5), 1431-1440.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). Performance analysis of elite rugby league match play using global positioning systems. *Journal of Strength and Conditioning Research*, *25*(6), 1703-1710.

McLellan, C. P., & Lovell, D. I. (2013). Performance analysis of professional, semi-professional and junior elite rugby league match-play using global positioning systems. *Journal of Strength and Conditioning Research*, *27*(12), 3266–3274.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2010). Creatine kinase and endocrine responses of elite players pre, during and post rugby league match play. *Journal of Strength and Conditioning Research, 24*(11), 2908-2919*.*

Meir, R. A., Arthur, D., & Forrest, M. (1993). Time and motion analysis of professional rugby league: a case study. *Strength and Conditioning Coach*, *1*(3), 24-29.

Minett, G. M., & Duffield, R. (2014). Is recovery driven by central or peripheral factors? A role for the brain in recovery following intermittent-sprint exercise. *Frontiers in Physiology*, *5*(24), https://doi.org/10.3389/fphys.2014.00024.

Mohr, M., Draganidis, D., Chatzinikolaou, A., Barbero-Álvarez, J. C., Castagna, C., Douroudos, I., ... & Jamurtas, A. Z. (2016). Muscle damage, inflammatory, immune and performance responses to three football games in 1 week in competitive male pmorellayers. *European Journal of Applied Physiology*, *116*(1), 179-193.

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

Morehen, J. C., Routledge, H. E., Twist, C., Morton, J. P., & Close, G. L. (2015). Position specific differences in the anthropometric characteristics of elite European Super League rugby players. *European Journal of Sport Science, 15*(6), 523-529.

Morel, B., Rouffet, D. M., Bishop, D. J., Rota, S. J., & Hautier, C. A., (2015). Fatigue induced by repeated maximal efforts is specific to the rugby task performed. *International Journal of Sports Science and Coaching, 10*(1)*,* 11-20.

Mullen, T., Highton, J., & Twist, C. (2015). The internal and external responses to a forward-specific rugby league simulation protocol performed with and without physical contact. *International Journal of Sports Physiology and Performance*, *10*(6), 746-753.

Nicholas, C. W., Nuttall, F. E., & Williams, C. (2000). The Loughborough Intermittent Shuttle Test: a field test that simulates the activity pattern of soccer. *Journal of Sports Sciences*, *18*(2), 97-104.

Newham, D. J. (1988). The consequences of eccentric contractions and their relationship to delayed onset muscle pain. *European Journal of Applied Physiology and Occupational Physiology*, *57*(3), 353-359.

Nicol, C., Avela, J., & Komi, P. V. (2006). The stretch-shortening cycle: A model to study naturally occurring neuromuscular fatigue. *Sports Medicine, 36*(11), 977-999.

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. *Medicine and Science in Sports and Exercise*, *42*(1), 170-178.

Ostrowski, K., Rohde, T., Asp, S., Schjerling, P., & Pedersen, B. K. (1999). Pro-and anti-inflammatory cytokine balance in strenuous exercise in humans. *Journal of Physiology*, *515*(1), 287-291.

Oxendale, C. L., Twist, C., Daniels, M., & Highton, J. (2016). The relationship between match-play characteristics of elite rugby league and indirect markers of muscle damage. *International Journal of Sports Physiology and Performance*, *11*(4), 515-521.

Paulsen, G., Mikkelsen, U. R., Raastad. T., & Peake, J. M. (2012). Leucocytes, cytokines and satellite cells: what role do they play in muscle damage and regeneration following eccentric exercise? *Exercise Immunology Review*, *18*, 42-97.

Peake, J. M., Suzuki, K., Wilson, G., Hordern, M., Nosaka, K., Mackinnon, L., & Coombes, J. S. (2005). Exercise-induced muscle damage, plasma cytokines, and markers of neutrophil activation. *Medicine and Science in Sports and Exercise*, *37*(5), 737-745.

Pedersen, B. K., & Hoffman-Goetz, L. (2000). Exercise and the immune system: regulation, integration and adaptation. *Physiological Reviews*, *80*(3), 1055-1081.

Phillips, T., Childs, A. C., Dreon, D. M., Phinney, S., & Leeuwenburgh, C. (2003). A dietary supplement attenuates IL-6 and CRP after eccentric exercise in untrained males. *Medicine and Science in Sports and Exercise*, *35*(12), 2032-2037.

Pointon, M., & Duffield, R. (2012). Cold water immersion recovery after simulated collision sport exercise. *Medicine and Science in Sports and Exercise*, *44*(2), 206-216.

Pointon, M., Duffield, R., Cannon, J., & Marino, F. E. (2012). Cold water immersion recovery following intermittent-sprint exercise in the heat. *European Journal of Applied Physiology*, *112*(7), 2483-2494.

Rampinini, E., Bosio, A., Ferraresi, I., Petruolo, A., Morelli, A., & Sassi, A. (2011). Match-related fatigue in soccer players. *Medicine and Science in Sports and Exercise*, *43*(11), 2161-2170.

Ramsbottom, R., Brewer, J., & Williams, C. (1988). A progressive shuttle run test to estimate maximal oxygen uptake. *British Journal of Sports Medicine*,*22*(4), 141-144.

Reardon, C., Tobin, D. P., Tierney, P., & Delahunt, E. (2017). Collision count in rugby union: A comparison of micro-technology and video analysis methods. *Journal of Sports Sciences*, *35*(20), 2028-2034.

Roberts, S. P., Stokes, K. A., Weston, L., & Trewartha, G. (2010). The Bath University Rugby Shuttle Test (BURST): a pilot study. *International Journal of Sports Physiology and Performance*, *5*(1), 64-74.

Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J., ... & Jones, B. (2017). The effect of physical contact on changes in fatigue markers following rugby union field-based training. *European Journal of Sport Science*, *17*(6), 647-655.

Roe, G., Halkier, M., Beggs, C., Till, K., & Jones, B. (2016). The use of accelerometers to quantify collisions and running demands of rugby union match-play. *International Journal of Performance Analysis in Sport*, *16*(2), 590-601.

Sampson, J. A., Gabbett, T., & Fullagar, H. H. K. (2015). Knowledge of bout duration influences pacing strategies during small-sided games. *Journal of Sports Sciences, 33*(1), 85-98.

Scanlan, A. T., Dascombe, B. J., & Reaburn, P. R. (2012). The construct and longitudinal validity of the basketball exercise simulation test. *Journal of Strength and Conditioning Research*, *26*(2), 523-530.

Scott, A., Malone, J. J., Morgans, R., Burgess, D., Gregson, W., Morton, J. P., & Drust, B. (2016). Creatine Kinase concentration is not related to indicators of physical match performance in English Premier League soccer players. *International Journal of Sports Science & Coaching*, *11*(6), 846-852.

Scott, B. R., Lockie, R. G., Knight, T. J., Clark, A. C., & Janse de Jonge, X. A. (2013). A comparison of methods to quantify the in-season training load of professional soccer players. *International Journal of Sports Physiology and Performance*, *8*(2), 195-202.

Scott, T. J., Dascombe, B. J., Delaney, J. A., Sanctuary, C. E., Scott, M. T., Hickmans, J. A., & Duthie, G. M. (2017). Running momentum: a new method to quantify prolonged high-intensity intermittent running performance in collision sports. *Science and Medicine in Football*, Epub ahead of print.

Seminati, E., Cazzola, D., Preatoni, E. & Trewartha, G. (2017). Specific tackling situations affect the biomechanical demands experienced by rugby union players. *Sports Biomechanics, 16*(1), 58-75.

Singh, T. K., Guelfi, K. J., Landers, G., Dawson, B., & Bishop, D. (2011). A comparison of muscle damage, soreness and performance following a simulated contact and non-contact team sport activity circuit. *Journal of Science and Medicine in Sport*, *14*(5), 441-446.

Sirotic, A. C., Knowles, H., Catterick, C., & Coutts, A. J. (2011). Positional match demands of professional rugby league competition. *Journal of Strength and Conditioning Research, 25*(11), 3076-3087.

Sirotic, A. C., Coutts, A. J., Knowles, H., & Catterick, C. (2009). A comparison of match demands between elite and semi-elite rugby league competition. *Journal of Sport Sciences, 27*(3), 203-211.

Souglis, A., Bogdanis, G. C., Giannopoulou, I., Papadopoulos, C. H., & Apostolidis, N. (2015). Comparison of inflammatory responses and muscle damage indices following a soccer, basketball, volleyball and handball game at an elite competitive level. *Research in Sports Medicine*, *23*(1), 59-72.

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. *Journal of Sports Sciences*, *22*(9), 843-850.

Speranza, M. J., Gabbett, T. J., Johnston, R. D., & Sheppard, J. M. (2015). Relationship between a standardized tackling proficiency test and match-play tackle performance in semiprofessional rugby league players. *International Journal of Sports Physiology and Performance, 10*(6), 754-760.

Steensberg, A., Fischer, C. P., Keller, C., Møller, K., & Pedersen, B. K. (2003). IL-6 enhances plasma IL-1ra, IL-10, and cortisol in humans. *American Journal of Physiology-Endocrinology and Metabolism*, *285*(2), 433-437.

Sykes, D., Nicholas, C., Lamb, K., & Twist, C. (2013). An evaluation of the external validity and reliability of a rugby league match simulation protocol. *Journal of Sports Sciences*, *31*(1), 48-57.

Sykes, D., Twist, C., Nicholas, C., & Lamb, K. (2011). Changes in locomotive rates during senior elite rugby league matches. *Journal of Sports Sciences, 29*(12), 1263-1271.

Tabachnick, B. G., & Fidell, L. S. (2013). Using multivariate statistics (6th, International ed.). London: Pearson Education.

Takarada, Y. (2003). Evaluation of muscle damage after a rugby match with special reference to tackle plays. *British Journal of Sports Medicine*, *37*(5), 416-419.

Till, K., Cobley, S., O'Hara, J., Chapman, C., & Cooke, C. (2013). A longitudinal evaluation of anthropometric and fitness characteristics in junior rugby league players considering playing position and selection level. *Journal of Science and Medicine in Sport, 16*(5), 438-443.

Till, K., Jones, B., & Geeson-Brown, T. (2016). Do physical qualities influence the attainment of professional status within elite 16–19 year old rugby league players? *Journal of Science and Medicine in Sport*, *19*(7), 585-589.

Toft, A. D., Jensen, L. B., Bruunsgaard, H., Ibfelt, T., Halkjær-Kristensen, J., Febbraio, M., & Pedersen, B. K. (2002). Cytokine response to eccentric exercise in young and elderly humans. *American Journal of Physiology-Cell Physiology*, *283*(1), 289-295.

Twist, C., & Eston, R. (2005). The effects of exercise-induced muscle damage on maximal intensity intermittent exercise performance. *European Journal of Applied Physiology*, *94*(5-6), 652-658.

Twist, C., & Highton, J. (2013). Monitoring fatigue and recovery in rugby league players. *International Journal of Sports Physiology and Performance, 8*(5), 467-474.

Twist, C., & Sykes, D. (2011). Evidence of exercise-induced muscle damage following a simulated rugby league match. *European Journal of Sport Science*, *11*(6), 401-409.

Twist, C., Highton, J., Daniels, M., Mill, N., & Close, G. (2017). Player responses to match and training demands during an intensified fixture schedule in professional rugby league: A case study. *International Journal of Sports Physiology & Performance,* Epub ahead of print.

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. *International Journal of Sports Physiology and Performance*, *9*(6), 925-930.

Twist, C., Waldron, M., Highton, J., Burt, D., & Daniels, M. (2012). Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *Journal of Sports Sciences*, *30*(4), 359-367.

Usman, J., McIntosh, A. S. & Frechede, B. (2011). An investigation of shoulder forces in active shoulder tackles in rugby union football. *Journal of Science and Medicine in Sport, (14)*6, 547-552.

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. *Journal of Sports Sciences*, *30*(2), 121-127.

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

Waldron, M., & Highton, J. (2014). Fatigue and pacing in high-intensity intermittent team sport: an update. *Sports Medicine, 44*(12), 1645-1658.

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

Waldron, M., Highton, J., & Twist, C. (2013b). The reliability of a rugby league movement-simulation protocol designed to replicate the performance of interchanged players. *International Journal of Sports Physiology and Performance*, *8*(5), 483-489.

Waldron, M., Thomson, E., Highton, J., & Twist, C. (2017). Transient fatigue is not influenced by ball-in-play time during elite rugby league matches. *Journal of Strength and Conditioning Research*, Epub ahead of print.

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. *Journal of Sports Sciences*, *29*(11), 1223-1230.

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2014). The relationship between physical abilities, ball-carrying and tackling among elite youth rugby league players. *Journal of Sports Sciences, 32*(6), 542-549.

Warren, G. L., Lowe, D. A. & Armstrong, R. B. (1999). Measurement tools used in the study of eccentric contraction-induced injury. *Sports Medicine, 27*(1), 43-59.

Weaving, D., Marshall, P., Earle, K., Nevill, A., & Abt, G. (2014). Combining internal- and external-training-load measures in professional rugby league. *International Journal of Sports Physiology and Performance, 9*(6), 905-912.

Wehbe, G., Gabbett, T., Dwyer, D., McLellan, C., & Coad, S. (2015). Monitoring neuromuscular fatigue in team-sport athletes using a cycle-ergometer test. *International Journal of Sports Physiology and Performance, 10*(3), 292-297.

West, D. J., Finn, C. V., Cunningham, D. J., Shearer, D. A., Jones, M. R., Harrington, B. J., ... & Kilduff, L. P. (2014). Neuromuscular function, hormonal, and mood responses to a professional rugby union match. *Journal of Strength and Conditioning Research*, *28*(1), 194-200.

Williams, S., Trewartha, G., Kemp, S., & Stokes, K. (2013). A meta-analysis of injuries in senior men's professional rugby union. *Sports Medicine*, *43*(10), 1043-1055.

Woods, C. T., Sinclair, W., & Robertson, S. (2017). Explaining match outcome and ladder position in the National Rugby League using team performance indicators. *Journal of Science and Medicine in Sport*, Epub ahead of print.

Wundersitz, D. W., Gastin, P. B., Robertson, S. J., & Netto, K. J. (2015a). Validity of a trunk-mounted accelerometer to assess peak accelerations during walking, jogging and running. *European Journal of Sport Science, 15*(5), 382-390.

Wundersitz, D. W., Gastin, P. B., Robertson, S. J., & Netto, K. J. (2015b). Validity of a trunk-mounted accelerometer to measure physical collisions in contact sports. *International Journal of Sports Physiology and Performance*, *10*(6), 641-686.

Zaldivar, F., Wang-Rodriguez, J., Nemet, D., Schwindt, C., Galassetti, P., Mills, P. J., . . . & Cooper, D. M. (2006). Constitutive pro- and anti-inflammatory cytokine and growth factor response to exercise in leukocytes. *Journal of Applied Physiology, 100*(4), 1124-1133.

Appendices

Appendix 1: Ethics approval letter for Chapters 3, 4 and 5

Faculty of Life Sciences

Research Ethics Committee

frec@chester.ac.uk

Jonathan Norris
Department of Sport and Exercise Sciences
University of Chester

19th December 2014

Dear Jonathan,

Study title: **The reliability of a rugby league match simulation protocol using a weighted tackle sled to replicate tackle intensity.**

FREC reference: **865/13/JN/SES**

Version number: **1**

Thank you for sending your application to the Faculty of Life Sciences Research Ethics Committee for review.

I am pleased to confirm ethical approval for the above research, provided that you comply with the conditions set out in the attached document, and adhere to the processes described in your application form and supporting documentation. However, the Committee would like to make the following recommendation:-

- For participant information, provide instructions for completion and a worked example of the diet diary. Please forward an electronic copy to frec@chester.ac.uk

The final list of documents reviewed and approved by the Committee is as follows:

Document	**Version**	**Date**
Application Form	1	November 2013

Appendix 1 – List of References	1	November 2013
Appendix 2 – C.V. for Lead Researcher	1	November 2013
Appendix 3 – Participant Information Sheet	1	November 2013
Appendix 4 – Participant Consent Form	1	November 2013
Appendix 5 – Risk Assessment Form	1	November 2013
Appendix 6 – Pre-test Health Questionnaire	1	November 2013
Response to FREC request for further information and clarification		December 2013
FREC Application Form pages 7 & 9	2	December 2013
Appendix 3 – Participant Information Sheet	2	December 2013
Appendix 4 – Participant Consent Form	2	December 2013

Appendix 6 – Pre-test Questionnaire	2	December 2013
Appendix 7 – Food Diary	1	December 2013
Appendix 8 – Flow Chart	1	December 2013

Please note that this approval is given in accordance with the requirements of English law only. For research taking place wholly or partly within other jurisdictions (including Wales, Scotland and Northern Ireland), you should seek further advice from the Committee Chair / Secretary or the Research and Knowledge Transfer Office and may need additional approval from the appropriate agencies in the country (or countries) in which the research will take place.

With the Committee's best wishes for the success of this project.

Yours sincerely,

Dr. Stephen Fallows

Chair, Faculty Research Ethics Committee

Enclosures: Standard conditions of approval.

Cc. Supervisor/FREC Representative

Appendix 2: Ethics approval letter for Chapter 6 and 7

University of Chester

Faculty of Life
Sciences Research
Ethics Committee

frec@chester.ac.uk

12/06/2015

Jonathan Norris

Department of Sport and Exercise Science

University of Chester

Study title: Influence of physical contact and fitness qualities in the micro cycle of inflammation and performance changes after simulated rugby league match play.

FREC reference: 1081/15/JN/SES

Version number: 1

Thank you for sending your application to the Faculty of Life Sciences Research Ethics Committee for review.

I am pleased to confirm ethical approval for the above research, provided that you comply with the conditions set out in the attached document, and adhere to the processes described in your application form and supporting documentation. However, the Committee would like to request the following minor amendment:-

- Check all documents for typo's and grammatical errors.

- Add times to PIS.
- Include blood volume to PIS.
- Identify JF as additional researcher.
- Remove Sarah Andrew's name from PIS — refer only to job title 'Dean'.

Please forward an amended electronic copy to frec chester.ac„uk

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Application Form	1	May 2015
Appendix 1 — List of References	1	May 2015
Appendix 2 — Summary CV for Lead Researcher	1	May 2015
Appendix 3 — Participant Information Sheet [PIS]	1	May 2015
Appendix 4 — Participant Consent Form	1	May 2015
Appendix 5 — Risk Assessment	1	May 2015
Appendix 7 — Flow Chart	1	May 2015
Appendix 8 — Health Screening questionnaire	1	May 2015
Appendix 6 - Venpuncture SOP	1	May 2015

Please note that this approval is given in accordance with the requirements of English law only. For research taking place wholly or partly within other jurisdictions (including Wales, Scotland and Northern Ireland), you should seek further advice from the Committee Chair / Secretary or the Research and Knowledge Transfer

Office and may need additional approval from the appropriate agencies in the country (or countries) in which the research will take place.

With the Committee's best wishes for the success of this project.

Yours sincerely,

Dr. Stephen Fallows

Chair, Faculty Research Ethics Committee

Enclosures: Standard conditions of approval.

Cc. Supervisor/FREC Representative

Appendix 3: Participant information sheet for Chapter 3, 4 and 5

University of Chester

Participant information sheet

The reliability of a rugby league match simulation protocol using a weighted tackle sled to replicate tackle intensity.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

What is the purpose of the study?

Rugby League is an extremely popular sport across the world. With the advancement of sport science, players and coaches are becoming more informed on how to appropriately prepare to win games.

The aim of this study is to investigate whether a match simulation protocol can consistently replicate the physical demands of a competitive rugby league fixture. The findings from this study will help to further examine the demands of rugby league and identify which aspects of rugby league lead to fatigue during and after the game.

Why have I been chosen?

You have been chosen because you have experience of playing competitive rugby. It is thought that collisions may be important in the fatigue process and having technical knowledge will be beneficial during the protocol.

Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect you in any way.

What will happen to me if I take part?

If you decide to take part, you will be given this information sheet to keep, asked to sign the consent form and also complete a health screening questionnaire to ensure you are fit to take part on each visit. Once these forms have been completed, your first visit to the university will be to complete a shuttle running test to assess your level of fitness to ensure you will be able to complete the protocol. You will also be tested for your bench press one repetition maximum and familiarised with the other testing protocols and the match simulation. You will not be asked to undertake any exercise that is beyond a normal training session.

The study will require your attendance at the University of Chester on 3 further occasions separated by 7-10 days. During your visits to the university you will be asked to complete a trial of the match simulation protocol. Two visits will include a weighted sled collision and one visit will use a soft tackle bag. Before the trials you will be taken through the tests of upper and lower body power. The power tests will be repeated after of the protocol. During the trials you will be asked to wear a GPS unit and heart rate monitor to provide information as you complete the trial. In addition you will be asked to provide a finger prick blood sample and your rating of exertion before the trial and at the end of each of the two bouts of exercise.

If you decide to take part, the research team does ask that you will avoid any strenuous exercise and alcohol in the 24 hours that precede the trial. We would also ask that you keep a record of your diet during the 24 hours leading into the trial, using a diary sheet provided, so that you will be able to replicate it before each of the following trials.

Please note, this information will not be required by the research team, it is for your own record.

What are the possible disadvantages and risks of taking part?

Upon completion of the simulation protocol and during the following days, it may be possible to suffer from some stiffness and soreness in the muscles. These symptoms will be short lived and will pass after a few days.

What are the possible benefits of taking part?

This research will enable a greater understanding of collisions in rugby and provide insight into ways to improve training. As rugby players, you will get to be a part of the advancement of knowledge in your sport. The testing procedures will also provide information to help with your personal training.

What if something goes wrong?

If you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Professor Sarah Andrew, Dean of the Faculty of Applied Sciences, University of Chester, Parkgate Road, Chester, CH1 4BJ, 01244 513055.

Will my taking part in the study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential so that only the researcher carrying out the research will have access to such information.

What will happen to the results of the research study?

The results will be written up into a chapter for my Phd. Individuals who participate will not be identified in any subsequent report or publication.

Who is organising the research?

The research is conducted as part of a PhD in Mechanisms of fatigue and recovery in rugby league within the Department of Sport and Exercise Science at the University of Chester. The study is organised with supervision from the department, by Jonathan Norris, a PhD student.

Who may I contact for further information?

If you would like more information about the research before you decide whether or not you would be willing to take part, please contact:

Jonathan Norris

j.norris@chester.ac.uk

Thank you for your interest in this research.

Appendix 4: Participant information sheet for Chapter 6 and 7

Participant information sheet

Participant information sheet

Influence of physical contact and fitness qualities in the micro cycle of inflammation and performance changes after simulated rugby league match play.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

What is the purpose of the study?

Rugby League is an extremely popular sport across the world. With the advancement of sport science, players and coaches are becoming more informed on how to appropriately prepare to win games.

The aim of this study is to investigate whether enhanced physical qualities influence recovery after a match simulation protocol. The findings from this study will help to identify methods of training that can improve recovery time after competitive rugby league performance.

Why have I been chosen?

You have been chosen because you have experience of playing competitive rugby. It is thought that collisions may be important in fatigue and recovery processes and having technical knowledge will be beneficial during the protocol.

Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect you in any way.

What will happen to me if I take part?

If you decide to take part, you will be given this information sheet to keep, asked to sign the consent form and also complete a health screening questionnaire to ensure you are fit to take part on each visit. Once these forms have been completed, your first visit to the university will be to complete a number of fitness tests including a shuttle running test to assess your level of fitness to ensure you will be able to complete the protocol. In addition you will also perform sprinting, jumping and upper and lower body strength and power testing. You will not be asked to undertake any exercise that is beyond a normal training session.

The study will require your attendance at the University of Chester on 4 further occasions over 7 days. During your second visit to the university you will be asked to provide a 11 ml venous blood sample and perform baseline tests of exercises that you completed during a prior visit. The third visit will involve performance of the match simulation followed by a venous sample and repeat tests of muscular function. The muscle function tests and venous blood sampling will be repeated after 24 and 72 hours of completing the protocol. During the trials you will be asked to wear a GPS unit and heart rate monitor to provide information as you complete the trial. In addition you will be asked to provide your rating of exertion during the trial and at the end of each of the two bouts of exercise.

If you decide to take part, the research team does ask that you will avoid any strenuous exercise and alcohol in the 24 hours that precede the trial and until all follow up procedures have been completed. Each visit will last approximately 45 minutes with the exception of visit 3 which will be approximately 90 minutes.

What are the possible disadvantages and risks of taking part?

Upon completion of the simulation protocol and during the following days, you might suffer from some stiffness and soreness in the muscles. These symptoms will be short lived and will pass after a few days.

Venous blood sampling may cause moderate pain, alternatively you might feel only a prick or stinging sensation. Most people will have a small bruise for several days after. It is not uncommon for some individuals to feel dizzy or light headed during or after venous blood sampling. You will be encouraged to rest for a short period after sampling to recover before any further tests are performed.

What are the possible benefits of taking part?

This research will enable a greater understanding of collisions in rugby and provide insight into ways to improve training. The testing procedures will also provide information to help with your personal training.

What if something goes wrong?

If you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Dean of the Faculty of Applied Sciences, University of Chester, Parkgate Road, Chester, CH1 4BJ, 01244 513055.

Will my taking part in the study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential so that only the researcher carrying out the research will have access to such information.

What will happen to the results of the research study?

The results will be written up into a chapter for my Phd. Individuals who participate will not be identified in any subsequent report or publication.

Who is organising the research?

The research is conducted as part of a PhD in Mechanisms of fatigue and recovery in rugby league within the Department of Sport and Exercise Science at the University of Chester. The study is organised with supervision from the department, by Jonathan Norris, a PhD student.

Who may I contact for further information?

If you would like more information about the research before you decide whether or not you would be willing to take part, please contact:

Jonathan Norris

j.norris@chester.ac.uk

Thank you for your interest in this research.

Appendix 5: Participant Health Questionnaire (Example)

University of Chester

Pre-test Questionnaire

<u>The reliability of a rugby league match simulation protocol using a weighted sled to replicate tackle intensity.</u>

Researcher *: Jonathan Norris*

Name:____________________________________ Test date:_________________

Contact number:______________________________ Date of birth:____________

Resting Heart Rate: ____________________ Blood Pressure: _____________

In order to ensure that this study is as safe and accurate as possible, it is important that each potential participant is screened for any factors that may influence the study. Please circle your answer to the following questions:

1. Has your doctor ever said that you have a heart condition *and* that you should only perform physical activity recommended by a doctor?
YES/NO

2. Do you feel pain in the chest when you perform physical activity?
YES/NO

3. In the past month, have you had chest pain when you were not performing physical activity?
YES/NO

YES/NO

4. Do you lose your balance because of dizziness *or* do you ever lose consciousness?

YES/NO

5. Do you have bone or joint problems (e.g. back, knee or hip) that could be made worse by a change in your physical activity?

6. Is your doctor currently prescribing drugs for your blood pressure or heart condition?
YES/NO

7. Have you injured your hip, knee or ankle joint in the last six months?
YES/NO

8. Do you know of any other reason why you should not participate in physical activity?
YES/NO

Thank you for taking your time to fill in this form. If you have answered 'yes' to any of the above questions, unfortunately you will not be able to participate in this study.

Appendix 6: Informed consent form (Example)

University of Chester

QUI·DOCET·IN·DOCTRINA

Title of Project: The reliability of a rugby league match simulation protocol using a weighted tackle sled to replicate tackle intensity.

Name of Researcher: Jonathan Norris

Please initial box

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason and without my legal rights being affected. ☐

3. I agree to take part in the above study. ☐

______________________ ____________________ _______________

Name of Participant Date Signature

____

__________________________ _______________

Researcher Date Signature

1 for participant; 1 for researcher

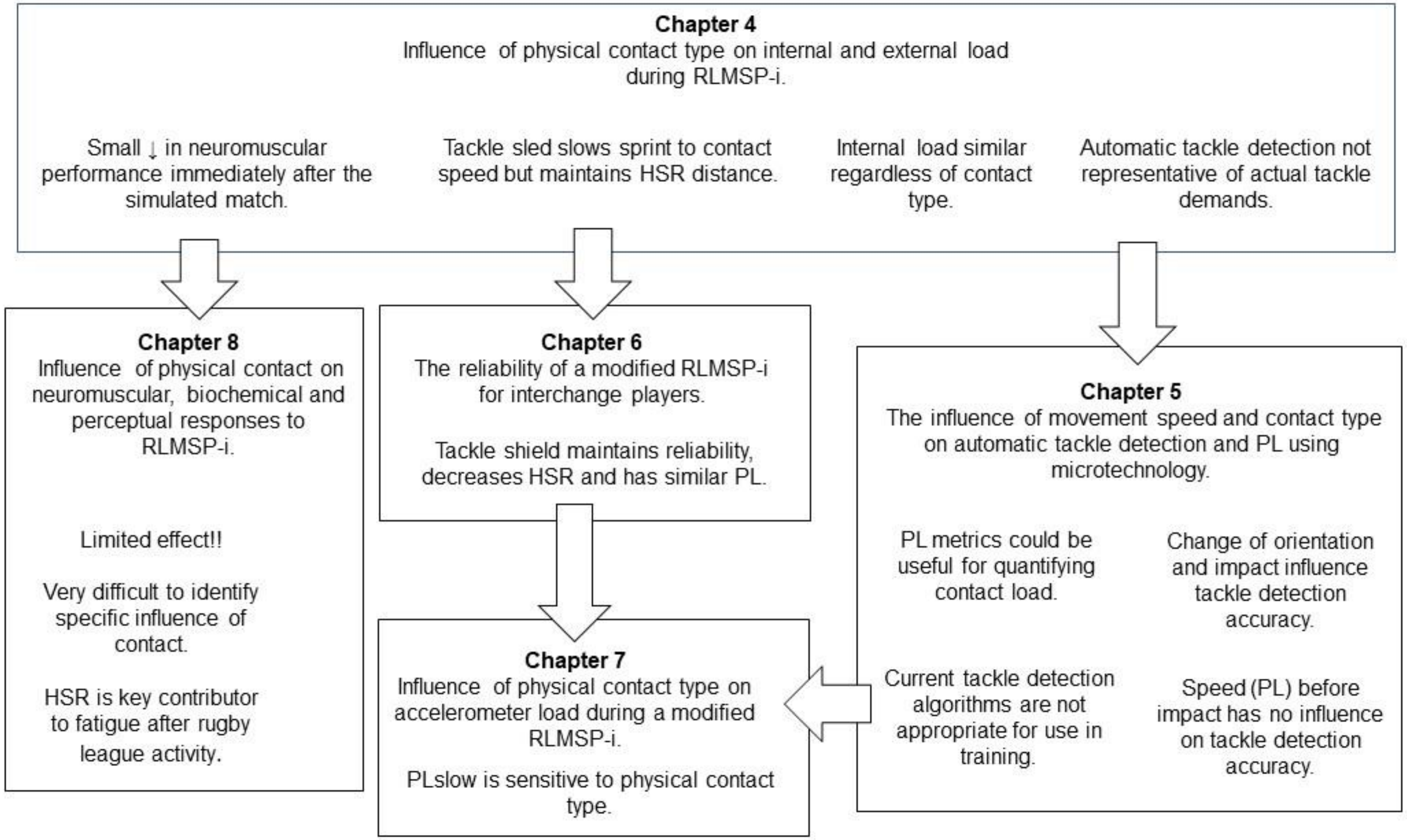
Appendix 6: Raw data

Access to raw data files is through the following link:

https://www.dropbox.com/sh/8n9772xajzedvn4/AABVdE48NIHM3xWYIvP8hwW3a?dl=0

Appendix 7: Synthesis

Evaluating the detection of physical contact using wearable microtechnology and the influence on running performance in rugby players during a rugby league match simulation.



Chapter 4
Influence of physical contact type on internal and external load during RLMSP-i.

Small ↓ in neuromuscular performance immediately after the simulated match.

Tackle sled slows sprint to contact speed but maintains HSR distance.

Internal load similar regardless of contact type.

Automatic tackle detection not representative of actual tackle demands.

Chapter 8
Influence of physical contact on neuromuscular, biochemical and perceptual responses to RLMSP-i.

Limited effect!!

Very difficult to identify specific influence of contact.

HSR is key contributor to fatigue after rugby league activity.

Chapter 6
The reliability of a modified RLMSP-i for interchange players.

Tackle shield maintains reliability, decreases HSR and has similar PL.

Chapter 7
Influence of physical contact type on accelerometer load during a modified RLMSP-i.

PLslow is sensitive to physical contact type.

Chapter 5
The influence of movement speed and contact type on automatic tackle detection and PL using microtechnology.

PL metrics could be useful for quantifying contact load.

Change of orientation and impact influence tackle detection accuracy.

Current tackle detection algorithms are not appropriate for use in training.

Speed (PL) before impact has no influence on tackle detection accuracy.

Key: RLMSP-i = Rugby League Match Simulation Protocol for Interchange; HSR = high speed running; PL = PlayerLoad^{TM}; PLslow = PlayerLoad^{TM} slow.