WORKLOADS AND INJURY RISK IN PREMIER LEAGUE FOOTBALL

By

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ABSTRACT

The English Premier League is faster and more intensive than ever, requiring an enhanced physical capacity from the players. In addition, the financial rewards for success have never been greater. This has increased the pressure on clubs to produce and develop talented players who can consistently perform under physical stress, whilst remaining injury free. To augment the chance of success, practitioners must prescribe workloads which stimulate positive adaptations, without unduly increasing injury risk. Therefore, the primary aim of this thesis was to understand the relationships between workload and injury in both youth and senior professional football. Chapter 2 investigated the validity, reliability and interchangeability of the systems used to measure workload in this thesis. Chapter 3 determined that the youth and senior squads have different training demands, and were therefore studied separately when identifying the workload-injury relationships. Chapters 4 (youth) & 5 (senior) explored the relative risks associated with given workloads. Both studies found that acute spikes in workload increased the risk of injury; however, this increase could be reduced with progressive increases in the chronic workload. The secondary aim of this thesis was then to determine the effectiveness of informed workload prescription as an injury prevention strategy. By applying the findings from the previous chapters into elite football practice, Chapter 6 found that appropriate workload prescription appears to increase workload tolerance, although it is not sensitive enough to be used as an isolated injury prevention tool.

For my Grandpa, Tom

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Bowen L, Gross AS, Gimpel M, Bruce-Low S, & Li F-X. Using the ACWR in practice augments workload capacity in English Premier League football players. **In preparation.**

LIST OF ABBREVIATIONS

ACC	accelerations
ACWR	acute:chronic workload ratio
ANOVA	analysis of variance
AU	arbitrary units
CI	confidence intervals
cm	centimetres
COD	change of direction
CV	coefficient of variation
DEC	decelerations
Decel	deceleration task
EPL	English premier league
EWMA	exponentially weighted moving average
FC	football club
FIFA	Fédération Internationale de Football Association
g	grams
GNSS	global navigation satellite system
GPS	global positioning systems
HSD	high speed distance
HSR	high speed running task
Hz	hertz
km	kilometres
km/h	kilometres per hour
LID	low intensity distance
m	metres
m/min	metres per minute
m/s	metres per second
MAS	maximal aerobic speed
MID	moderate-intensity distance
mm	millimetres
MSS	maximal sprinting speed
n.d.	no date
no.	number of
RPE	rating of perceived exertion
RR	relative risk
SACS	semi-automated camera systems
SD	sprint distance
SD	standard deviation
SEE	standard error of estimate
sRPE	session duration multiplied by rating of perceived exertion

TD	total distance
TL	total load
U18	under 18
U21	under 21
UEFA	union of European football associations
vs	versus
vVO_{2max}	velocity at maximum oxygen uptake
Z	zone

CHAPTER 1. LITERATURE REVIEW

1.01 General Introduction

Southampton Football Club (FC) have played within the top tier of English football for the last seven seasons and have achieved four top ten league position finishes. However, they recorded annual financial revenues that are less than half of the top 6 teams, and more than 20% less than the Premier League average (Cox, 2018). Success in elite football relies on maximising the performance and availability of talented players. The wealthier teams can short-cut the route to success by buying the best, most robust, available talent (Saether & Solberg, 2015). However, teams with more limited financial resources, such as Southampton FC, have to rely more heavily on player development to increase the chances of success (Figure 1).

Figure 1. The Southampton way: We don’t just buy success, we breed it. Adapted version of the “Wall of fame” displayed at the Southampton FC training ground, listing successful Academy graduates.

Thus, poorer teams may have to field a team of predominantly young, inexperienced, developing players (Saether & Solborg, 2015). These players arguably have to work harder to develop their physical and technical abilities in order to compete with some of the best, most experienced players in the world. As Sir Alex Ferguson stated

“***Hard work will always overcome natural talent when natural talent does not work hard enough***."

In addition, financial strength also allows teams to invest in a larger number of players, reducing the significant impact of injury on success, due to augmented player availability (Hagglund, et al., 2013). Therefore, at Southampton FC players must be able to train hard to develop the skills and qualities required to perform at the top level, work hard in games to compensate for lower natural talent, whilst also remaining injury-free and available for team selection. For the youth players, they must be physically robust enough to cope with the training levels required to develop them into professional athletes. For the senior, more experienced players, they must have the physical capacity to compete with world-class players. As longer possession time is associated with more successful teams (Casal, Maneiro, Arda, Mari, & Losada, 2017), less successful teams like Southampton FC must be conditioned for a high physical demand, to repeatedly press the ball and intercept possession.

Consequently, the performance question this thesis aims to answer is “how hard can the players at Southampton FC work without increasing their risk of injury?” Specifically, the aim is to investigate the relationships between workload and injury risk at Southampton FC, to inform and improve daily sport science and coach practice.

1.02 Real World Implications of Performance and Injury in the English Premier League

1.02.1 Success in the English Premier League.

The English Premier League (EPL) is the richest, most popular and most competitive football league in the world (Fynn, 2017). The 2018/19 season marked the greatest combined points tally for the top two teams (195), as well as the second time ever that two English teams have played in the UEFA Champions League final. Regardless of where a team sits within the league table, the target is success. For the top teams, this is defined by the league title, as well as qualification to the UEFA Champions League (top four clubs). For mid-table teams, success means qualification into the UEFA cup (5th and 6th place) and for the rest, success is the avoidance of relegation. Regardless, for all clubs, the motivation is the same; the greater the success, the higher the financial reward, the more money that can be invested in talent to augment the chance of future success (Fynn, 2017).

For over a decade, the EPL has generated revenues of up to €3 billion more than for any of the other ‘major’ European leagues. The 12% increase in EPL revenue to €5.4 billion from the 2015-16 season to the 2017-18 season was mainly dictated by television broadcasting, and is expected to increase by another 10% in the next two seasons (Barnard, Boor, Winn, Wood, & Wray, 2019). The EPL centrally controls the selling of broadcasting rights for live matches. A proportion of this revenue is distributed equally between the individual clubs, providing a minimum guarantee for each club. This creates a level of competitive balance and entertainment unique to the EPL (Cox, 2018). For the 2016-17 season, this equated to £95-150 million per club, an increase of 46% from the previous season (Barnard, Dwyer, Wilson, & Winn, 2018).

Leicester City's success in the 2015/16 campaign marked the fourth consecutive different winner of the top flight in England. In comparison, the 2015/16 season also saw the fourth year that Paris-Saint Germain, Bayern Munich and Juventus won the leagues in France, Germany and Italy respectively, whilst Barcelona claimed their third title in four years in Spain (Barnard, Ross, Savage, & Winn, 2017). Thus, the strength and depth of talent across the EPL clubs makes it one of the most competitive sporting leagues in the world.

However, whilst the centrally controlled revenue may produce a more level playing field and greater chance of success than the other European leagues, the dispersion in resources between the teams who finish top and bottom of the EPL is still increasing (Pawlowski, Breuer, & Hovemann, 2010). This is due in part to the remaining broadcasting revenue being paid out in merit fees based on league position, as well as the large financial rewards gained from competing in the UEFA Champions League and UEFA cup (Barnard, Ross, Savage, & Winn, 2017). In addition, being at the top of the EPL is more likely to attract investment, as well as positively affecting merchandise sales and commercial sponsorship (Cox, 2018). Supporting this; during the 2017/18 season, the average revenue of the top three clubs was over four times higher than the three teams at the bottom (£516m vs £126m) (Barnard, et al., 2019). Thus the incentive for clubs to maximise their on-pitch success has never been greater.

It is generally accepted that this chance of success can be largely augmented by investing in talented players (Szymanski & Kuypers, 2000). As a result, the average EPL club spends 59% of their total revenue on wages, despite 15 of the 20 clubs being in a position of net debt in the 2017/18 season (Barnard, et al., 2019). Thus, football clubs hope that their expenditure on talent will eventually lead to an increase in club profits due to the greater financial rewards for success (Nielsen & Storm, 2017).

1.02.2 Injuries in football and their impact on success.

Success, defined by league ranking, and points per match, has been strongly associated to player availability, within 24 European clubs (Hagglund, et al., 2013). When the injury burden was lower ($p=0.01$) and the match availability was greater ($p=0.03$) than the previous season, average points per match and final league ranking were significantly higher. Ultimately, a reduction in available talent resulted in reduced team performance. An 11-year follow up study using the same cohort found muscle/tendon injuries to the hamstring and groin and ligament/joint injuries to the knee and ankle to have the largest injury burden (Ekstrand, Hagglund, Kristenson, Magnusson, & Walden, 2013), and therefore the greatest negative effect on team performance. Most of these injuries have been found to be preventable in football (Hagglund, et al., 2013). However elite players still sustain two injuries per season on average, resulting in 50 injuries within a standard squad of 25 (Ekstrand, Hagglund, & Walden, 2011). Of these, 12% of them are hamstring injuries (5-6 per team), which result in approximately 80 days of missed training or match activity. Whilst overall muscle injury rates have remained unchanged for over a decade, hamstring injury incidence and burden has increased annually by 4% (Ekstrand, Walden, & Hagglund, 2016; Jones, et al., 2019). This has been attributed in part to the increased intensity of the EPL (Barnes, Archer, Hogg, Bush, & Bradley, 2014), highlighting the need for effective injury prevention strategies.

Furthermore, during 2017/18 football season, £214million was paid out in wages to injured EPL players, with the average wage-per-injury being over £323,000 (Green, 2018). Consequently, throughout a season, clubs could pay on average £16.2million in wages alone, not including additional treatment costs, to players who are unavailable to play due to injury.

Additionally, significant reductions in club annual income as a result of reduced team performance and consequential lower final league position have been demonstrated (Rohde & Breuer, 2016). The financial advantages of being in the top half of the EPL typically means that these clubs would have a larger squad, with multiple players of quality in each position. Therefore, these teams are less affected by injuries to a number of key players than lower placed teams with less depth of quality within their squads (Ekstrand, et al., 2016). For these lower half clubs, the risk of relegation is greater, which would result in a reduction of club turnover through reduced broadcasting revenue, gate receipts, merchandising etc (Smith, 2018). Conversely, whilst they may be at less risk of relegation, larger, higher placed clubs are subject to the greatest financial losses with reduced team performances. This is due to the significant financial implications of dropping only a few league places, mainly by failing to qualify for European competition (Barnard, et al., 2018). Thus, injury prevention strategies are not only essential to maximise player availability and subsequent chance of success but also to minimise the significant financial losses associated with injury. Without effective strategies in place, clubs are at risk of entering a vicious cycle of reduced available talent, reduced performance, reduced capital to invest in talent.

1.02.3 Breeding talent from within.

UEFA ruling stipulates that each squad must contain eight home-grown players. To be defined as home-grown, a player must have been registered within an English Academy for at least three years prior to the age of 21 (Premier League, Premier League, 2018). Therefore, to be successful, clubs not only have to recruit talent, but also produce it. As the EPL has the financial capability to attract the best players globally (Rohde & Breuer, 2016), home-grown players not only have to be the best in England, but in the world (Mills, Butt, Maynard, & Harwood, 2014). Furthermore, with Britain potentially set to leave the European Union this year, the Football Association are appealing for the number of foreign players allowed per squad to be cut from 17 to 12 (Levitt, 2019). Therefore, EPL clubs are under more pressure than ever to develop English talent, without reducing the competitive level of the league.

To be given the greatest chance to develop and progress into the senior team, youth players must be kept as injury-free as possible (Reilly, Williams, Nevill, & Franks, 2000). Considering the importance of player availability to team performance (Hagglund, et al., 2013), players coming through the academy pathway must be robust and resilient enough to deal with the physical demands, not only of the squad they are in, but the squad they are progressing to. To inform this process, Chapter 3 will explore the differences in training and match demands between academy and senior squads.

Irrespective of successful integration within the senior team, academy players are ‘marketable assets’ for the clubs to gain future financial benefit from the development and subsequent sale of talent (Relvas, Littlewood, Nesti, Gilbourne, &

Richardson, 2010). As injury history is taken into consideration when recruiting players, it is essential to make sure injury rates are kept as low as possible (Coles, 2017). Therefore, as with the elite adult footballers, the importance of injury prevention for youth football players is two-fold; to augment the chance of progression through the academy into the senior team and to maximise player marketability to other clubs.

1.03 The Demands of Football

1.03.1 Typical match demands.

During a 90-minute football match, players typically cover between 10-13km interspersed with brief bouts of high intensity actions (Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007; Mohr, Krustrup, & Bangsbo, 2003; Barnes, et al., 2014). Although football is often considered an endurance sport, the average heart rate is between 80-90% of maximal values, as players are required to repeatedly perform explosive accelerations, decelerations, jumps, sprints, tackles and changes of direction (Stolen, Chamari, Castagna, & Wisloff, 2005). Thus, football players must train and develop both their aerobic and anaerobic capacity in order to cope with the demands of the game (Bekris, Mylonis, Gioldasis, Gissis, & Kombodieta, 2016). Whilst the majority of the distance is covered at low intensity, it is the high intensity actions that constitute the more crucial aspects of the game, contributing directly to keeping possession of the ball and scoring or conceding goals (Reilly, Williams, Nevill, & Franks, 2000; Faude, Koch, & Meyer, 2012; Delaney, Cummins, Thornton, & Duthie, 2017). The intensity and duration of these actions is often unpredictable and dependent on environmental conditions, tactical decisions of both teams, the fitness and capabilities of the individuals, elements of chance and strength of the opposition as well as many other factors (Drust, Atkinson, & Reilly, 2007).

1.03.2 Positional differences.

A player's positional role within the team also influences their activity profile; attackers and wide players generally cover the most high speed distance, whilst central midfielders cover greater total distances and number of accelerations than all other positions (Abbott, Brickley, & Smeeton, 2018). Central defenders have a lower physical demand, yet an important tactical responsibility, as the last line of defence (Bangsbo, Mohr, & Krustup, 2006). Furthermore, despite the greater high-speed running demand, attackers have been found to cover lower total distances than wide players and central midfielders (Abbott, et al., 2018). This was attributed to the limited defensive requirements of the position, with the focus being on repeated speed efforts to challenge the opposition defence (Abbott, et al., 2018). Thus, football performance involves a combination of technical and tactical aspects, which directly impact the physical demands.

1.03.3 The technical, tactical and physical requirements of elite performance.

Technical proficiency has been identified as the best indicator of a team's success (Castellano, Casamichana, & Lago, 2012; Carling, 2013). Studies have found increases in the number of passes, ball speed and passing success rate over time (Barnes, et al., 2014). These findings are indicative of a greater game tempo, which has been associated with an augmented performance advantage. Playing speed in invasion-style team sports particularly during attacking play has been related to an increased success rate (Frencken, Lemmink, Delleman, & Visscher, 2011). Additionally, the ability to reach a higher velocity than the opponent has been reported as an advantage for both goals scored and defensive interceptions (Edgecomb &

Norton, 2006). Furthermore, player density has increased over a 44-year period of FIFA World Cup final matches (Wallace & Norton, 2014), suggesting an improvement in defensive strategies aimed at reducing the attackers time and space on the ball. This increase in density results in greater skill, speed and precision requirements to move through player traffic (Pollard, Ensum, & Taylor, 2004). Players must be able to accelerate, decelerate and change direction quickly to either find space to increase the probability of scoring as an attacker or anticipate and match the attacker's movements to reduce the space as a defender (Bradley, et al., 2011). In line with these findings, the amount of high speed running and sprint distance covered has increased by 30-50% across seven seasons in the EPL, across all positions (Barnes, et al., 2014; Bush, Barnes, Archer, Hogg, & Bradley, 2015), despite an increase in stoppage time during the games (Wallace & Norton, 2014). Consequently, the game of football is more intense than ever before, highlighting the importance of understanding the physical capabilities required to achieve the fast-paced technical and tactical demands of successful performance.

1.04 Workload Monitoring in Football

1.04.1 Athlete response to workload.

The process of planning workloads to appropriately prepare players for the demands of competition is a multi-disciplinary, athlete-centred process (Ekstrand, Lundqvist, Davison, D'Hooghe, & Pensgaard, 2019). However, within many professional sport environments, sport scientists advocate higher workloads to maximise physical capacity, whilst medical staff recommend lower workloads with the intention of reducing injury risk (Gabbett & Whiteley, 2017). In order for all stakeholders (coach, sport science, medical staff) to plan and implement workloads in synergy, a heightened understanding of the relationship between workload, injury and performance is required (Gabbett & Whiteley, 2017).

Workloads have been defined as “the cumulative amount of stress placed on an individual from multiple training sessions and games over a period of time” (Gabbett, Whyte, Hartwig, Wescombe, & Naughton, 2014, p.989). Thus, training programmes should periodise workloads which provide a systematic application of stress with the target of enhancing physical capacity and improving athletic performance (Meeusen, et al., 2013). The general adaptation syndrome (Seyle, 1946) identified three stages after the exposure to ‘stress’ (Figure 2); initially, a period of alarm (fatigue), where there is a reduction in the body’s resistance, followed by the resistance stage, where an adaptation occurs that increases the body’s resistance beyond baseline (supercompensation). However, if continuous exposure to a stressor exceeds the adaptive capacity of the body, resistance decreases, and the exhaustion stage occurs (Esmaeli, 2018). The appropriateness of the stimulus for inducing optimal performance adaptations has been categorised into three levels:

- Undertraining – the stimulus fails to exceed the adaptation threshold required to disrupt homeostasis and therefore does not facilitate supercompensation.
- Optimal Training and Overreaching – appropriate stimulus or overload which disrupts homeostasis. When combined with adequate recovery, positive adaptations occur.

- Overtraining – excessive training combined with incomplete recovery. Maladaptation, fatigue and performance decrements occur (Polman & Houlahan, 2004).

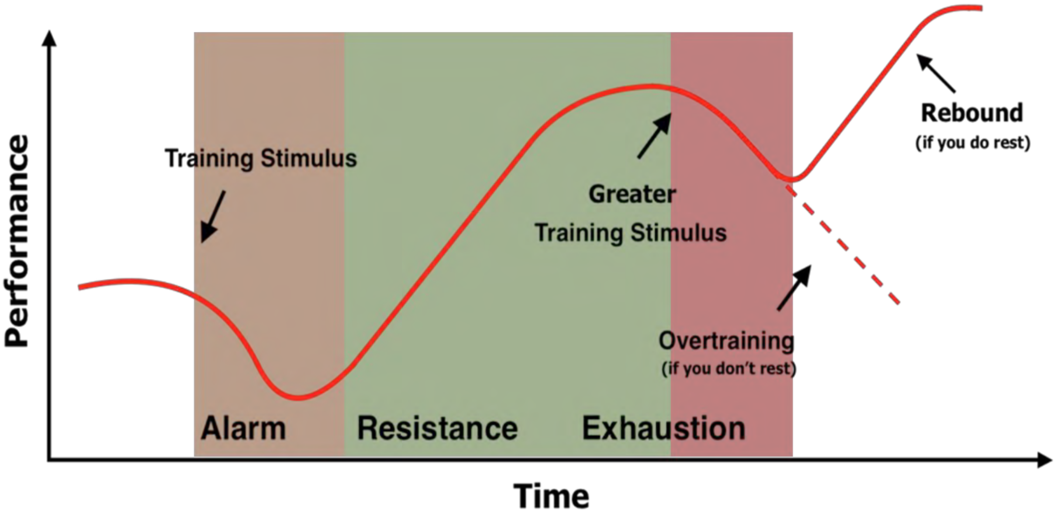

Figure 2. The three stages of the general adaptation syndrome (Akenhead & Nassis, Training Load and Player Monitoring in High Level Football: Current Practice and Perceptions, 2016) (Seyle, 1946). Adapted from *Progressing as a Derby City Athlete* by S. Coe, 2018, Retrieved from https://derbycitycf.com/progressing-as-a-derby-city-athlete/.

Selye's work has been criticised for the oversimplification of the biological stress-adaptation response in more recent years, as well as not taking into consideration the multitude of factors which individualise the response (Kiely, 2012; Kiely, 2018). Despite this, the general adaptation syndrome still forms the foundation of workload application in modern-day practice.

Banister and colleagues proposed a statistical model to explain an athlete's performance in response to a given stimulus (Calvert, Banister, Savage, & Bach, 1976). They originally suggested that performance increases linearly with training, until the athlete's performance capacity is reached. This rise in performance is proportionate to the difference between an individual's inherent maximal performance level and their current performance (Calvert, et al., 1976). Conversely, as soon as training ceased, performance decreased. However, when they tried to predict the performance of a swimmer using the model, the actual performance data did not fit. After several weeks of intense training, the swimmer's performance decreased, despite increases in fitness over that time. Calvert, et al. (1976) subsequently updated the model to calculate performance as an estimate of the difference between fitness (positive) and fatigue (negative). Both fitness and fatigue decay exponentially once the stimulus is over and recovery begins; but changes in fitness occur at a slower, more gradual rate (Windt & Gabbett, 2017). Consequently, repeated exposure to adequate workloads results in the accumulation of fitness and performance improvements, as long as there is enough recovery to allow for fatigue to subside (Meeusen, et al., 2013) (Figure 3). Ultimately, optimal workloads should be high enough to disturb an athlete's homeostasis and induce adaption, without the accumulation of negative fatigue effects leading to overtraining or non-functional overreaching (Windt & Gabbett, 2017).

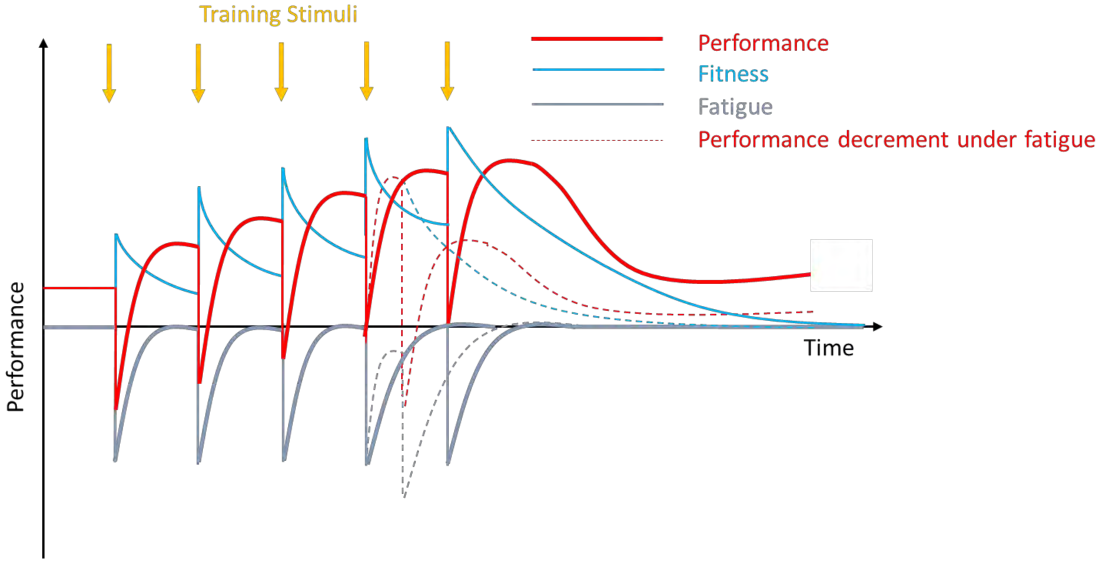

Figure 3. The influence of fitness and fatigue on performance. Adapted from *The Dual Factor Theory* by G. Baldi, 2017, Retrieved from https://www.giovannibaldi.com/dual-factor-theory/. Copyright 2019 by Giovanni Baldi.

In order to ensure workloads are effective and adhered to, they must be quantified (Borresen & Lambert, 2009). The introduction and advancement of workload monitoring technology has allowed for quantification of these workloads, and therefore a heightened understanding of how to maximise performance (Cardinale & Varley, 2017). Thus, monitoring workloads is now common practice in elite sports; a recent survey of 41 football clubs from around the world found that all clubs monitor workloads for injury prevention and performance (Akenhead & Nassis, 2016).

Workload can be defined as either internal or external. External workloads are an objective measure of the work completed, whilst internal workloads quantify the biological (psychological and physiological) response of the athlete to the external workload (Bourdon, et al., 2017). Examples of internal measures include but are not limited to, subjective wellbeing questionnaires, heart rate and rating of perceived exertion (RPE), measured on a scale of 1-10. External workload can be measured using a variety of methods including duration, frequency, distance covered, weight lifted, power output and time-motion analysis. This thesis will focus purely on external workloads, quantified using time-motion analysis, predominantly global positioning systems (GPS).

1.04.2 Time-motion analysis in football.

The satellite-based GPS is a navigational technology originally invented for military use (Lachow, 1995). Low-power radio signals transmitted from the satellites contain information regarding the time taken to reach a ground-based receiver. Using this information, position, distance and speed of displacement can be calculated (Larsson, 2003). In 1983, GPS technology was made available for civilian use, prompting the development of lighter, smaller and less complex GPS receivers (Townsend & Stewart, 2008). These units are approximately the size of a smart phone and can be worn between the shoulder blades in a custom-design vest. The increased practicality and availability created new opportunities to advance the quantification of workload in sport.

In 2012, the EPL introduced the Elite Player Performance Plan aimed at promoting more talented home-grown players, by providing a structured, player-centred development programme (Premier League, 2017). Within the ruling it states that all category 1 academies (top-rated based on various conditions) must utilise GPS to monitor training and match activity in the youth development (U12-U16) and professional development phases (U17-U23) (English Football League, 2018). However, at senior level, GPS use was not permitted in the EPL until the 2015/16 season. Despite this change, very few teams have since used the devices during match play. Asking players to disrupt their usual match day routine, or to wear an extra layer is considered invasive by some practitioners and coaches, particularly on a match day when there is a pressure to perform (Bloomfield, 2015). Furthermore, the obstruction by stadium walls can cause intermittent satellite signal or reduce the reliability of the signals that are received (National Coordination Office, 2017).

Consequently, semi-automated camera systems (SACS) are most commonly used for recording match data at the elite level. However the associated cost of installation and time taken for camera-based analysis makes GPS a more practical method of monitoring training (Bucheit, et al., 2014). As such, the two systems are used inter-changeably within the EPL for quantifying the combined physical workload of training and match play. Chapter 2 will address the interchangeability of the two systems for establishing a complete workload profile.

1.04.3 Validity and reliability of GPS for monitoring sporting performance.

The first study to investigate commercially-available GPS for sporting application measured the validity and reliability of GPS-derived distance around various pre-determined circuits specific to Australian football (Edgecomb & Norton, 2006). Authors concluded that GPS was valid and reliable enough to track player movements, despite small, predictable measurement errors (Edgecomb & Norton, 2006).

Further investigations did not occur until 2009-10, when an extensive body of literature was published regarding the validity and reliability of GPS as a performance measurement tool (Aughey, 2011). Commercially-available GPS devices using various sampling rates of 1, 5, 10 and 15 Hz were tested, with a consensus in the literature that precision in distance measurement increased uniformly with higher sample rates (Aughey, 2011). The recent release of 18Hz units has resulted in a further increase in the validity of distance covered and sprint mechanical properties than earlier units with lower sampling rates (Hoppe, Baumgart, Polglaze, & Freiwald, 2018). Regardless of sampling frequency, error of measurement was found to increase with speed (Scott, Scott, & Kelly, 2016). Portas, Rush, Barnes, & Batterham (2007) found that measurement error was lowest during walking (SEE 0.7%) and highest during running (SEE 5.6%). The distance covered also effected validity, with an increase in measurement accuracy over longer distances (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010). Higher sampling rates improved reliability during constant velocity trials (Varley, Elias, & Aughey, 2012) and a team-sport specific circuit (Hoppe, et al., 2018). Increasing the sampling frequency from 10Hz to 15Hz appeared to have no benefit due to 15Hz units typically up-sampling 5Hz units (Rawstorn, Maddison, Ali, Foskett, & Gant, 2014). However, units with a true sampling rate of 18Hz demonstrated greater reliability compared to 10Hz units (Hoppe, et al., 2018). In line with validation findings, reliability was improved at lower velocities and negatively affected by increases in change of direction movements, most likely due to a high number of speed changes (Jennings, et al., 2010). Generally, intra-reliability of the devices has reported better than inter-reliability, suggesting that where possible athletes should wear the same unit across multiple sessions (Scott, et al., 2016).

In summary, GPS has been found to be a valid and reliable measure of movement patterns over lower speeds and greater distances (Portas, et al., 2007; Jennings, et al., 2010). Conversely, the reduced reliability of the devices during high intensity, short bursts of activity is a limitation when assessing movement demands in sport (Scott, et al., 2016). The development of custom algorithms which use the data from integrated 100-Hz accelerometers to improve accuracy (Coutts & Duffield, 2010), alongside technological advancements and greater sampling frequencies have helped to reduce this limiting factor; however, caution must still be taken when interpreting this data.

1.04.4 The application of GPS in football.

The physical size of modern, commercially-available GPS units (Apex, StatSports, Ireland; Size: 30mmx80mm, Mass: <50g) is not only what makes them suitable to be used in a wide range of sports. Integrated accelerometers, gyroscopes and heart rate technology permit greater accuracy, and a more in-depth understanding of movement patterns and the associated energy costs (Dellaserra, Gao, & Randsell, 2014). Primarily, research using these units described the activity profiles of athletes during competition (Aughey, 2011). Due to the inability for GPS to track movement indoors, the application of GPS to team sports, has been limited to field-based sports. However, the literature is still relatively widespread with studies from Australian football (e.g. Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014; Duhig, et al., 2016), rugby union (e.g. Cunningham, et al., 2016; Swaby, Jones, & Comfort, 2016), rugby league (e.g. Blanch & Gabbett, 2016; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016), Gaelic football (e.g. Malone, Roe, Doran, Gabbett, & Collins, 2017), football (e.g. Saward, Morris, Nevill, & Sunderland, 2019; Lu, Howle, Waterson, Duncan, & Duffield, 2017), field-hockey (e.g. Vescovi, 2016) and cricket (e.g Hulin, et al., 2014; Greig & Nagy, 2017).

Within football, the majority of descriptive studies have quantified total distance within match play (Taylor, Wright, Dischavi, Townsend, & Marmon, 2017), as well as distance in various locomotor zones (e.g. standing, walking, jogging, running, high speed running and sprinting) (Dwyer & Gabbett, 2012). These zones have typically been based on six manufacturer-driven, evidence-based thresholds, with zone 1 being the lowest and zone 6 being the highest level of effort (McLellan, Lovell, & Gass, 2011).

Arbitrary thresholds allow for comparisons across both athletes and research, as well as the establishment of normative data, although they do not account for individual differences (Hunter, et al., 2015). Furthermore, previous studies that have used absolute thresholds have failed to provide a research-supported rationale for threshold selection. Predominantly, either default classifications from the manufacturer or modified zone thresholds from rugby union and Australian Rules football are used, where most of the initial GPS research was completed (Docherty, Wegner, & Neary, 1988). However, the diverse natures of these different sports suggest that these classifications may not accurately replicate sport-specific demands. Reflecting this, Dwyer and Gabbett (2012) found varying velocity ranges between male and female football players and Australian Rules Football players. Therefore, absolute zone classification may need to be more sport-specific and consider the short, high intensity bursts present in many team sports (Dwyer & Gabbett, 2012).

Individualised speed zones provide a solution to these issues, by comparing an athlete's performance to themselves, rather than an average. A wide range of physical attributes have been used in research to individualise speed zones, including measures of the anaerobic threshold, maximal aerobic speed (MAS) and maximum sprinting speed (MSS). Due to its practicality, calculating percentages of MSS is a common method for defining speed zones in sport (Harley, et al., 2010). However, it assumes that an athlete's ability to hit high speeds corresponds with their endurance capacity and vice versa. Consequently, this can result in erroneous overestimation of high intensity activity for the players with lower peak speeds and underestimation for those with higher peak speeds (Mendez-Villanueva, Bucheit, Simpson, Peltola, & Bourdon, 2011). Determination of MAS is a better method to ascertain an individual's relative high-speed running (Hunter, et al., 2015). However, using this method in isolation is not sensitive enough to distinguish between the high-end locomotor categories such as very high speed running and sprinting (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009). Furthermore, as laboratory-based tests are both expensive and time-consuming, estimations of MAS through field tests (e.g. the VAM-EVAL (Mendez-Villanueva, Buchheit, Simpson, & Bourdon, 2013) may be more applicable to team sport environments (Hunter, et al., 2015). However, without a laboratory assessment of the anaerobic threshold (e.g. VVO_2 max), these estimations do not account for individual differences in the transition point between exercise intensities or the change in training status over time (Hunter, et al., 2015).

Ultimately, the use of a single physical attribute to define multiple locomotor categories prevents accurate measurement of a player’s intensity distribution. Hunter, et al. (2015) recommended the use of two attributes to characterise both the aerobic and anaerobic demands of the game. Using a combination of laboratory-derived MAS and MSS would appear to provide the most accurate interpretation of an individual’s dose response, and therefore the best method for the individualisation of speed zones.

With advancements in technology, the quantification of accelerations and decelerations has also been increasingly reported. Profiling football demands based on distance covered at different speeds may underestimate workloads, due to the energy expenditure associated with accelerating and decelerating (Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). Acceleration and deceleration duration, distance and magnitude have all been found to decay throughout a match (Russell, et al., 2016; Newans, Bellingger, Dodd, & Minahan, 2019). It was originally reported that deceleration ability is hampered by fatigue during the later stages of the game (Russell, et al., 2016; Akenhead, Hayes, Thompson, & French, 2013). However, recent literature suggests that the decline may be attributed to a lack of opportunity to perform those actions, rather than an inability to (Newans, et al., 2019). Whilst these findings provide important insights into the acceleration and deceleration demands of the game, the reliability of GPS to accurately measure these is still questionable, due to their rapid, intensive nature (Varley, 2013). Specifically, banding these actions by intensity is inaccurate, whilst averaging the demands over a selected period of time may provide a more reliable measure, without affecting sensitivity (Delaney, et al., 2017).

As well as quantifying the demands, studies have described workload differences based on age (e.g. Harley, et al., 2010), gender (e.g. Dwyer & Gabbett, 2012), ability (e.g. Di Salvo, Pigozzi, Gonzalez-Haro, Laughlin, & De Witt, 2013) and position (e.g. Abbott, et al., 2018). Furthermore, the literature has compared competition demands with physical fitness tests, finding that different playing positions excel in different tests (Bujnovky, et al., 2019). This provides sport scientists with objective information to identify individual strengths and weaknesses and design training protocols which enhance the specific fitness requirements of each position (Bujnovky, et al., 2019).

To further aid the development of training programmes which are specific to the demands of football, research has also compared the demands of training versus competition (Bompa & Jones, 1983). Specifically, there has been a large focus on small sided games, which are played in reduced pitch areas, with adapted rules and often fewer players than a traditional football game (Hill-Haas, Dawson, Impellizzeri, & Coutts, 2011). The main advantages of this training modality are that they mimic the movements of football, as well as being modifiable to train the various energy systems and physical demands (Gamble, 2004; Little, 2009). They also require players to make decisions under pressure and fatigue (Gabbett & Mulvey, 2008), facilitating the development of technical skill and tactical awareness (Little, 2009). With the introduction of GPS, research into small sided games has focused primarily on the effect of various conditions on physical demands (Sarmento, Clemente, da Costa, Owen, & Figueiredo, 2018). These conditions include pitch area (e.g. Hodgson, Akenhead, & Thomas, 2014; Joo, Hwang-Bo, & Jee, 2016); number of players (e.g. Owen, Wong, McKenna, & Dellal, 2011; Katis & Kellis, 2009; Little & Williams, 2007), coach encouragement (e.g. Rampinini, et al., 2007), rules (e.g. Davids, Araujo, Correia, & Villar, 2013; Casamichana, Suarez-Arrones, Castellano, & Roman-Quintana, 2014) and use of goals (e.g. Clemente, 2016; Koklu, Alemdaroglu, & Arslan, 2015). Ultimately, the large number of variables that have been studied and manipulated provide a broader understanding of the demands of small sided games. However, the lack of consistency across the expansive body of research makes it difficult to generalise the findings across players of different ages and abilities (Sarmento, et al., 2018). Thus, clubs are recommended to conduct their own internal research into the effect of the various conditions on physical output and how this compares to their players' match demands.

More recent research has gone beyond describing workloads, to identifying relationships between workload with fatigue (e.g. Zurutuza, Castellano, Echeazarra, & Casamichana, 2017), nutrition (e.g. Anderson, et al., 2017), wellness (e.g. Sampson, Murray, Williams, Sullivan, & Fullagar, 2019), performance (e.g. Gimenez, Leicht, & Ruano, 2019) and most notably injury (e.g. Gabbett, 2016). A recent review revealed that there has been a rapid increase in workload, performance and injury research growing from 9 papers in 2000 to 145 papers in 2017 (Gabbett, 2018).

1.05 Workload and Injury

1.05.1 Defining injury in football.

Despite the cause of injury being complex and multi-factorial in nature, all sport injuries occur during exposure to training or competition workloads. Sport injury is the occurrence of structural damage resulting from the transfer of physical forces which exceed the body's ability to handle them (Fuller, 2010). Therefore, the challenge for sport scientists is to identify optimum workloads which push the boundaries of what a player can achieve, without exceeding what their bodies can tolerate (Piggott, Newton, & McGuigan, 2009). Thus, understanding and monitoring the training programmes of football players is essential to ensure that the optimal workload is implemented. Ultimately, this will potentially increase positive adaptations and reduce the prevalence of injury in football.

Injuries in football can be defined in three ways (Fuller, et al., 2006):

- Any physical complaint – resulting from a football match or training, irrespective of the need for medical attention.
- Medical attention injury – any injuries that needs medical attention
- Time loss injury – any injuries that results in a player missing training or match time.

Most research has utilised the time loss injury definition as it is most impactful on performance and can be collected more readily (Bahr, 2009). Based on this definition, injury severity is determined based on the number of days from injury to full participation in training and availability for match selection (Fuller, et al., 2006). Severity is often categorised as minimal (1-3 days), slight (4-7 days), moderate (8-28 days) and severe (>28 days) (Fuller, et al., 2006). According to consensus, injuries should be classified by location, type, body side, mechanism and whether it was a new or reoccurring injury (Fuller, et al., 2006). In football, whether the injury happened in training or match play, and whether it was contact or non-contact are also important elements to consider (Fuller, et al., 2006).

1.05.2 Workload management as an injury prevention strategy.

Injury prevention can either target a specific injury (primary, secondary and tertiary prevention), or aim to control potential risk factors (universal, selective or indicated prevention) (Jacobsson & Timpka, 2015). Workload has been placed within this framework to increase understanding on the role of workload management in injury prevention (Drew, Cook, & Finch, 2016). Primary prevention aims to remove or reduce potential injury risk factors. In the case of workload, this would be ensuring that workloads were neither too low or too high (Straker, Mathiassen, & Holtermann, 2018). Secondary prevention involves detecting an injury early enough to prevent it worsening (Drew, et al., 2016), i.e. modifying the workload based on the presence of internal or external risk factors. For example, players who are at risk of a hamstring injury may need to perform a reduced amount of high-speed running, as an augmented exposure of this has been related to hamstring strains (Duhig, et al., 2016). Tertiary prevention applies once an injury has occurred, aiming to reduce complications and long-term consequences (Drew, et al., 2016). In this case, workload management must ensure gradual progressive exposure back to training and playing demands to reduce the risk of subsequent injury (Blanch & Gabbett, 2016). Universal prevention involves considering any generic risk factors involved in sport, such as nutrition, mental health, sleep and physical activity (Jacobsson & Timpka, 2015). As workload has been related to injury across a number of sports, this can be considered a universal risk factor (Drew & Finch, 2016). Selective prevention targets risk modifiers in asymptomatic individuals, such as age, gender, sport training age and history (Drew, et al., 2016). In terms of workload management, making sure training programmes consider these factors in relation to individual ability to tolerate workload is key for injury prevention (Buckthorpe, et al., 2019). Indicated prevention targets athletes at high risk of injury (Jacobsson & Timpka, 2015). These athletes should have their workload closely monitored and managed by support staff to reduce the risk of injury occurrence.

1.05.3 The interaction of workload implementation and injury risk.

Integrating workloads into injury prevention strategies requires a heightened understanding of the interactions between workload and the multitude of injury risk factors. To provide clarity of the role of workload application, and to highlight the pathway to injury, Windt & Gabbett (2017) designed the Workload-Injury Aetiology Model (Figure 4). This expanded on previous models (Meeuwisse, 1994; Meeuwisse, Tyreman, Hagel, & Emery, 2007) which did not include the contribution of workload to injury risk. The model depicts three ways in which workload contributes to injury; firstly, exposure to external risk factors and potentially injurious events, secondly, negative adaptations (fatigue) and thirdly, positive adaptations (fitness). Ultimately, workloads not only pre-dispose an athlete to injury by exposing them to external risk factors, but also modify subsequent injury risk through positive and negative adaptations to the given stimuli; If an athlete does not get injured following exposure to a given workload, their risk becomes modified due to physiological adaptation to physical stress. However, the athlete does get injured, they may recover and return to play with a heightened injury risk, or not recover and have to stop participation (Windt & Gabbett, 2017).

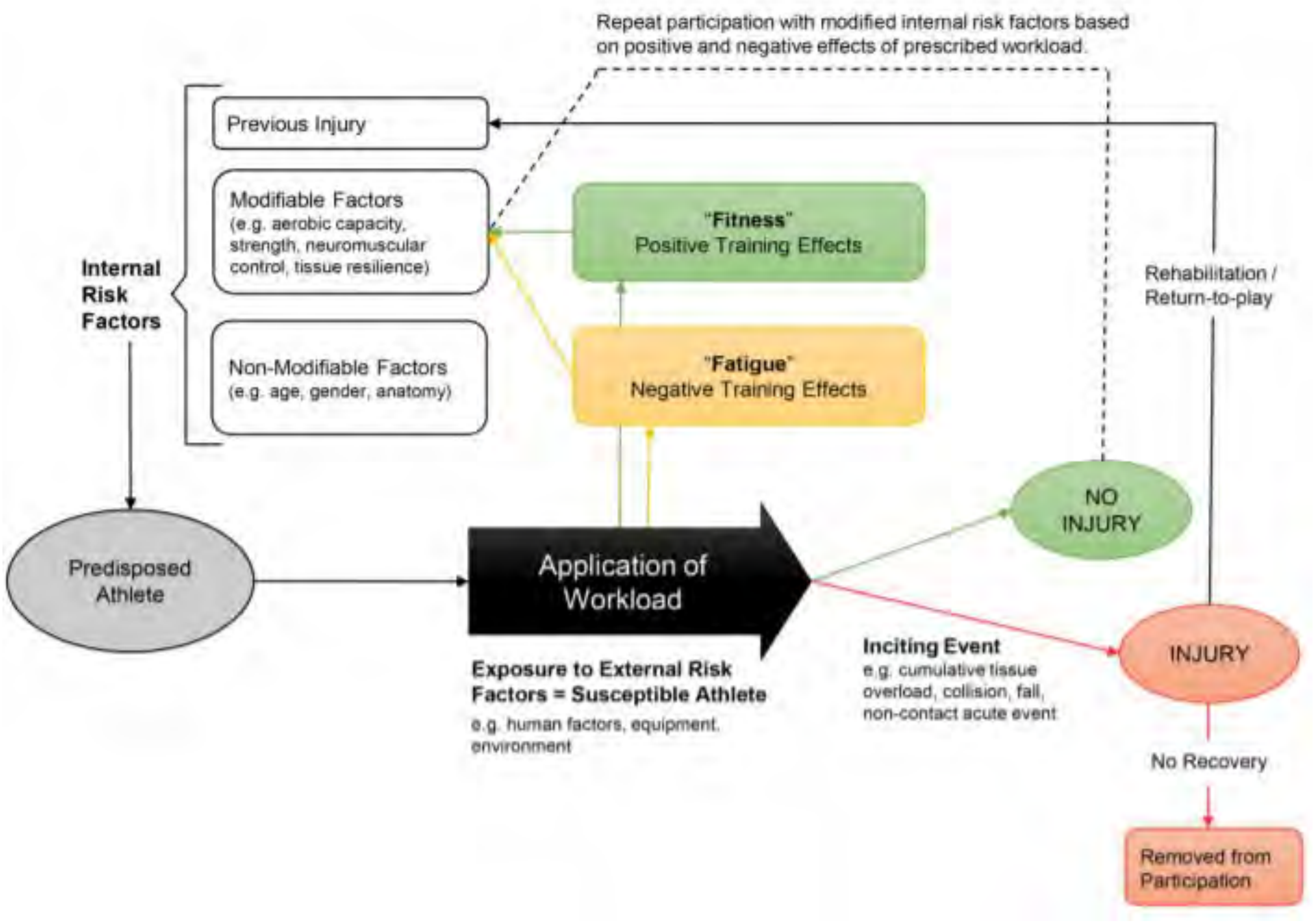

Figure 4. The Workload-Injury Aetiology Model. Reproduced from *How do training and competition workloads relate to injury. The workload —injury aetiology model* by J. Windt & T.J. Gabbett, 2017, *British Journal of Sports Medicine, 51,* p.433.

1.05.4 Higher workload-higher injury risk.

Despite association, the application of workloads is not a direct cause of injury; an inciting event is still required, even if the injury is considered workload-related. Instead, workloads are the ‘vehicle’ by which athletes are exposed to potentially injurious situations (Windt & Gabbett, 2017); the more they train and play, the greater exposure they have to these situations. Thus, the higher workload – higher injury risk relationship has been studied across numerous sports (Colby, et al., 2014; Hulin, et al., 2014; Lu, et al., 2017).

Initial research between injury risk and workload in elite sport focused primarily on rugby. Strong correlations were found between the intensity, duration and RPE-derived workload (session duration multiplied by RPE; sRPE) during training and matches with injury (Gabbett, 2004). The authors reported a positive relationship supporting the higher workload - higher injury risk theory. In addition, Gabbett and Ullah (2012) demonstrated a 2.7 times greater risk of injury in rugby players who performed over 9m of sprinting (>7m/s) in a session compared to those who performed less. More recently, a 2-14 times greater injury risk was indentified for rugby players who performed more than 29km in a week, compared to those who performed less (Hulin, et al., 2016). These findings provided unique insights into the effect of short, acute workloads on injury risk. However, workload is defined as the cumulative amount of stress placed on an individual from multiple training sessions and matches over time (Gabbett, et al., 2014). Therefore, only investigating one-weekly workload relationships with injury may not provide a complete understanding.

Consequently, in Australian football, Colby, et al., (2014) calculated cumulative 1-4 weekly workloads and the relationships with injury risk in Australian football. They reported a heightened risk of injury with greater three-weekly total distance and sprint distance. Rapid, transient increases in high speed running exposure has also been found to increase the odds of suffering a hamstring injury in Australian football players (Duhig, et al., 2016). Another study reported weekly high-speed running values over 653m or a week to week change over 218m to increase the risk of hamstring injury by

3-4 times (Ruddy, et al., 2018). These findings highlight the importance of monitoring the cumulative workload over longer periods of time in relation to injury risk.

Within football, recent research has shown a relationship between internal workload measured using sRPE and non-contact injury incidence (Malone, Owen, et al., 2017; Lu, et al., 2017; Delecroix, McCall, Dawson, Berthoin, & Dupont, 2018). An increased probability of injury with high 3- and 4-weekly sRPE was found in five professional football clubs across Europe (Delecroix, et al., 2018), as well as within the Under-21 squad of one team throughout 5 seasons (Delecroix, Delaval, Dawson, Berthoin, & Dupont, 2019). Exposure (minutes) and sRPE were also greater in the 3-weeks prior to injury in another study which analysed 39 non-contact injuries within one football club (Lu, et al., 2017). This relationship was not found for GPS-derived workloads, most likely because match workloads were not included, which encompass a large proportion of the weekly physical demands (Lu, et al., 2017). Thus, future research investigating the complete GPS-derived workload profiles of football players was required.

Research has found sRPE to be a valid measurement tool in football (Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004), as well as being sensitive enough to detect changes in injury risk (Jones, et al., 2019). However, there are several limitations to this method, which suggest an external workload measure should also be considered. Firstly, the personality (extraversion, depression, anxiety etc) and characteristics of the athlete (gender, age, fitness level etc) have been found to affect sRPE (Haddad, Stylianides, Djaoui, Dellal, & Chamari, 2017; Morgan, 1994). Secondly, environmental factors such as temperature, music/background noise, instructions given, consumption of caffeine, and varying sRPE scales can influence athlete perception (Haddad, Padulo, & Chamari, 2014). Finally, sRPE does not differentiate between short, high intensity sessions and long low intensity sessions (Soligard, et al., 2016). Ultimately, the combination of internal and external workload may provide a more comprehensive understanding of the workload-injury relationship.

Consequently, Jaspers, et al. (2018) investigated the association of both sRPE- and GPS derived-workloads with overuse injuries in thirty-five elite football players across two seasons. They found mainly external workloads to be associated with injury risk; the accumulation of total distance over 1, 2 and 3 weeks and number of decelerations over 2-4 weeks demonstrated the greatest risk. Furthermore, Malone, et al. (2018) found injury risk to increase with elevated high speed running and sprint distances, particularly when the increases were large and rapid. Thus ‘spikes’ in workload over both short and longer periods appear to augment the risk of injury.

Across the studied sports, authors acknowledged that whilst decreasing workloads may reduce injury risk, it may also prevent positive adaptations, such as the development of the physical qualities (Gabbett & Ullah, 2012; Hulin, et al., 2016; Malone, et al., 2018). Therefore, workloads that are too low may also augment the risk of injury. This has been demonstrated in youth players, where participants who completed additional training demonstrated physiological adaptations such as improved aerobic capacity, strength, optimal body composition and repeated-sprint ability, after 13 weeks, compared to a control group who followed a standard training protocol (Tonnessen, Shalfawi, Haugen, & Enoksen, 2011). These physical attributes are vital for performance and may also increase an athlete’s tolerance to injury risk

(Gabbett, 2016). Additionally, in both football and Gaelic football, players with superior aerobic capacity had a decreased relative risk of injury, as well as a greater tolerance for higher workloads and larger week to week changes in workload (Malone, Roe, et al., 2017; Malone, Owen, et al., 2017; Malone, et al., 2018). Therefore, the relationship between workload and physical capacity appears to be multi-directional, i.e. players with developed physical qualities can tolerate higher workloads, and exposure to higher workloads develops physical qualities (Gabbett, et al., 2019). Thus, focusing on the negative effects of training hard, detracts from the positive adaptations resulting from appropriate training stimuli.

1.05.5 Acute:chronic workload ratios and injury risk.

The EPL has evolved into a much faster, intensive and more competitive game, with physical and technical demands increasing substantially over the past few years (Barnes, et al., 2014). In addition, the fixture congested nature of the EPL means that players must repeatedly perform at these high workloads. Therefore, training workloads that are too low may underprepare the players for these demands through reduced fitness levels and tolerance to physical stress (Windt & Gabbett, 2017). In this case higher workloads would appear to be protective, whilst lower workloads may be insufficient to induce adaptations or result in detraining – increasing the risk of injury. This suggests a U-shaped relationship between workload and injury, where both doing too much or too little presents a heightened risk (Straker, et al., 2018). Furthermore, an athlete’s previous chronic exposure to workload appears to modify the injury risk associated with the current workload (Malone, et al., 2018).

Hence, there has been growing support for relative workload monitoring, primarily, the acute:chronic workload ratio (ACWR) (Bourdon, et al., 2017). This typically involves the assessment of the absolute one-week workload (acute workload) relative to four-week chronic workload (4-week average acute workload) (Hulin, et al., 2016). A workload index can then be calculated indicating whether the individual's acute workload is greater, less than or equal to the preceding chronic workload they have been prepared for. Based on the original work of Calvert, et al., (1976) on performance modelling, chronic workload is considered the 'fitness' component, and the acute workload as the 'fatigue' component (Hulin, et al., 2014). Therefore, if the chronic workload is high and the acute workload is low, the athlete is considered to be well prepared. However, if the acute workload 'spikes' beyond the chronic workload, the athlete is in a state of fatigue which could be both detrimental to performance and increase the risk of injury (Hulin, et al., 2016).

The first study to use the ACWR investigated workload and injury risk in elite cricket fast bowlers (Hulin, et al., 2014). Acute internal (sRPE) and external (balls bowled) workloads greater than 200% of the chronic workload were associated with 3-4 times higher injury risks than acute workloads that were 50-99% of the chronic workload (Hulin, et al., 2014). The study also reported a reduced injury risk with higher chronic workloads, which they attributed to the positive adaptations associated with training (Hulin, et al., 2014). The same research group then assessed the relationship between ACWR and injury risk in elite rugby league players (Hulin, et al., 2016). Similar to the study in cricket, they found very high ACWR, of GPS-derived total distance, to be associated with heightened injury risk. High chronic workloads demonstrated a smaller injury risk than low chronic workloads when combined with moderate and moderate to high acute workloads. They recommended that the ACWR method should be used to monitor workloads in elite sport as it is more sensitive to injury risk than the acute or chronic workloads in isolation (Hulin, et al., 2016).

Based on these findings, Gabbett (2016) proposed that the prescription of workload may be more indicative of injury than the workload itself. His Training-Injury Prevention Paradox concludes that excessive, rapid increases in workload heighten the risk of injury, whereas chronic exposure to higher workloads augments the physical capacities of the athletes making them more resilient to injury, whilst also enhancing performance. Using data from cricket, Australian football and rugby league, Blanch and Gabbett (2016) developed a guide to applying and interpreting the ACWR in practice. Using a second order polynomial curve to fit the data, they found that the ACWR explains 53% of the variance in likelihood of injury, compared to 34% by absolute workloads. This guide was developed further based on the concepts of the training-injury prevention paradox, highlighting ACWRs over 1.5 as the ‘danger zone’ for heightened injury risk, and ACWRs between 0.8-1.3 as the ‘sweet spot’ where injury risk is at its lowest (Gabbett, 2016) (Figure 5). Within the danger zone, injury risk increases exponentially, meaning at the highest ACWRs, very small changes in workload result in large changes in injury risk (Gabbett, 2016). Additionally, training workloads below the sweet spot demonstrated a greater likelihood of injury, although not to the level of ACWRs >1.5. Thus, as shown in previous work, both under- and over-training increase injury risk as well as adversely affecting performance. Undertraining results in a reduced ability to tolerate and adapt to the demands of competition, whilst overtraining promotes fatigue, psychological problems and decreased performance (Gabbett, Windt, & Gabbett, 2016).

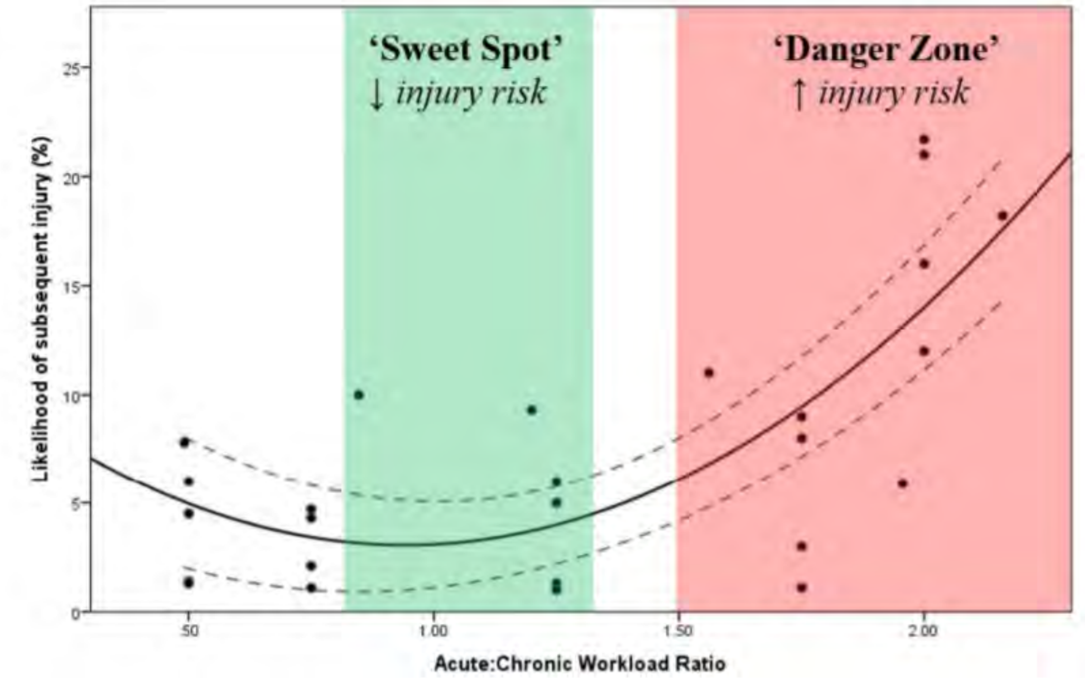

Figure 5. The U-shaped relationship between the injury risk and the acute:chronic workload ratio. Adapted from *The Training-Injury Prevention Paradox: Should Athletes be Training Smarter and Harder?* by T. J. Gabbett, 2016, Retrieved from The British Journal of Sports Medicine, 50, 278.

The work by Hulin, et al., (2014 and 2016), as well as the training-injury prevention paradox (Gabbett, 2016) provided the foundation for the studies carried out in Chapters 4 and 5. Prior to the commencement of Chapter 4, only one study had explored the concept of relative workloads in football; metres per minute were significantly higher than the seasonal average in the 1 and 4 weeks prior to injury in Australian league players (Ehrmann, Duncan, Sindhusake, Franzsen, & Greene, 2016). However, only 16 injuries were analysed, and match data was not recorded, warranting further research. Consequently, this thesis explores the associations of accumulated workloads and ACWR in elite youth (Chapter 4) and senior (Chapter 5) EPL football.

During the progression of this thesis, further work has been added to the literature regarding the ACWR and injury risk in a range of sports including Australian football (e.g. Carey, et al., 2017; Murray, Gabbett, Townshend, Hulin, & McLellan, 2017; Stares, et al., 2018), Gaelic football (e.g. Malone, Roe, et al., 2017), basketball (e.g. Weiss, Allen, McGuigan, & Whatman, 2017; Caparros, Casals, Solana, & Pena, 2018), cricket (e.g. Warren, Williams, McCaig, & Trewartha, 2018) and football (e.g. Malone, Owen, et al., 2017; Malone, et al., 2018; McCall, Dupont, & Ekstrand, 2018; Delecroix, et al., 2018; Jaspers, et al., 2018).

Specifically, in elite football, a U-shaped relationship was found between both sRPE (Malone, Owen, et al., 2017) and GPS-derived workload with injury risk (Malone, et al., 2018), supporting the existing literature. Malone, et al. (2018) found that players who completed moderate high-speed running (701-750m) and sprint distances (201-350m), were at less risk than those who completed lower or higher amounts. Furthermore, players with higher chronic workloads, and/or greater aerobic fitness, demonstrated a reduced risk of injury when completing moderate workloads, compared to lower workloads. Conversely, those with lower chronic workloads and/or lesser aerobic fitness where at a heightened risk when completing moderate workloads as opposed to lower workloads (Malone, et al., 2018). Therefore, increased chronic exposure, as well as aerobic fitness appear to have a protective effect against injury as workload increases.

Whilst these findings were only demonstrated in 1-2 teams over one season, two studies involving 5 teams has also found similar results (McCall, et al., 2018; Delecroix, et al., 2018). As the traditional 7 day acute and 28 day chronic workload ratios may not apply to all football schedules due to additional cup fixtures, they also examined sRPE workload ratios of 1:2 and 1:3 weeks, as well as accumulated workloads over 1-4 weeks and week to week changes. McCall, et al. (2018) found moderate ACWR for both 1:3 and 1:4 weeks demonstrated a reduced injury risk compared to higher or lower ratios, similar to previous work. However, no associations with injury risk were found for the 1:2 method, the week to week changes or acute and chronic workloads in isolation. The authors speculated this may be due to the strict inclusion of non-contact injuries only, which was not the case in previous work (Malone, Owen, et al., 2017), or potential player manipulation of the sRPE, to give a false perception of effort, invalidating some results (McCall, et al., 2018). In contrast Delecroix, et al., (2018) found associations between non-contact injury risk only and cumulative acute sRPE as well as week-to-week changes. Studies including external workloads across larger sample sizes may provide more clarity and consistency. Furthermore, in support of research completed in Australian football (Stares, et al., 2018), neither the 1:3 or 1:4 ACWR were considered superior to the other (McCall, et al., 2018), and therefore practitioners should identify the ratio most suited to their training and competition schedules.

The first study to use both internal and external workloads in elite football found that external workloads were more sensitive to increases or decreases in injury risk (Jaspers, et al., 2018). Specifically, a high ACWR for high speed running was associated with a greater relative risk of injury, similar to the findings of Malone, et al. (2018). Furthermore, high accumulated total distance, decelerations and sRPE over 2 and 4 weeks also demonstrated a heightened risk. Consequently, both accumulated workloads and ACWRs should be considered to optimise workload management in football. Whilst this study provided a unique level of workload-injury understanding, match workload was estimated for an entire season, based on the averages of the following season. Buchheit (2017) stated that whilst estimated values are better than no values, the accuracy and validity of this method is questionable. Therefore, further research is warranted into the contribution of match demands to the workload-injury relationship.

In addition to its application in football, the method by which the ACWR is calculated has also been critically examined. The ACWR is typically calculated using rolling averages; either each day or each week, the ‘x’ number of days or weeks are averaged as the chronic workload. However, Menaspa (2017) highlighted that this method does not consider variations in stimulus within the set period of time, or when the stimulus occurs. The effect of a training stimulus decays over time, however, the rolling average method applies the same weighting to a stimulus applied the day before, as one applied 4-weeks before (using the 7:28 day method) (Menaspa, 2017). An alternative method was proposed by Williams, West, Cross, and Stokes (2017), who recommended an exponentially weighted moving average (EWMA) which applies a decreasing weighting to each older workload value. The EMWA is calculated for each day as follows:

$$EWMA_{today} = Load_{today} * \lambda_a + ((1 - \lambda_a) * EWMA_{yesterday})$$

Where λ_a is a value between 0 and 1 that represents the degree of decay, with higher values discounting older observations at a faster rate. The λ_a is given by:

$$\lambda_a = 2/(N + 1)$$

Where *N* is the chosen time decay constant, typically 7 and 28 days for acute and chronic workloads, respectively (Williams, et al., 2017).

The two methods (rolling averages and EWMA) were compared in a study of 59 Australian football players (Murray, et al., 2017). In agreement with the literature in football (Jaspers, et al., 2018), very high ACWR (>2.0) were associated with injury risk for both methods, however the EWMA was more sensitive to the risks associated with greater ACWRs (Murray, et al., 2017). Regardless the basic concept is still the same; building the chronic workload prepares players to tolerate the acute workloads. It must also be considered that the weighting applied to the acute and chronic workloads in the EWMA method makes it difficult to use for workload modification in practice. For example, if the aim was to de-load a player (reduce the stimulus), a practitioner could establish their current chronic workload using the rolling averages method (e.g. 30,000m of total distance) and reduce their acute exposure based on this value (a 10% decrease would result in an acute target of 27,000m (Gabbett, 2016). However, using the EWMA method, a target absolute value is much harder to achieve within a strict training and competition schedule because the distance covered (in this case) is then given a weighting. That is, if 10,000m was covered on day 1, it would have a lesser effect on the total acute workload than if 10,000m was also covered on day 7. Therefore, whilst injury risks may be detected at lower ACWR using the EWMA, the rolling averages method may be more useful in practice. More research is required to determine the most appropriate method.

With the vast, growing body of literature, the earlier training-injury prevention paradox model must only be considered as a basic framework for utilising the ACWR.

The numbers and thresholds set do not apply to every athlete in every sport. Furthermore, increased risk does not guarantee an injury will occur, and the rate at which it does or does not happen is influenced by several moderators (Gabbett, 2018). Moderators increase or decrease injury risk at a given workload and include age, training history, injury history, physical qualities (e.g. strength, aerobic capacity, speed), and chronic workload (Windt & Gabbett, 2017). Players who are more robust to workload due to their individual moderators, are less likely to sustain an injury when their ACWR is in the 'danger zone', compared to those who are more fragile (Gabbett, 2018).

It has been proven that well-developed physical qualities increase the workload capacity (maximal workload they can tolerate safely) of an athlete (Malone, Roe, et al., 2017), making them more robust. As previously mentioned however, this relationship has circular causality. That is, workload develops physical qualities, which are required to tolerate workload (Gabbett, et al., 2019). The "which comes first?" question arising from this is easily solved by appropriate workload management. Gradually progressing the chronic workload, whilst avoiding acute 'spikes' improves physical qualities, which in turn improves an athlete's workload capacity (Gabbett, et al., 2019). In order to do this safely and specific to the individual, the workload-injury moderators must also be considered (Figure 6). The interaction of these moderators with workload to influence injury risk explains why the ACWR cannot predict injury, despite association (Fanchini, et al., 2018). In line with previous research, accumulated workloads, week to week changes and ACWR for sRPE were calculated in 34 elite football players across three seasons. Whilst the ACWR was the most sensitive measure for increases in injury risk, all measures had poor predictive ability

(Fanchini, et al., 2018). This was also the case in the two studies involving five elite European teams; both accumulated and ACWR methods showed poor predictive power, and low sensitivity and specificity (McCall, et al., 2018; Delecroix, et al., 2018). This was attributed both to the multifactorial nature of injury occurrence, as well as the probability of sustaining and injury in football being ≤1% (Delecroix, et al., 2018). Therefore, when using workload to inform decisions, practitioners must consider that even when the risk of injury is increased, the probability of sustaining an injury remains low.

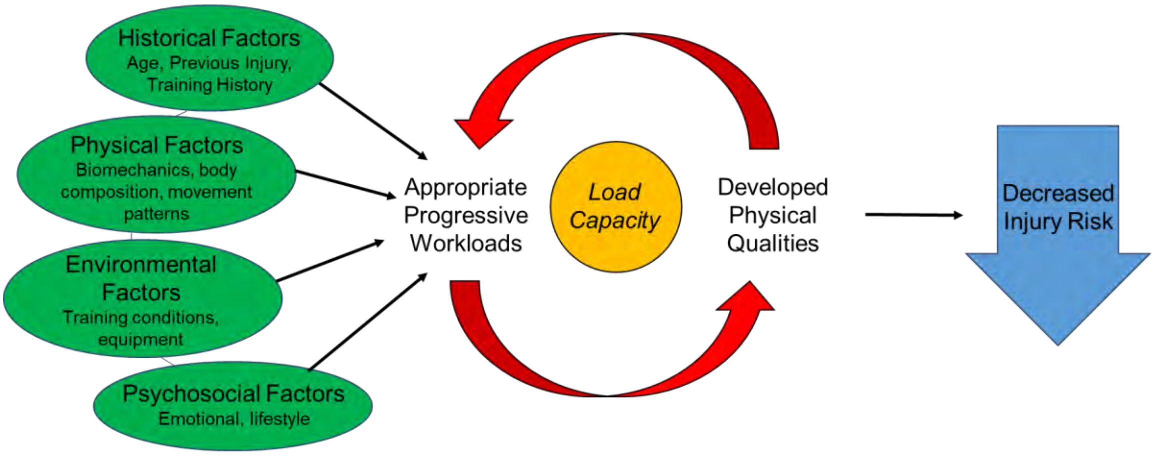

Figure 6. Injury risk moderators and the circular causation between workloads and physical qualities. Adapted from *In pursuit of the 'Unbreakable' Athlete: what is the role of moderating factors and circular causation?* by T. J. Gabbett, et al., 2019, Retrieved from The British Journal of Sports Medicine, 53, 395.

Despite the poor predictive ability, the overwhelming evidence of an association between workload and injury supports the use of workload monitoring for injury prevention. By focusing purely on prediction of injury, practitioners may limit their ability to reduce injury incidence through management of the relevant risk and protection factors. However, research has not examined the success of workload monitoring as an injury prevention tool, once the risks associated with given workloads has been identified. That is, we do not know if applying an understanding of which workloads increase injury risk helps us to limit future injury occurrence. Therefore, Chapter 6 applies the previous findings on workload and injury in Chapters 4 and 5 to the current daily practices of the same football club. The aim was to ascertain the effectiveness of informed workload modification via ACWRs for injury prevention and player workload capacity.

1.06 Research in Practice

Sport science is a scientific process used to guide the practice of sport with the aim of improving performance (Bishop, Burnett, Farrow, Gabbett, & Newton, 2006). In order to do this appropriate research should be translated into everyday practice. However, evidence suggests that the transfer of research to practice is poor (Webb & Mackenzie, 1993) based on factors such as conservative or outdated coaching practice, publication of findings in highly specialised journals and most notably, the lack of relevance of the research to practice (Ginexi & Hilton, 2006). This disconnect between research and practice is highlighted by the large number of workload error-related injuries (Drew & Purdam, 2016). Despite the growing body of evidence aimed at increasing the understanding of the associations between workload, performance and injury (Gabbett, 2018), the prevalence of these supposedly preventable injuries is still unchanged in football (Ekstrand, Walden, & Hagglund, 2016).

Consequently, coach philosophy has largely dictated the workloads performed by the athletes in relation to injury risk (Gabbett, et al., 2016). Some coaches have wanted to maximise performance gains through higher workloads, accepting that this may cause more frequent injuries. Other coaches have wished to avoid injuries and the associated costs, at the potential sacrifice to performance (Gabbett, et al., 2016).

However, effective communication, supported by relevant and applicable research, may facilitate the relationship between coaches and sport scientists, increasing the chances of successful workload monitoring for injury prevention and performance (Gabbett & Blanch, 2019).

As part of their applied research model for the sport sciences, Bishop (2008) recommended that the final stage of research should test the effectiveness and feasibility of the findings in real sport settings. It must be accepted that methodological designs may be more variable and contain larger sources of error and bias than under controlled conditions whilst carrying out applied research. However, it is important to include the complexity of sport, rather than ignore it or reduce it by isolating the controllable factors (Bishop, 2008). Thus, before undertaking research in practice, the barriers affecting the scientific rigour should be determined, including but not limited to environmental conditions, participant motivation and coach perspectives (Bishop, 2008).

The primary goal of applied research in elite football in relation to workload monitoring is to assist and inform coaching decisions on session content and player availability (Bourdon, et al., 2017). Feedback and recommendations should be specific to the circumstances to increase the chances of implementation. Therefore, the research must be applicable to the target population and directly address the performance question (Bishop, 2008).

Considering this, the research presented in this thesis has been carried out in an applied setting, and the findings have been used to inform and influence daily practices within an EPL football club. The various limitations resulting from this uncontrollable, dynamic environment are discussed throughout. However, the purpose was to understand the interactions between workload and injury within this environment, not in isolation from it, to ensure the greatest transfer between the research carried out and the impact on practice.

1.07 Thesis Aims and Objectives

With the huge pressure to perform and succeed within the EPL and the substantial cost of injury, understanding the relationships between the workloads implemented and the resultant risk of injury is potentially a key factor in optimising performance and maximising player availability. Yet there is very limited research exploring the relationships between workload and injury in professional football. Specifically, despite its growing popularity as a workload monitoring method, the ACWR and the associated injury risks is seldom investigated. Hence, the purpose of this thesis is to explore these relationships using global positioning systems (GPS) to quantify workload. The primary aim is to assess the associations between workload and injury in youth and senior EPL football. The final experimental chapter will then apply the findings from the previous chapters on workload and injury to elite football practice. Thus, the secondary aim is to determine the effectiveness of informed workload prescription as an injury prevention strategy. The objective of the following studies is to provide initial guidelines for implementing optimal workloads, with the purpose of minimising injury occurrence whilst maximising physical tolerance to workload.

Chapter 2 – A methodological study assessing the validity, reliability and comparability of GPS and SACS for quantifying football demands. Within EPL football, the majority of clubs, including Southampton FC, use GPS in training and SACS in matches. Despite TRACAB being the official provider of SACS data for the EPL, no studies have investigated its accuracy as a measurement tool prior to this chapter. Within this thesis, this chapter provides support for the use of GPS and SACS interchangeably to track external workload within both training and matches.

Chapter 3 – A descriptive study, quantifying the differences in training and match demands between the three squads investigated throughout this thesis; the under-18s, under-21s and seniors. This chapter provides the first insight within the literature of to the demands required to play youth versus senior football at the elite level. Within the context of this thesis, this chapter gives justification for studying the youth players separately to the adult players within the same club, and not merely treating the younger players as miniature adults (Dighton, 2018).

Chapter 4 – Published: **Bowen L, Gross AS, Gimpel M, and Li FX. Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players.** ***British Journal of Sports Medicine*** **2017;51:452-459.** A novel investigation into the relationship between GPS-derived workloads and injury. This chapter provides the first ever study exploring the association of both accumulated workloads and acute:chronic workload ratios with injury in elite youth football. Within the context of this thesis, this chapter provides initial guidelines for implementing optimal workloads to minimise injury occurrence within the U18 and U21 squads at Southampton FC.

Chapter 5 – Published. **Bowen L, Gross AS, Gimpel M, Bruce-Low S, Li, FX. Spikes in acute:chronic workload ratio (ACWR) associated with a 5–7 times greater injury rate in English Premier League football players: a comprehensive 3-year study. *British Journal of Sports Medicine* Published Online First: 21 February 2019. doi: 10.1136/bjsports-2018-099422.** The first ever study to explore the relationship of both accumulated GPS-derived workloads and ACWR with contact and non-contact injury risk in EPL players. Due to the differences identified in Chapter 3, the senior team were analysed separately to the youth team (Chapter 4). This chapter is therefore based on the design of Chapter 4, but involving senior players. Within the context of this thesis, this chapter provides initial guidelines for implementing optimal workloads to minimise injury occurrence within the senior squad at Southampton FC.

Chapter 6 - This study applied the findings of Chapter 5 into practice within an elite football environment. Both Chapter 4 and 5 establish the associations between workload and injury to determine workloads which result in minimal injury risk whilst promoting physical adaptation. Chapter 6 uses this knowledge to prescribe workloads in practice and assess how this affects injury incidence and workload tolerance.

Chapter 7 – A discussion of the major findings and learnings from the above chapters as well as the research journey throughout the creation of this thesis. This chapter summarises the outcomes, impact on practice and areas for future research.

CHAPTER 2. THE VALIDITY AND RELIABILITY OF GLOBAL POSITIONING SYSTEMS AND SEMI-AUTOMATED CAMERA SYSTEMS DURING A FOOTBALL-SPECIFIC CIRCUIT AND THE INTERCHANGEABILITY OF THE SYSTEMS DURING MATCH PLAY

2.01 Abstract

This study aimed to determine if GPS and SACS are valid, reliable and comparable measurement tools for quantifying physical workload in football. Five participants completed a football-specific circuit, involving linear and multi-directional tasks covered at a range of velocities. In addition, 10 U21 professional football players competed in an U21 EPL fixture in a stadium. All players wore GPS (StatSports) units and were simultaneously tracked by SACS (TRACAB). Validity (bias and percentage (%) bias compared to criterion distance) and reliability (CV%) were calculated during the circuit. Linear regressions and the resultant correlation coefficient were used to determine the relationships between the two systems. The standardised typical error (SEE) between the two measurement systems was also calculated. Both StatSports and TRACAB reported a mean % bias of <2% for the football-specific circuit, although this increased to >10% for the tasks involving multi-directional movement and decelerations. Reliability was good, with both systems recording <5% CV for distance covered across all discrete tasks within the circuit. In match-play, strong correlations and small % differences were found between GPS and SACS for distances covered at all speeds except sprint distance. Overall, both systems were valid and reliable, and can be used concurrently to monitor external workload in football. However, caution must be taken when utilising the systems interchangeably during high speed, multi-directional movements.

2.02 Introduction

Being able to quantify the external workload encountered by players is essential for optimising performance and managing injury risk in elite football. This workload can be monitored via the use of either GPS or SACS. From the start of the 2015/16 season, GPS use was permitted in EPL competition. Despite this, the obstruction caused by stadium infrastructure can limit the number of accessible satellites, causing intermittent satellite signal, or reduce the reliability of the signals that are received (Anderson, 2007). In addition, player or coach compliance to the devices being worn is often reduced during competition. Therefore, SACS are most commonly used for recording match data. However, the associated cost of installation and time for camera based analysis makes GPS a more practical method of monitoring training. As such, the two systems are used inter-changeably within the EPL for quantifying the combined physical workload of training and match play.

TRACAB has recently become the SACS supplier of physical performance data to the EPL and major leagues across Europe. However, there is no available research on the validity and reliability of TRACAB or comparisons with GPS technology. Thus, there is currently no evidence to suggest whether TRACAB data is an accurate method of assessing external workload or if it is inter-changeable with GPS data. Prozone has been the leading SACS over the last decade and has been found to be both valid and reliable for assessing movement demands by a small body of research (Harley et al., 2011). High correlations (0.99) and a low typical error were reported (1.27%) between Prozone and timing gates for mean velocity during pre-determined runs (Di Salvo, et al., 2006). However, these runs did not involve multi-directional movements, a key component of football, nor did they assess the validity of the system for distance measurement. Despite only using two participants and two observers, a more recent study reported good reliability for the measurement of distance covered and time spent in each speed zone during a match (CV 1.5-6.5%), although differences between observers increased with velocity of movement (Di Salvo, et al., 2009). Ultimately, the current research is limited and not applicable to the SACS most commonly used to quantify the physical outputs in professional football matches.

Multiple studies have determined the validity and reliability of GPS systems for quantifying external workload; All GPS units, regardless of sampling rate, are sufficient to track total distance covered during team sports with adequate intra-unit reliability (Aughey, 2011). High speed movements and changes of direction over short distances reduce the accuracy of the units, particularly at sampling rates of 1 and 5Hz (Kelly, Scott, & Scott, 2014). The introduction of 10Hz units markedly improved this limitation, although it is still evident, whilst 15Hz units seem to add no further benefit (Johnston, et al., 2014).

Although there is a vast body of literature on the validity and reliability of the systems, very little research has assessed the interchangeability of the two, despite this being common practice in team sports. Harley, et al. (2011) found GPS to under report high intensity activity compared to Prozone whilst overestimating total distance during match play in a stadium. However, this study was only performed on six players and without a criterion measure, making it difficult to draw conclusions about the accuracy and interchangeability of the two systems. Consequently, Buchheit, et al. (2014) compared Prozone and 5Hz GPS in a stadium during match play and pre-determined runs with 82 elite youth football players. In line with the earlier work, GPS reported lower distances at greater velocities than Prozone, whilst both systems overestimated the criterion distance, despite being strongly correlated with one another. In addition, they also found validity reduced with shorter distances and multi-directional movements. Furthermore, Prozone demonstrated a consistent overestimation of distance covered, regardless of intensity (Buchheit, et al., 2014). Whilst this suggests that the interchangeability of the two systems is task specific, these findings cannot be generalised to TRACAB and 10Hz GPS units without further research.

All EPL clubs monitor training using GPS and matches using SACS; thus ascertaining whether these systems closely reflect one another, and whether the data is valid or reliable is vital. Therefore, this study aims to assess the reliability and validity of TRACAB and StatSports (GPS) technologies within a stadium and determine any discrepancy between these systems in both a football-specific circuit representative of football constraints and during match play. It is hypothesised that both systems will be valid, reliable and interchangeable; however, the speed and complexity of the movements will affect the validity of both systems, preventing complete, accurate quantification of workload in football.

2.03 Method

2.03.1 Reliability and validity.

The primary investigation involved the assessment of the reliability and criterion validity of the two systems. Five participants (age: 28.02±9.01yrs, height: 176.20±5.07cm, mass: 74.56±6.75kg) completed three bouts of a football specific circuit. The circuit was designed to replicate match-specific movements, as well as actions where GPS had previously been deemed to be less valid and reliable. They wore a GPS unit (Apex, StatSports, Dundalk, Ireland) and were simultaneously tracked by SACS (TRACAB, ChyronHego, New York, USA). The total circuit was 260.5m involving sprints, accelerations and decelerations (linearly and whilst changing direction) jogging and high speed running. Each specific exercise was treated as a discrete activity and separated by a 10 second rest [R] in a 1mx1m square to enable accurate data extraction (Figure 8). Intensity was controlled using the following speed thresholds; low intensity distance; 0-3m/s (LID), moderate intensity distance; 3-.5.5m/s (MID), high speed running; 5.5-7m/s (HSD) and sprinting; >7m/s (SD).

The testing took place at the club's stadium in the centre of the pitch to limit satellite interference. The weather was clear with light cloud throughout the day. Participants underwent a thorough warm up before being walked through the circuit. All participants were also familiarised to the circuit a week prior to the testing. All distances were measured with a trundle wheel (Silverline, Digital Measuring Wheel, Yeovil, UK) and marked out with colour co-ordinated cones and poles for each activity. Timing gates (Brower, TC Timing System, Utah) were set up at discrete points to measure the average velocity of each high speed activity and provide instant feedback on maximal efforts to encourage full commitment (Figure 7).

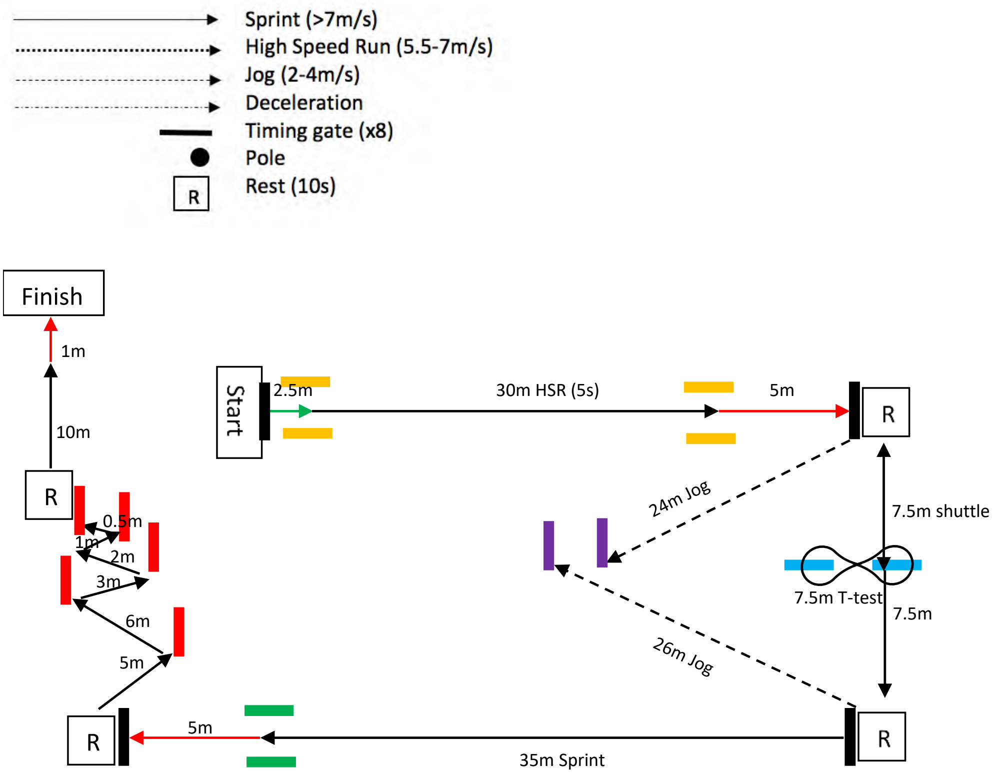

Figure 7. Circuit design used to determine the criterion validity and reliability of each system. 1) 28.5m sprint, 2) 5m deceleration, 3) 48m jog, 4) 7.5m shuttle run, 5) 30m modified T-test, 6) 2.5m deceleration, 7) 52m jog, 8) 2.5m acceleration, 9) 30m high speed run, 10) 5m deceleration, 11) 30m 'zig-zag' run, 12) 2.5m deceleration.

The GPS units were placed between the scapulae of the participants in bespoke vests. Participants wore numbered garments to enable identification by SACS. The GPS units were switched on 30 minutes prior to conducting the study and left in the centre of the pitch to allow for optimal satellite initialisation. Distances during each type of movement were analysed and the criterion distance path reported. This allows for distance comparisons across the various speeds and movements. Ethical approval was obtained from the relevant Ethics Committee.

2.03.2 System comparison during a match.

An under 21 fixture was held at the stadium. Ten players (age: 20.49±2.60yrs, height: 178.52±8.65cm, mass: 74.23±4.78kg) wore a StatSports unit and were simultaneously tracked by TRACAB throughout the game. Only players that completed 90 minutes were included for analysis (n=8). Physical performance data was analysed in the same speed zones as listed above for the circuit, as well as total distance covered (TD). Instantaneous maximal running speed (Max Speed) was also calculated throughout and peak running speeds of each player for each measurement system was reported.

2.03.3 Statistical analyses.

Linear regressions were computed with the significance level set at $p<0.05$. From this a correlation co-efficient was derived to determine the relationships between measurement systems. The standardised typical error (SEE) between measurement systems was also determined, with thresholds set at <0.1; trivial, 0.1-0.3; small, 0.3-0.6; moderate, 0.6-1.0; large, 1.0-2.0; very large, >2.0; extremely large (Hopkins, 2000). To examine the mean error of each system compared to the criterion, the bias was calculated as the mean absolute difference. Percentage bias was then determined as the bias divided by the criterion measure. Coefficient of variation (CV%) was determined for both systems as a measure of inter- and intra-reliability. Based on previous recommendations, reliability was categorised as good (<5%), moderate (5-10%) and poor (>10%) (Duthie, Pyne, & Hooper, 2003). Data was analysed using IBM SPSS Statistics 25.0 and a custom-built spreadsheet for analysis of validity and reliability (Hopkins, 2015). Data was reported as means and standard deviations.

2.04 Results

2.04.1 Football-specific circuit.

Overall, the distance covered reported by TRACAB was on average 0.44% higher than the criterion distance, whilst Statsports reported values 1.89% lower. Both systems demonstrated good reliability (CV <5%) for the total distance covered all discrete tasks (Table 1). Only the COD and Decel tasks elicited percentage (%) biases greater than 10% for both systems. The COD was underestimated by 22.62% for StatSports and 14.22% by TRACAB, whilst the Decel was overestimated by 12.48% by StatSports and 10.18% by TRACAB. However, as the CV was <5%, the biases in both systems are consistent. Significant moderate correlations were found between TRACAB and StatSports for Jog 1 and 2, T-Test, COD, and Decel ($p<0.05$). For the HSR, Shuttle and Sprint, no significant correlations between the two systems were found (Table 2). The standardised typical error (SEE) was very large to extremely large between systems for all tasks.

Maximum speed reached during the circuit was not significantly correlated between StatSports and TRACAB and showed an extremely large SEE (2.60).

Both StatSports and TRACAB demonstrated good within player reliability for all discrete tasks (CV <3), showing greater CVs for multi-directional tasks (Table 3).

Table 1. *Validity and Reliability of StatSports and TRACAB for measuring distance covered during discrete tasks of a football-specific circuit*

		StatSports			**TRACAB**		
Test	**Criterion (m)**	**Bias (m±SD)**	**%Bias (%±SD)**	**CV (%)**	**Bias (m±SD)**	**%Bias (%±SD)**	**CV (%)**
HSR	38.5	0.25 (±0.35)	0.65 (±0.92)	0.91	0.56 (±0.87)	0.11 (±1.46)	1.46
Jog 1	48	-0.35 (±0.51)	-0.73 (±1.06)	1.07	0.42 (±0.30)	0.89 (±0.62)	0.62
Shuttle	16	-1.23 (±0.47)	-7.67 (±2.96)	3.21	-1.22 (±0.49)	-7.60 (±3.08)	3.34
T-Test	33	-0.10 (±0.40)	-0.31 (±1.22)	1.22	0.57 (±0.65)	2.03 (±1.55)	1.94
Jog 2	52	0.70 (±1.06)	1.35 (±2.03)	2.00	1.77 (±0.67)	3.41 (±1.28)	1.24
Sprint	41	0.72 (±0.57)	1.75 (±1.39)	1.37	0.28 (±0.72)	0.67 (±1.75)	1.74
COD	21	-4.75 (±0.63)	-22.62 (±3.02)	3.90	-2.99 (±0.86)	-14.22 (±4.11)	4.79
Decel	11	1.37 (±0.43)	12.48 (±3.88)	3.45	1.12 (±0.18)	10.18 (±1.62)	1.12

Note: m = metres, %bias = percentage bias (bias divided by criterion), SD = standard deviation, CV = coefficient of variation, HSR = high speed running task, COD = change of direction task, Decel = deceleration task.

Table 2*. Relationships between TRACAB and StatSports distance measurements during discrete tasks of a football-specific circuit*

	HSR	**Jog 1**	**Shuttle**	**T-Test**	**Jog 2**	**Sprint**	**COD**	**Decel**
SACS	39.68 (±0.56)	48.43 (±0.30)	14.78 (±0.49)	33.57 (±0.65)	53.77 (±0.67)	41.28 (±0.72)	18.01 (±0.86)	12.12 (±0.18)
GPS	38.54 (±0.35)	47.65 (±0.51)	14.77 (±0.47)	32.90 (±0.40)	52.70 (±1.06)	41.72 (±0.57)	16.25 (±0.63)	12.37 (±0.43)
Mean diff (±SD)	-0.21 (±0.66)	0.78 (±0.44)	0.01 (±0.66)	0.67 (±0.50)	1.07 (±0.92)	-0.44 (±0.96)	1.77 (±0.72)	-0.25 (±0.37)
Mean diff (%)	0.57	1.60	1.08	1.97	1.99	1.11	9.69	2.09
Pearson's r	0.02	0.49*	0.06	0.63*	0.51*	0.10	0.58*	0.50*
SEE	>2.00	1.76	>2.00	1.23	1.69	>2.00	1.41	1.74

Note: SD = standard deviation, SEE = standardised typical error, HSR = high speed running task, COD = change of direction task, Decel = deceleration task.

Table 3*. Within player reliability of StatSports and TRACAB for each discrete task.*

Test	StatSports CV	TRACAB CV
HSR	0.53	1.61
Jog 1	0.91	0.43
Shuttle	1.70	2.82
T-Test	0.82	1.25
Jog 2	1.41	0.70
Sprint	1.04	1.37
COD	1.76	2.48
Decel	1.88	1.23

Note: CV = coefficient of variation, HSR = high speed running task, COD = change of direction task, Decel = deceleration task.

2.04.2 In game comparison.

Strong correlations were found between StatSports and TRACAB for TD, LID, MID and HSD (r=0.73-0.91, p<0.05), with moderate to large SEE (0.45-0.93). The mean % difference between the two systems was <10% for all metrics except SD, ranging from 1.62% for TD to 8.37% for MID. SD and Max Speed were not significantly correlated between the two systems and showed very large and extremely large SEE respectively (Table 4).

Table 4*. Relationships between TRACAB and StatSports in each activity zone during the match (n=10).*

	TD	LID (Z1-2)	MID (Z3-4)	HSR (Z5)	Sprint (Z6)	Max Speed
TRACAB	11495.05 (±877.28)	5989.83 (±451.01)	4721.13 (±1046.60)	640.81 (±158.37)	143.28 (±92.02)	8.34 (±0.62)
STATSPORTS	11308.33 (±851.99)	6143.38 (±395.63)	4326.15 (±732.56)	665.58 (±190.89)	173.23 (±102.31)	8.65 (±0.40)
Mean diff (±SD)	165.97 (±345.19)	-136.48 (±301.54)	351.09 (±681.74)	-22.02 (±101.77)	-21.62 (±81.09)	-0.27 (±0.76)
Mean diff (%)	1.44	2.56	8.37	3.87	20.90	3.67
Pearson's r	0.91*	0.73*	0.73*	0.82*	0.52	0.20
SEE	0.45	0.93	0.93	0.69	1.29	4.99

Note: SD = standard deviation, SEE = standardised typical error, TD = total distance, LID = low intensity distance, MID = moderate intensity distance, HSR = high speed running, max speed = maximum speed.

2.05 Discussion

The aims of this study were to determine whether GPS and SACS were valid and reliable measurement tools and to ascertain whether they could be used interchangeably when quantifying the external workload of football. Both systems were found to be valid and reliable (CV <5%) for measuring distance covered during a football-specific circuit, although multidirectional tasks reduced the validity of both systems. During match play the systems were strongly correlated (r=0.73-0.91) with low % mean differences (<10%) of distances covered at all speeds except sprint distance.

During the football-specific circuit, both systems reported a % bias lower than 10% compared to the criterion, indicative of valid measurement, except for the COD and decel. SACS underestimated the COD task by 14%, whilst GPS underestimated it by 23%. Jennings, et al., (2010) also found GPS to underestimate distance covered during tight COD tasks by 9-32%, with validity reducing with increasing velocities. Similarly, validity of a 5Hz GPS unit was markedly reduced when using GPS during a curvilinear run compared to a shuttle run, reporting a systematic underestimation (Rawstorn, et al., 2014). This was also the case for SACS, with poor-moderate accuracy for zig zag and multi-directional tasks (Buchheit, et al., 2014). Additionally, GPS and SACS overestimated the decel task by 13 and 10% respectively. This has also been demonstrated during a straight line running task, where GPS reported overestimations up to 19.3% for the deceleration (Varley, Fairweather, & Aughey, 2012). They concluded that quantification of decelerations in team sports may be limited to the number of occurrences as opposed to distance covered or duration. Therefore, as rapid accelerations, decelerations and changes of direction constitute some of the crucial aspects of match play (Di Salvo, et al., 2009), the available literature, alongside the current results suggest caution must be taken when using either GPS or SACS to evaluate the complete activity profiles of football.

Overall both systems demonstrated good reliability (<5% CV) for every task. Hence, the bias of both systems in reference to the criterion was both small and predictable, consistent with the current literature (Edgecomb & Norton, 2006). Similarly, both TRACAB and STATSPORTS demonstrated good within player reliability between trials for all tasks (<5% CV).

For both systems, accuracy and reliability were reduced during multi-directional movements, in line with previous research, most likely due to the high number of speed changes (Jennings, et al., 2010). The overestimation shown by both systems could also be associated with the difference between the measured distances of the pre-determined circuit, and the actual course taken by the participants. Whilst using human participants increases the ecological validity of the study, the effect of human error on the validity and reliability cannot be quantified (Coutts & Duffied, 2008).

The systems reported very large or extremely large SEE for all discrete tasks suggesting that the two systems were not interchangeable during the football-specific circuit. Also, similarly to Buchheit, et al. (2014) distances across the tasks were only moderately correlated between two systems. They attributed this discrepancy to the small area size used, as high speed movements over short distances demonstrated the lowest relative accuracy, as with the current study (HSR, Shuttle and Sprint demonstrated the highest SEE). Furthermore, TRACAB is designed to track players on a full pitch during match play. Therefore, data collection and analysis with TRACAB throughout the football-specific circuit was unlikely to have the same level of accuracy as applied to the match (Buchheit, et al., 2014).

Within game total distance was strongly correlated between the two systems (r=0.91) with low mean % difference of 1.44%. All other activity zones also demonstrated a strong correlation (r=0.73-0.82) and small mean % differences (<10%) except sprint distance (r=0.59, % difference=20.90%). GPS reported lower total distance than SACS but greater high speed running distances. However, as the % mean differences between the two systems for both these distances was low (<4%), this may just be a reflection of acceptable field-based within-system measurement. Crucially, the strong correlations between the two systems for these distances suggests the data can be used interchangeably.

In contrast to the findings of the current study, previous research has found GPS to under report high intensity activity compared to SACS whilst overestimating total distance during match play (Harley, et al., 2011). Furthermore, both systems reported good validity for speeds over 30-40m, however, this was markedly reduced over shorter distances and with changes of direction (Buchheit, et al., 2014). The findings of both studies may be an indication of GPS data drop out during high velocity movements, which is then interpolated by the software, resulting in underestimation of speed but overestimation of distance. One possible explanation was the obstruction of the satellite signal caused by the stadium walls; a common problem in most large football stadiums. This can result in a reduced number of satellites used or a decrease in the reliability within the signal, thus augmenting the chance of data drop out

(Anderson, 2007). Technological advancements since then may have prevented that being the case in this study. The StatSports system utilises a multi-band GNSS receiver, in combination with signal augmentation methods to enhance data quality, thus improving the validity and reliability of the system (Malone, Lovell, Varley, & Coutts, 2017). However, practitioners are advised to inspect raw velocity and acceleration traces for irregularities, particularly in sub-optimal conditions with high-rise stadia, where signal loss is more likely to occur. Future research comparing pre-determined runs in both a stadium and an open space, is required to ascertain the potential signal obstruction caused by the stadium.

During match play, sprint distance and recorded maximum speed were not significantly correlated between the two systems and reported a very large and extremely large SEE respectively. Previously, Harley, et al. (2011) reported a 40% difference in sprint distance covered during match play between GPS and SACS, concluding that the two systems should not be used interchangeably for this measure. The discrepancy between the two systems in the current study was lower than previously reported at 21%. However, in practical terms, this would still result in a variation in sprint distance ranging from 120-180m within 90 minutes of football, based on average sprint distances reported in the literature (Bradley et al., 2009). Therefore, caution must still be taken when using this data interchangeably, especially with the high SEE.

2.06 Conclusions

Based on the findings of this study both StatSports and TRACAB provide valid and reliable measurements of distance during a football specific circuit. Despite this, and in line with previous research (Jennings, et al., 2010), increases in multi-directional movements compromise the accuracy of the systems. Therefore, caution must still be taken when quantifying movements involving high intensity actions over short duration/distance and rapid changes of direction, common to football.

Within professional football, GPS and SACS are widely used interchangeably to monitor competition and training. Strong correlations and low % differences between the two systems during match play suggests that practitioners can concurrently monitor both components of external workload. However, caution must still be applied, especially when interpreting sprint distance, in order to reduce any misinterpretation resulting from both within and between system errors.

CHAPTER 3. GPS-DERIVED WORKLOAD COMPARISONS BETWEEN UNDER 18, UNDER 21 AND PREMIER LEAGUE FOOTBALL PLAYERS

3.01 Abstract

A large body of research has quantified the physical demands of football. However, to date, no studies have compared the workload demands of youth and senior players during training and match play. The purpose of the study was to compare the workloads between under 18 (U18), under 21 (U21) and senior EPL football players within one club. Workload data was collected from all training sessions and matches of 52 players over the course of one season. One-way ANOVAs were used to determine the differences in workload between the three squads for specific GPS-derived variables: Total distance (TD), low-intensity distance (LID), moderate-intensity distance (MID), high speed distance (HSD), sprint distance (SD), accelerations (ACC) and decelerations (DEC). Match outputs were not significantly different across all three squads ($p>0.05$). The U18s trained for the longest duration, but with the lowest physical outputs compared to the other two squads as a daily average. The U21s covered the least TD but most SD on a weekly basis, highlighting the sporadic nature of their training schedule. The match demands did not vary; however, squad-specific training demands were evident. This may be due to the developmental requirements of each squad, although future research using multiple clubs is required to rule out other external factors.

3.02 Introduction

Football is the most popular sport in the world with approximately 270 million people participating in the game (FIFA, 2016). However, only 110,000 players are officially registered as professional, highlighting the difficulty of reaching the elite level. For English youth players this pathway may be even more challenging due to the EPL's financial capability to attract some of the best players globally (Røynesdal, 2015). Consequently, youth players not only have to be the best in England, but in the world (Mills, et al., 2012).

Since the creation of the EPL, there has been a downward trend in home-grown player appearances from 69.4% in 1992-93 to 35.5% in 2007-08 (Bullough & Mills, 2014). To increase the opportunities for indigenous players, UEFA stipulated that from the 2008/09 season, a minimum of eight home-grown players must be registered within a 25-man squad (UEFA, 2014). To ensure this, elite youth academies in England are part of and funded by the professional clubs.

For these academies, successful development of players requires a comprehensive understanding of the demands of elite football. The physical and physiological demands have been extensively reported; Research has typically focused on match play, reporting that players cover 10-13km throughout a game, the majority of which is at a low intensity (Mohr, et al., 2003). However, anaerobic activity constitutes the more crucial aspects of the game, contributing directly to keeping possession, as well as defending and scoring goals (Reilly, et al., 2000). Thus, the amount of high intensity activity performed is the most important physical data to distinguish between top class and lower level players. A study comparing the match demands of the top three tiers of English football found that players in League 1 (third tier) and Championship (second tier) performed more high speed running (>19km/h) than those in the EPL (881, 803 and 681m, respectively) (Bradley et al., 2013). Supporting this, Di Salvo, et al. (2013) also reported greater high speed running and sprint distances for Championship compared to EPL players. High intensity activity in EPL matches has also increased over time, with both high-speed running and sprint distance increasing by over 35% across seven seasons (Bush, et al., 2015). Consequently, the game of football is constantly developing, highlighting the importance of quantifying the demands of successful performance.

To increase the chances of success and maximise player availability, training must produce adaptations within the boundaries of physical tolerance (Piggott, et al., 2009). Often these training sessions consist of small-sided games or possession drills, as they promote physical and technical development whilst aiming to replicate match demands (Little, 2009). According to review (Sarmento, et al., 2018), the majority of research has focused on the effect of various conditions such as pitch size, number of players, type of drill, rules and motivation on the outputs of these sessions. More recently, research has described the periodisation of training throughout the week, finding the day before the match to show the lowest outputs, although the hardest training day varied between teams (Akenhead, et al., 2016; Anderson, et al., 2016, Malone, et al., 2015). A study in elite Dutch football has recently analysed both training and match demands, finding that total weekly workload is equivalent to ~3.5 matches for accelerations and ~2.1 matches for high speed running (Stevens, de Ruiter, Twisk, Savelsbergh, & Beek, 2017). However, match data was only collected from three non-competitive matches, making it difficult to generalise the findings to seasonal competitive match play. Therefore, whilst the body of research around training demands is growing, it still remains unclear how physically conditioned a player must be to cope with the training and match play demands of senior professional football.

A number of studies have also quantified the physical match demands of youth football, with a general focus on comparison across age groups. In under 12s to under 16s, match activity increased in absolute terms (m) with age, due to pitch sizes, match duration and rolling substitutions. However, in relative terms (m/min) it remained consistent (Harley, et al., 2010). Similarly, Buchheit, Mendez-Villanueva, Simpson and Bourdon (2010) found no differences in running distances between under 14s, 15s, 16s and 17s when adjusted for playing time. The only significant difference was at sprint speed, where the older players (under 18s) covered significantly more than the younger players (under 13-17). Contrastingly, recent research suggests competition outputs do increase with age until 16-17 years old, highlighting a potential effect of maturity (Saward, Morris, Nevill, Nevill & Sunderland, 2016). Thus, disagreement in the literature exists regarding age and maturity as determinants of physical outputs in youth football matches.

Training demands have been found to increase with age in youth football. Abade, Gonçalves, Leite and Sampaio (2014) reported lower training demands for under 15s, with a greater focus on technical and tactical demands than under 17 and under 19 elite level Portuguese players, where the training replicated physiological match demands more closely. Whilst this study provides an insight into the overall training demands of youth players at one club, as with the research on senior players, the current literature focuses mainly on the physiological responses to small sided games, using small sample sizes (Sarmento, et al., 2018). Consequently, there is no consensus on the most effective training stimuli for developmental and competitive success.

Despite this substantial body of literature and the importance of elite player development, to date, no studies have compared both the training and match demands of youth and senior players within an EPL club. The present study aims to compare the physical demands of under 18 (U18), under 21 (U21) and senior football players at a professional football club during training and competition. It is hypothesised that the younger players will train more often, but at a lower intensity than the senior players due to the focus on development over performance in the academy. It is also hypothesised that the senior players will produce higher physical outputs during competition than the younger players.

3.03 Method

3.03.1 Participants.

Data was collected from senior and professional development football players (n=52) from one EPL club. The participants were categorised into three groups; seniors, U21s and U18s (Table 5). The players trained on a full-time basis and played competitive fixtures within the Premier League, Premier League 2 or U18 Premier League during the 2015-16 season. Goalkeepers were excluded from the study due to the different nature of their activity. Ethical approval was obtained from the Research Ethics Committee of The University of Birmingham.

Table 5. Participant characteristics.

Squad	n	Age (years)	Stature (cm)	Body Mass (kg)
Seniors	20	25.2±3.3	180.8±7.9	80.1±94
Under 21s	12	19.3±0.9	180.4±7.7	76.7±7.0
Under 18s	20	17.0±0.0	178.9±6.8	74.2±5.8

3.03.2 Quantifying workload.

Workload was quantified using GPS, with data collected from all on-pitch training sessions and professional development matches. The GPS units (Viper 2, StatSports, Ireland) sampled at 10Hz. Following each session, the data was downloaded into the specialised analysis software (Viper, 2.6.1.49). For sessions when GPS data was unavailable for a participant (Senior: n=163 of 2,865; 6%, U21: n=55 of 1,519; 4%, U18: n=57 of 3,149; 2%) as a result of them not wearing a unit, not completing the entire session or the data being deemed unreliable due to intermittent satellite signal, data was estimated as follows:

Main training session data: estimated by calculating squad averages for drills completed.

Game data: estimated using individual season game averages (from a minimum of 3 matches) whilst considering individual game time.

From the start of the 2015/16 season, GPS use was permitted in EPL competition. Despite this, the obstruction caused by stadium walls can limit the number of accessible satellites, causing intermittent satellite signal, or reduce the reliability of the signals that are received (Nur, Feng, Ling, & Ochieng, 2013). Therefore, in this study EPL match data was recorded using SACS (TRACAB, ChyronHego, New York, USA). The SACS tracks player movement in true real time through fixed cameras installed around the stadium. The video stream from the cameras was analysed through the TRACAB Image Tracking SystemTM, producing a data file (XML) of X, Y and Z co-ordinates, as well as speed and acceleration of the players. This data was then imported into the aforementioned GPS analysis software (Viper, 2.6.1.49). Chapter 2 demonstrates the interchangeability of GPS and SACS providing the correct calibrating algorithms are used. The variables defined in Table 6 were selected for use in this study due to their relevance to football demands. All variables were taken from the StatSports software (Viper).

Table 6. *Definition of GPS variables.*

Variable	Definition
Total Distance (TD)	Total distance covered (m)
Low Intensity Distance (LID)	Total distance covered (m) between 0-3m/s
Moderate Intensity Distance (MID)	Total distance covered (m) between 3-5.5m/s
High Speed Distance (HSD)	Total distance covered (m) between 5.5-7m/s
Sprint Distance (SD)	Total distance covered (m) above 7m/s
Accelerations (ACC)	An increase in GPS speed data for at least half a second with maximum acceleration in the period at least 0.5m/s/s
Decelerations (DEC)	A decrease in GPS speed data for at least half a second with maximum deceleration in the period at least 0.5m/s/s

3.03.3 Data analyses.

Across the three groups, 129 matches (Seniors; n=59, U21s; n=33, U18s; n=37) and 507 training sessions (Seniors; n=191, U21s; n=118, U18s; n=141, U21s and U18s combined; n=57) were analysed over an entire season, resulting in a total of 7,533 cases. The average daily and weekly training demands were compared between the groups as well as competition demands. For match data comparisons, only players who had completed the entire game (90 minutes) were included. All variables in Table 6 were analysed in both absolute and relative (per minute) terms.

3.03.4 Statistical analyses.

The data are presented as mean ± SD. One-way ANOVAs were performed to identify the differences in workload across the groups for the variables described in Table 1. Pairwise differences and post hoc comparisons were tested with Bonferroni post hoc test. Data was analysed using IBM SPSS Statistics 25.0 with significance accepted at $p<0.05$.

3.04 Results

3.04.1 Match workloads.

No differences were found between the match outputs of the three squads for any GPS metric except ACC ($F(2,47)=9.96$, $p=0.00$). Post-hoc analysis revealed that the seniors performed significantly more ACC than both academy squads (797±80 vs 704±87 (U18s) and 692±67 (U21s), $p=0.00$). Table 7 shows the means and standard deviations for the measured metrics of each squad during matches.

3.04.2 Daily training workloads.

Daily workloads varied significantly between the three squads for all GPS metrics except MID. The U18s trained for the longest duration (68±2mins), followed by the U21s (66±2mins) and then the seniors (65±1mins) ($p=0.00$). A significant difference was found between the squads for TD ($F(2,49)=13.77$, $p=0.00$), HSD ($F(2,49)=7.51$, $p=0.00$) and LID ($F(2,49)=5.21$, $p=0.01$) during training. Post-hoc analysis revealed that the U18s covered significantly less TD, LID and HSD than the seniors and U21s, who did not differ from each other. In an average training session the U21s covered more SD (F(2,49)=14.70, p=0.00) than both the seniors and the U18s (45±10m vs 31±9m and 26±11m, respectively). They also performed more ACC and DEC than the U18s (372±17 and 340±19 vs 340±23 and 313±22, p<0.05). Whilst there were no differences between the seniors and U21s for max speed, the U18s performed max speeds significantly lower than the seniors in training (9.19±0.39m/s vs 9.55±0.31m/s, p=0.014). Table 8 shows the means and standard deviations for the measured metrics of each squad during training sessions.

Table 7. *Match outputs for the three squads represented as means and standard deviations.*

	TD (m)	LID (m)	MID (m)	HSD (m)	SD (m)	ACC (no.)	DEC (no.)	Max Speed (m/s)
Seniors	10490 ±823	5943 ±670	2010 ±411	518 ±143	155 ±95	797^{b,c} ±80	689 ±66	9.12 ±0.40
U21s	10132 ±447	5562 ±459	2051 ±250	545 ±137	167 ±63	692^{a} ±67	641 ±63	9.00 ±0.37
U18s	10480 ±698	5790 ±630	2241 ±374	545 ±131	109 ±54	704^{a} ±87	659 ±79	8.97 ±0.40

Note: TD=total distance covered, LID=low intensity distance covered between 0-3m/s, MID=moderate intensity distance covered between 3-5.5m/s, HSD=high speed distance covered between 5.5-7m/s, SD=sprint distance covered between >7m/s, ACC=count of accelerations, DEC=count of decelerations, a=significant difference vs seniors (p<0.05), b=vs U21, c=vs U18.

Table 8. *Daily training outputs for the three squads represented as means and standard deviations.*

	Duration (mins)	TD (m)	LID (m)	MID (m)	HSD (m)	SD (m)	ACC (no.)	DEC (no.)	Max Speed (m/s)
Seniors	$65^{b,c}$ ±1	4519^{c} ±234	2278^{c} ±196	622 ±80	163^{c} ±29	31^{b} ±9	354 ±22	325 ±22	9.55^{c} ±0.39
U21s	$66^{a,c}$ ±2	4454^{c} ±275	2215^{c} ±183	622 ±86	163^{c} ±30	$45^{a,c}$ ±10	372^{c} ±17	340^{c} ±19	9.49 ±0.43
U18s	$68^{a,b}$ ±2	$4119^{a,b}$ ±309	$2049^{a,b}$ ±212	611 ±76	$136^{a,b}$ ±31	26^{b} ±11	340^{b} ±23	313^{b} ±22	9.19^{a} ±0.39

Note: TD=total distance covered, LID=low intensity distance covered between 0-3m/s, MID=moderate intensity distance covered between 3-5.5m/s, HSD=high speed distance covered between 5.5-7m/s, SD=sprint distance covered between >7m/s, ACC=count of accelerations, DEC=count of decelerations, a=significant difference vs seniors ($p<0.05$), b=vs U21, c=vs U18.

3.04.3 Relative daily training workloads (per minute).

Workloads per minute were significantly different between all three squads. The seniors covered significantly more TD and LID than the U21s and then the U18s (TD: F(2, 49)=36.42, LID: F(2,49)=81.86, p=0.00). The U18s performed significantly less HSD than the other two squads (1.20±0.39m vs seniors; 2.51±0.43m, p=0.00, U21s; 2.45±0.40m, p=0.01). The U21s did significantly more SD per minute than the other two squads (0.68±0.14m vs seniors; 0.48±0.13m, p=0.00, U18s; 0.38±0.15m, p=0.00). Figure 8 shows the distance covered per minute at the various speeds across the three squads. ACC and DEC also varied significantly across the three squads (ACC; 14.22, p=0.00, DEC; 11.57, p=0.00). Post-hoc analysis revealed that the U18s did significantly less ACC and DEC per min than the other two squads (5.02±0.36 and 4.61±0.40 vs seniors; 5.46±0.35 and 5.01±0.34, p=0.00, U21s; 5.62±0.31 and 5.14±0.30, p=0.00).

3.04.4 Weekly training workloads.

Over the course of a week the training duration varied significantly between the squads (F(2,49)=33.42, p=0.00), with the U18s training for significantly longer than the other two squads (335±16mins vs seniors; 298±14mins and U21s; 296±20mins). The U21s covered significantly less TD than the seniors and U18s (21,501±1,477m vs seniors; 23,290±1,656m, p=0.01, U18s; 23,083±1,672m, p=0.03) who were not significantly different to each other (p=1.00). The only other GPS metric that varied significantly between the squads across a week was SD (F(2,49)=5.09, p=0.01). Post-hoc analysis revealed that the U21s covered more SD than the U18s (265±61m vs 178±69m, p=0.01), whilst the seniors did not differ significantly for either squad. Table 5 shows the means and standard deviations of the weekly workloads for each squad.

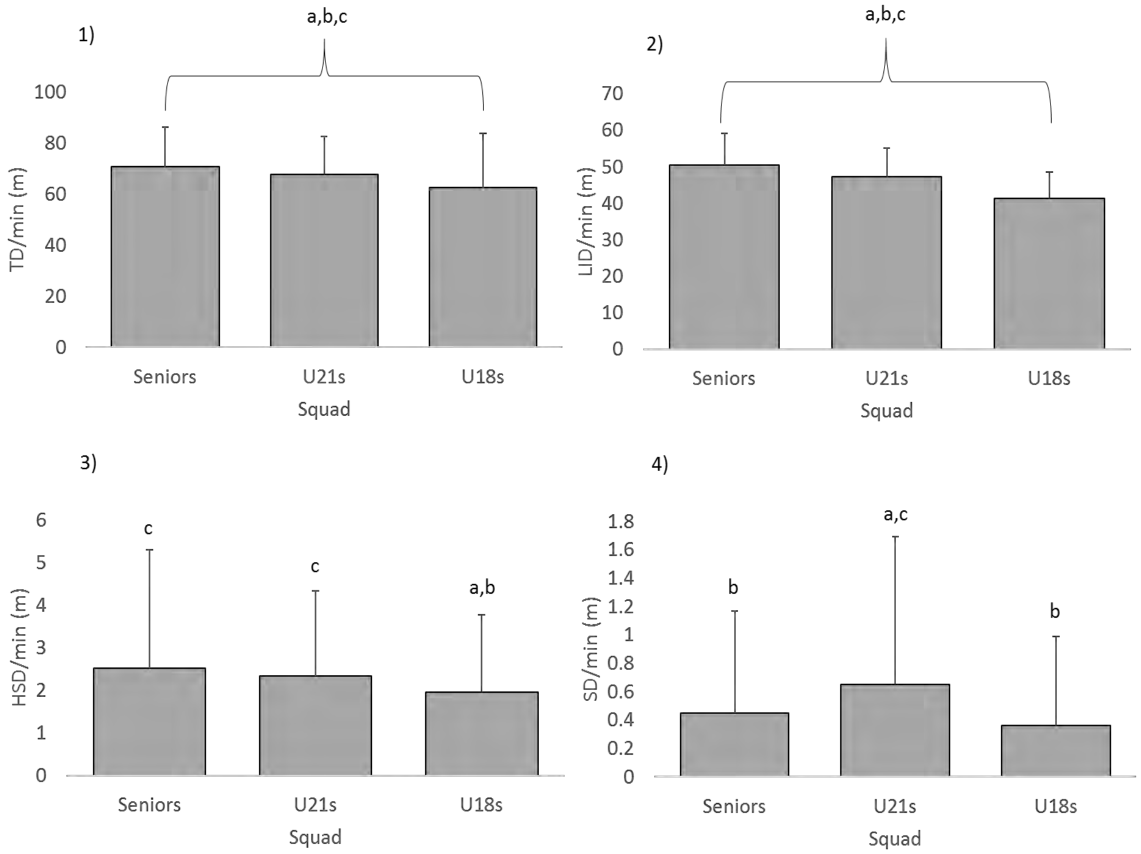

Figure 8. Differences in distance covered at various speeds between the Under U18s, Under 21s and senior teams. TD = total distance, LID = low intensity distance, HSD = high intensity distance, SD = sprint distance, a= significantly different to the seniors (p<0.05), b= significantly different to the U21s (p<0.05), c= significantly different to U18s (p<0.05).

Table 9. *Weekly training outputs for the three squads represented as means and standard deviations.*

	Duration (mins)	TD (m)	LID(m)	MID (m)	HSD (m)	SD (m)	ACC (no.)	DEC (no.)
1sts	298 ±14^{c}	23290^{b} ±1656	12224 ±1157	3636 ±456	952 ±179	219 ±89	1803 ±145	1631 ±124
U21s	296 ±20^{c}	21501^{a,c} ±1477	11591 ±962	3476 ±426	917 ±161	265^{c} ±61	1714 ±101	1677 ±92
U18s	335 ±16^{a,b}	23083^{b} ±1749	11930 ±1280	3856 ±462	901 ±172	178^{b} ±81	1806 ±137	1698 ±146

Note: TD=total distance covered, Z1=distance covered between 0-1.5m/s, Z2=distance covered between 1.5-3m/s, Z3=distance covered between 3-4m/s, Z4=distance covered between 4-5.5m/s, Z5=distance covered between 5.5-7m/s, Z6=distance covered between >7m/s, ACC=count of accelerations, DEC=count of decelerations, a=significant difference vs 1st team ($p<0.05$), b=vs U21, c=vs U18.

3.05 Discussion

This was the first study to quantify and compare the training and competition demands of the professional development phase (U18s and U21s squads) and the senior squad within one football club. Match demands were similar between the three squads, whilst the training demands varied significantly.

There was very little difference in physical outputs between the U18s, U21s and seniors during match play. Only ACC showed a significant difference, with the senior players performing more than the academy teams. To the authors' knowledge, there are no papers comparing match demands between youth and seniors; however, research analysing the effect of age/maturity on the physical demands of youth matches has reported contrasting conclusions. Buchheit, et al. (2010), assessed the differences in match demands from U13s to U18s. They found only very small differences when the measured outcomes were adjusted for playing time, concluding that age/maturity are not major determinants of physical match requirements. A more recent study supported this, finding no differences in the match running intensities of 96 elite junior football players between U15 and U17 (Duthie, Thornton, Delaney, Connolly & Serpiello, 2018). In contrast, another study found that total distance, high speed running and sprinting in competition did increase with age, until 16-17 years, when a plateau or slight decrease occurred (Saward, et al., 2016). Research on 36 under-15 football players found maturity to have a greater effect on match running performance than age or body size (Buchheit & Mendez-Villanueva, 2014). In the current study, all players were over the age of 16, and therefore close to or at complete physical maturity (NHS, 2016). Furthermore, the match outputs of this study were similar to those of other major European leagues (e.g. Bradley, et al., 2013; Ingebrigtsen, Dalen, Hjelde, Drust & Wisløff, 2015; Stevens, et al., 2017), highlighting the elite-standard of physical match performance at this EPL academy. Therefore, once full maturity is reached, any potential differences in match demands may no longer exist. However, future research is required comparing maturity vs tactical implications on physical match demands from youth to senior football.

Despite the similarities in match demands, the training outputs of the three squads were significantly different across a number of measures. Overall, the U18s trained for a longer duration than the other two squads but covered less TD, LID and HSD as a daily average, both in absolute terms and per minute. In addition, the U18s recorded the lowest max speeds during training. Thus, the physiological demand of the training sessions was less despite the increased duration. One potential explanation is the greater focus on technical skill development and tactical understanding in the younger age group, resulting in greater coach intervention (Abade, et al., 2014). According to FIFA's "Youth Football" document (n.d.), training for the U18s squad is an opportunity to learn, reinforce and develop the key technical, tactical, physical and mental requirements of the game. This development focused and coach led training environment is further supported by the U18s covering a greater distance than U21s over the course of a week, despite the daily average being lower. This demonstrates that they completed a higher number of sessions, but with lower physical demand per session. Ultimately, as the understanding of football increases with age and experience, less time is spent on the explanation of drills, and more on the execution.

The U21s performed more ACC and DEC on average in a complete training session than the U18s both in absolute and relative terms. Therefore, both the intensity and volume of ACC and DEC increased from U18s to U21s. In addition, the U21s displayed the greatest SD values, both daily and weekly. However, they covered significantly less distance than both the seniors and the U18s over a week, as well as trained for the lowest total weekly duration. The combination of these findings may be a result of the sporadic training schedule of this squad. As they are required to occasionally train with the senior team, they often miss out on a regular training schedule (FIFA, n.d.). In addition, three over-aged outfield players are able to compete in the Premier League 2 (U23 League) (Premier League, 2018), reducing the opportunities for playing time for the U21 players (Vaeyens, Coutts & Philppaerts, 2005). Thus, maintaining fitness across this particular squad is difficult with a wide variance in exposure to workload; Typically, all players still get 1-2 recovery days a week, regardless of whether or not they play (Anderson et al., 2016), and therefore additional physical conditioning for the non-starters must be scheduled around team training or after matches, limiting duration, volume and content (Stevens, et al., 2017).

Furthermore, the small squad size at this age group due to players being called up to the seniors or going out on loan further restricts the training content. Consequently, training sessions for this squad are regularly comprised of small-sided games, with low team numbers and tight pitch sizes. These conditions have been found to increase ball touches, dribbles and duels, which in turn heighten ACC and DEC outputs (Martin-Garcia, Gomez Diaz, Bradley, Morera, & Casamichana, 2018). These were supplemented with individualised running drills to ensure high speed running and sprint qualities were also developed, in order to more effectively prepare the players for match demands (Windt, Ekstrand, Khan, McCall & Zumbo, 2018). The top up drills potentially explain the heightened high intensity distances for the U21s over the course of a week, despite lower total distances than the U18s or seniors.

Training at the senior level often replicates game situations, hence the greater TD and LID per minute compared to the other two squads. The lower SD per minute in the seniors, could be attributed to the intermittent, tactical nature of training, to make adjustments based on the more readily available opposition statistics at the highest level (Rein & Memmert, 2016). Additionally, the focus of the senior team training is to ensure performance success, whereas the U18 and U21 teams focus on the development of future talent (Vaeyens, et al., 2005). To augment the chance of this success, workloads must stimulate adaptation without exceeding individual physical capacity (Piggott, et al., 2009). With the fast-paced, fixture congested-nature of the EPL, finding the balance between training, competition and recovery is crucial to optimum performance (Bowen, Gross, Gimpel & Li, 2017). Consequently, training sessions involving higher intensity movement such as sprinting, are periodised furthest away from the game, to allow for adequate recovery and adaptation to take place. This periodisation of SD explains why the senior team have lower SD/min in an average training session, but not a lower weekly total than the U21s.

As this study was conducted on three squads from one club, it is difficult to determine whether training differences exist due to age, or whether the identified variations were due to other factors such as coaching styles, fixture schedules or squad sizes. Whilst the findings are in line with the hypotheses, indicating an age related effect; future research using data from multiple clubs is required to confirm this.

Regardless of the variations in training demands, all squads performed the equivalent of approximately two games worth of TD, ACC and DEC within a week of training, as well as 1.5 games worth of HSD and SD. Similarly, when match workloads were included, Stevens, et al. (2017) reported total weekly workload values of 3-4 games worth for accelerations and 2-2.5 games worth for running. These findings highlight the importance of playing time on physiological workload, and the need to provide game-simulating training for players not in the squad, to maintain fitness and workload tolerance.

A complete understanding of the weekly workloads of senior players has previously been limited due to studies having only assessed training workload, or used extrapolations of incomplete games to increase the match data available (Stevens, et al., 2017). This study has attempted to overcome this by including all match data. However, as the senior team match data was collected using a different system than training or academy matches, the precision and sensitivity of the data maybe decreased, despite it being calibrated to maximize between system agreements

(Buchheit, et al., 2014). With technological advancements, and the recent admittance of GPS in league matches, future research should aim to use a single monitoring system for both competition and training.

Furthermore, as all squads were exposed to a similar amount of workload in reference to a game throughout a week, it is impossible to deduce from this study whether one age group, training focus or coaching style best prepares athletes for transitions to senior football or competition success at the top level. Future research should assess the effect of various weekly workloads on match performance.

3.06 Conclusions

In conclusion, contrary to the hypothesis, there were no differences in match physical outputs between the U18s, U21s and senior team. This study suggests that at the elite level, any age-related differences no longer exist once full maturity is reached. However, various training differences were identified both on a daily and weekly basis. It appears that these differences are due to the developmental or performance requirements specific to each squad; although further research using players from multiple clubs is required to eliminate the influence of different coaching styles etc. on physical demands. This study provides an initial insight into the physical requirements at both the youth and senior levels of EPL football, however caution must be applied when generalising these findings to other clubs.

CHAPTER 4. ACCUMULATED WORKLOADS AND THE ACUTE:CHRONIC WORKLOAD RATIO RELATE TO INJURY RISK IN ELITE YOUTH FOOTBALL PLAYERS

4.01 Abstract

The purpose of this study was to investigate the relationship between physical workload and injury risk in elite youth football players. The workload data and injury incidence of 32 players were monitored throughout 2 seasons. Multiple regressions were used to compare cumulative (1, 2, 3 and 4-weekly) workloads and acute:chronic workload ratios (ACWR) (acute workload divided by chronic workload) between injured and non-injured players for specific GPS and accelerometer-derived variables: total distance (TD), high-speed distance (HSD), accelerations (ACC) and total load (TL). Workloads were classified into discrete ranges by z-scores and the relative risk was determined. A very high number of ACC (≥9254) over 3 weeks was associated with the highest significant overall (relative risk (RR)=3.84) and non-contact injury risk (RR=5.11). Non-contact injury risk was significantly increased when a high acute HSD was combined with low chronic HSD (RR=2.55), but not with high chronic HSD (RR=0.47). Contact injury risk was greatest when ACWR TD and ACC were very high (1.76 and 1.77, respectively) (RR=4.98). In general, higher accumulated and acute workloads were associated with a greater injury risk. However, progressive increases in chronic workload may develop the players' physical tolerance to higher acute workloads and resilience to injury risk.

4.02 Introduction

An appropriate balance between training, competition and recovery is required to attain peak performance and injury avoidance (Gabbett & Domrow, 2007). However, this balance is not always adequately maintained, as highlighted by the higher injury rate in football than in many other team sports (Koutoures & Gregory, 2010). Thus, understanding and monitoring the training programmes of football players is vital to ensure that the optimal workload is implemented (Piggott, et al., 2009). Ultimately, this will potentially increase positive training adaptations and reduce the prevalence of injury in football (Rogalski, et al., 2013).

The introduction of GPS into sports has led to many studies which objectively quantify workloads. However, despite growing interest, research into the relationship between these workloads and injury is still in its infancy. A higher injury risk has been found with increased acute GPS-derived workloads in Australian football and rugby league (Piggott, et al., 2009; Gabbett & Ullah, 2012). Research conducted over a longer period of time with larger sample sizes was required to further understand the injury–workload relationship. Consequently, Colby, et al., (2014) examined the relationship between accumulated GPS and accelerometer-derived workloads and injury in Australian football players. During both the preseason and in season, 3-weekly workloads were indicative of a greater injury risk. Ultimately, studies must consider the effect of the accumulation of workload to fully understand the relationship between injury and workload.

Furthermore, because of the individual physiological responses to movement demands in football (Hunter, et al., 2015), categorising risk by absolute workloads alone may not completely explain relationships with injury across all players. Previous studies examining the relationship between workload and performance have assessed the absolute 1-week workload (acute workload) relative to 4-week chronic workload (4-week average acute workload) (Hulin, et al., 2014). An ACWR can then be calculated, indicating whether the individual's acute workload is greater than, less than or equal to the preceding chronic workload they have been prepared for (Hulin, et al., 2016).

The 'Training-Injury Prevention Paradox' recently proposed that the prescription of workload may be more indicative of injury than the workload itself (Gabbett, 2016). Excessive, rapid increases in workload were speculated to heighten the risk of injury, whereas chronic exposure to higher workloads augmented the physical capacities of the athletes making them more resilient to injury, while also enhancing performance (Gabbett, 2016). Thus, the assessment of the ACWR, for high and low chronic workloads, may provide a more comprehensive monitoring of injury risk than absolute workload alone. Evidence of this has been demonstrated in Australian League football (soccer), where metres per minute in the 1 and 4 weeks prior to injury were significantly higher than the seasonal average (Erhmann, et al., 2016). Although this was the first study to examine the relationship between GPS-derived workloads and injury in football, only 16 injuries were analysed and match data were not recorded, consequently warranting further research.

Despite the inflated injury incidence (Koutoures & Gregory, 2010) and physical demands of the sport (Barnes, et al., 2014), to date, there is very limited research exploring the relationships between GPS-derived/accelerometer-derived workload and injury risk. Therefore, this study aimed to examine the relationships between accumulated workloads and ACWRs with injury risk in elite youth football players across two seasons.

4.03 Methods

4.03.1 Participants.

Data were collected from elite youth football players (n=32) from one EPL category 1 academy (age: 17.3±0.9 years, stature: 180.0±7.3 cm, body mass: 74.1±7.0 kg). The players trained on a full-time basis and played competitive fixtures within the Under 18 or Under 21 EPL during the 2013–2014 and 2014–2015 seasons. Twenty (63%) participants competed in both seasons and 12 (38%) participants competed in one season—resulting in 52 individual football seasons. Goalkeepers were excluded from the study due to the different nature of their activity. Ethical approval was obtained from the Research Ethics Committee of The University of Birmingham.

4.03.2 Quantifying workload.

Workload was quantified using GPS, with data collected from all on-pitch training sessions and matches. The GPS units (Viper V.2, StatSports, Ireland) were placed between the scapulae of the players in bespoke vests. These units sampled at 10 Hz and the accelerometers at 100 Hz. Following each session, the data were downloaded using the specialised analysis software (Viper, V.2.1.3.0). For sessions when GPS data were unavailable for a participant (n=480 of 12 117; 4%) because he was not wearing a unit, he could not complete the entire session or the data were deemed unreliable due to the intermittent satellite signal; the data were estimated as follows:

Main training session data were estimated by calculating squad averages for drills completed. Game data were estimated using individual season game averages (from a minimum of three matches) while considering individual game time. The variables defined in Table 10 were selected for use in this study due to their relevance to running workloads (and potential injury). All the variables were obtained from the StatSports software (Viper).

Table 10. *Definition of GPS variables.*

Variable	Definition
TD	Total distance covered (m): this includes walking, jogging, fast running and sprinting
HSD	Total distance covered (m) above 20km/h
TL	Total of the forces on the player over the entire session based on accelerometer data alone $\surd((acat=i+1 - acat=i)2+(aclt=i+1 - aclt=i)2+(acvt=i+1 - acvt=i)2)$ *Where aca is acceleration along the anterior-posterior axis, acl is acceleration along the lateral axis and acv is acceleration along the vertical axis, i is current time and t is time. This is then scaled by 1,000.*
ACC	A change in GPS speed data for at least half a second with maximum acceleration in the period at least 0.5m/s/s

Note: ACC, accelerations; GPS, global positioning system; HSD, high-speed distance; TD, total distance; TL, total load.

4.03.3 Definition of injury.

Injury information was classified by the academy doctor and senior chartered physiotherapists, collated, then updated in the club’s database. A recordable injury was defined as one that caused any absence from future football participation (Fuller, et al., 2006). Injuries were classified as follows: minimal (1–3 days of football activity missed), mild (4–7 days of football activity missed), moderate (1–4 weeks of football activity missed) or severe (4+ weeks of football activity missed) (Fuller, et al., 2006).

Injuries were also categorised by injury type (description) and body site (injury location). The mechanism in which a participant acquired an injury was also classified as being non-contact or contact in nature.

4.03.4 Data analyses.

Data were categorised in weekly blocks from Monday to Sunday. Every time a player participated in a training session or match, and data were analysed in two ways. First, the previous 1-weekly, 2-weekly, 3-weekly and 4-weekly workloads were calculated. The workloads were then classified into discrete ranges from very low through to very high using z-scores (Wang & Chen, 2012) (Table 11). The relationships between these weekly cumulative workloads and subsequent injury were investigated. Second, acute workload was calculated as 1-week workload and chronic workload as the 4-week rolling average acute workload. The ACWR was calculated by dividing the acute workload by the chronic workload (Hulin, et al., 2014). A value of >1 represents an acute workload greater than the chronic workload and vice versa. Chronic workloads were also separated into high and low categories by the median score for each variable (Hulin, et al., 2016). From this, injury–workload relationships between ACWRs combined with high and low chronic workloads were analysed. As with accumulated workloads, the ratios were categorised based on z-scores (Table 12).

4.03.5 Statistical analyses.

The analysis was performed in a manner similar to the previous work of Colby, et al., (2014) and Hulin, et al., (2016) Injury incidence was determined by dividing total number of injuries by the ‘on-legs’ exposure time and reported as rates per 1000 hours (h). Injury risks were calculated as the number of injuries sustained relative to the number of exposures to each workload classification (Fuller, et al., 2006). Exposure data were recorded as per the consensus statement on data collection procedures outlined by the Fédération de Football Association Medical Assessment Research Centre (F-MARC) (Fuller, et al., 2006). A binary logistic regression model was used to compare workloads between injured and non-injured players for all GPS/accelerometer variables. Accumulated workload and ACWRs were independently modelled as predictor variables. Relative risk (RR) was calculated to determine the injury risk above and below given workloads or ratios. When a RR was greater than 1.00, an increased risk of injury was reported (ie, RR=1.50 is indicative of a 50% increased risk) and vice versa. For a RR to be significant, 95% CIs did not contain the null RR of 1.00. Data were analysed using IBM SPSS Statistics V.21.0 and reported as means and 95% CI. Significance was accepted at $p<0.05$.

Table 11. *Workload classifications and boundaries for accumulated workloads over 1 to 4 weeks.*

			No. of Weeks Accumulated			
	Classification	Z-Score	1	2	3	4
TD (m)	Low	-1.99 to -1.00	0-8,811	2,741-21271	9,334-34,841	17,555-49,034
	Mod-Low	-0.99 to 0.00	8,812-19,758	21,272-39,805	34,842-60,061	49,035-80,723
	Mod-High	0.00 to 0.99	19,759-30,714	39,806-58,405	60,062-85,549	80,724-112,243
	High	1.00 to 1.99	30,715-39,425	58,406-75,104	85,550-108,919	112,244-143-917
	Very High	≥2.00	39,426	75,105	108,920	143,918
HSD (m)	Low	-1.99 to -1.00	0-261	0-755	0-1,294	266-1,886
	Mod-Low	-0.99 to 0.00	262-855	756-1,726	1,295-2,609	1,887-3,501
	Mod-High	0.00 to 0.99	856-1,448	1,727-2,697	2,610-3,922	3,502-5,122
	High	1.00 to 1.99	1,449-2,047	2,698-3,675	3,923-5,254	5,123-6,740
	Very High	≥2.00	2,048	3,676	5,255	6,741
ACC (no.)	Low	-1.99 to -1.00	0-721	211-1,751	744-2,861	1,417-4,049
	Mod-Low	-0.99 to 0.00	722-1,640	1,752-3,329	2,862-4,987	4,050-6,688
	Mod-High	0.00 to 0.99	1,641-2,557	3,330-4,860	4,988-7,110	6,689-9,330
	High	1.00 to 1.99	2,558-3,474	4,861-6,485	7,111-9,253	9,331-11,982
	Very High	≥2.00	3,475	6,486	9,254	11,983
TL (AU)	Low	-1.99 to -1.00	0-129	32-319	130-525	256-743
	Mod-Low	-0.99 to 0.00	130-301	320-608	526-919	744-1,234
	Mod-High	0.00 to 0.99	302-473	609-898	920-1,314	1,235-1,727
	High	1.00 to 1.99	474-647	899-1,187	1315-1,709	1,728-2,222
	Very High	≥2.00	648	1,188	1,710	2,223

Note: TD = total distance in metres (m), HSD = high speed distance in metres (m), ACC = number of accelerations (no.), TL = total load in arbitrary units (AU).

Table 12. *Workload classifications and boundaries for: (A) acute:chronic workload ratios overall, (B) acute:chronic workload ratios combined with low chronic workloads and (C) acute:chronic workload ratios combined with high chronic workloads.*

	Classification	Z-Score	(A)	(B)	(C)
				(<22,335m)	(>22,335m)
TD (m)	Low	-1.99 to -1.00	0.04-0.43	0.00-0.31	0.28-0.59
	Mod-Low	-0.99 to 0.00	0.44-0.87	0.32-0.83	0.60-0.91
	Mod-High	0.00 to 0.99	0.88-1.31	0.84-1.35	0.92-1.24
	High	1.00 to 1.99	1.32-1.75	1.36-1.70	1.25-1.57
	Very High	≥2.00	1.76	1.71	1.58
				(<938m)	(>938m)
HSD (m)	Low	-1.99 to -1.00	0.00-0.35	0.00-0.26	0.11-0.46
	Mod-Low	-0.99 to 0.00	0.36-0.86	0.27-0.83	0.47-0.90
	Mod-High	0.00 to 0.99	0.87-1.38	0.84-1.40	0.91-1.33
	High	1.00 to 1.99	1.39-1.88	1.41-1.96	1.34-1.77
	Very High	≥2.00	1.89	1.97	1.78
				(<1856)	(>1856)
ACC (no.)	Low	-1.99 to -1.00	0.05-0.44	0.00-0.32	0.26-0.57
	Mod-Low	-0.99 to 0.00	0.45-0.87	0.33-0.84	0.58-0.91
	Mod-High	0.00 to 0.99	0.88-1.31	0.85-1.36	0.92-1.24
	High	1.00 to 1.99	1.32-1.76	1.37-1.89	1.25-1.59
	Very High	≥2.00	1.77	1.90	1.60
				(<344AU)	(>344AU)
TL (AU)	Low	-1.99 to -1.00	0.03-0.43	0.00-0.31	0.26-0.59
	Mod-Low	-0.99 to 0.00	0.44-0.87	0.32-0.83	0.60-0.92
	Mod-High	0.00 to 0.99	0.88-1.31	0.84-1.35	0.93-1.25
	High	1.00 to 1.99	1.32-1.75	1.36-1.86	1.26-1.57
	Very High	≥2.00	1.76	1.87	1.58

Note: TD = total distance in metres (m), HSD = high speed distance in metres (m), ACC = number of accelerations (no.), TL = total load in arbitrary units (AU).

4.04 Results

4.04.1 Injury incidence.

A total of 138 injuries (12.1/1000h) were recorded for the duration of this study (2013–2014, 13.8/1000h; 2014–2015, 10.1/1000h), including contact and non-contact injuries (Appendix A). The ankle/foot (4.7/1000h) was the most common site of contact and non-contact injury over the two seasons, with the most common types of contact injury being haematoma/contusion (3.8/1000h) and non-contact injury being ligament sprains (2.1/1000h). Overall, the incidence of injury in competition was over four times that of training (33.5/1000 hours and 7.9/1000h, respectively). In particular, the incidence of contact injuries was considerably greater in competition than in training (24.2 vs 2.3/1000h) and despite a lower exposure to competition, 44% of contact injuries occurred in matches. The total number of days that players were absent was 3110 (22.1±52.8 days per injury).

4.04.2 Absolute accumulated workloads.

Total distance.

High TD (112,244–143,918 m) over 4 weeks was associated with the greatest significant overall injury risk (RR=1.64, 95% CI 1.05 to 2.58, p=0.03). TD above 143,918 m demonstrated a risk but was statistically non-significant (RR=1.29, 95% CI 0.34 to 4.99, p=0.71). Conversely, a low (0–8,812 m) 1-weekly TD reduced the risk of overall (RR=0.25, 95% CI 0.11 to 0.82, p=0.02) and non-contact injury (RR=0.30, 95% CI 0.11 to 0.57, p=0.00).

High-speed distance.

Moderate–high 4-weekly HSD (3,502–5,123m) demonstrated the greatest significant increase in non-contact injury risk (RR=2.14, 95% CI 1.31 to 3.50, p=0.00) and moderate–high 1-weekly HSD (856–1449 m) showed the highest significant overall injury risk (RR=1.73, 95% CI 1.06 to 2.84, p=0.03). Overall and non-contact injury risks were significantly reduced at low 1-weekly HSD (0–756 m) (RR=0.30, 95% CI 0.13 to 0.68, p=0.00); RR=0.26, 95% CI 0.08 to 0.83, p=0.02, respectively).

Accelerations.

A very high number of ACC (≥9254) were performed in 3 weeks, there was a significant increase in the risk of overall (RR=3.84, 95% CI 1.57 to 9.41, p=0.00) and non-contact injuries (RR=5.11, 95% CI 1.75 to 14.96, p=0.00). Conversely, a low amount of ACC over 3 weeks (744–2861) significantly reduced non-contact (RR=0.21, 95% CI 0.05 to 0.87, p=0.03) and overall (RR=0.31, 95% CI 0.13 to 0.76, p=0.01) injury risk.

Total load.

High 1-weekly TL (474–648 AU) recorded the greatest significant RR for overall (RR=1.65, 95% CI 1.04 to 2.62, p=0.03) and non-contact injuries (RR=2.20, 95% CI 1.25 to 3.9, p=0.01). Furthermore, a very high 1-weekly TL (≥648 AU) significantly increased the incidence of a contact injury (RR=4.84, 95% CI 1.26 to 18.55, p=0.02). On the other hand, a low 1-weekly TL (0–130 AU) significantly reduced overall (RR=0.27, 95% CI 0.12 to 0.60, p=0.00), and non-contact injury risk (RR=0.31, 95% CI 0.11 to 0.86, p=0.02). Table 13 summarises the risk of contact, non-contact and overall injury for all accumulated workloads.

Table 13. *Injury risks associated with accumulated workloads over 1-4 weeks.*

		Relative Risk											
No. Of Weeks Accumulated		1			2			3			4		
		NC	C	Overall	NC	C	Overall	NC	C	Overall	NC	C	Overall
TD (m)	Low	0.30*	0.83	0.25**	0.61	0.76	0.62	0.67	0.84	0.53	1.01	1.04	0.89
	Mod-Low	1.45	0.68	1.38	0.95	0.65	0.76	0.87	0.87	1.23	0.77	0.92	0.73
	Mod- High	0.83	0.98	0.95	1.19	1.62	1.55*	1.08	0.84	1.36	1.06	0.88	1.19
	High	1.64	1.79	1.57	1.37	1.00	1.27	1.65	1.35	1.31	1.55	1.49	1.64*
	Very High	3.04	-	2.59	3.35	-	2.88	2.79	-	2.37	2.30	-	1.29
HSD (m)	Low	0.54	0.79	0.38*	0.26*	0.91	0.30*	0.68	0.83	0.67	0.94	1.14	0.79
	Mod-Low	1.10	0.41	1.16	0.95	0.67	0.81	0.79	0.78	0.84	0.61	0.97	0.73
	Mod- High	1.73*	1.74	1.73*	1.42	1.70	1.72*	1.40	1.24	1.15	2.14*	0.68	1.56*
	High	0.65	1.08	0.59	1.75	0.86	1.45	1.42	1.13	1.66*	0.68	1.74	1.26
	Very High	0.00	1.97	0.82	0.00	-	0.00	0.00	1.62	0.33	0.59	-	0.33
ACC (no.)	Low	0.47	0.72	0.35*	0.60	0.75	0.51	0.69	0.84	0.63	0.95	1.02	0.93
	Mod-Low	0.77	0.65	1.01	0.96	0.67	0.92	0.68	1.24	0.77	0.72	0.91	0.82
	Mod- High	1.03	1.39	1.00	1.27	1.51	1.21	1.29	0.76	1.32	1.02	0.92	1.01
	High	2.25*	1.27	1.83*	1.10	1.06	1.37	1.47	1.49	1.38	1.64	1.35	1.66*
	Very High	1.31	-	3.06*	4.25*	-	3.19*	5.11*	1.02	3.84*	4.25*	-	2.37
TL (AU)	Low	0.31*	0.77	0.27*	0.59	0.81	0.50	0.55	0.87	0.55	0.80	1.06	0.75
	Mod-Low	1.40	0.63	1.45	1.17	0.70	1.07	0.85	1.34	0.98	1.04	0.98	1.01
	Mod- High	0.79	1.12	0.98	1.13	1.76	1.38	1.37	0.77	1.39	0.94	0.89	1.12
	High	2.20*	1.42	1.65*	1.45	0.33	1.03	1.41	0.95	1.09	1.64	1.43	1.20
	Very High	0.00	4.84*	2.00	0.00	3.04	1.93	1.39	2.68	1.59	1.07	-	1.84

Note: TD = total distance in metres (m), HSD = high speed distance in metres (m), ACC= number of accelerations (no.), TL = total load in arbitrary units (AU), NC = Non-Contact, C = Contact. *p<0.05 and **p<0.001.

4.04.3 ACWR

Total distance.

ACWRs ≥1.76 (very high) significantly increased contact injury risk (RR=4.98, 95% CI 1.31 to 19.02, p=0.02). For low chronic TD (<22,335m), low ACWR (0–0.32) reduced overall injury risk (RR=0.28, 95% CI 0.09 to 0.91, p=0.03).

High-speed running.

For low chronic HSD (<938m), a high ACWR (1.41–1.96) increased non-contact injury risk (RR=2.55, 95% CI 1.15 to 5.68, p=0.02). For high chronic HSD (>938m), moderate–high ACWR (0.91–1.34) increased non-contact injury risk (RR=2.09, 95% CI 1.06 to 4.12, p=0.03). However, a low ACWR (0–0.36) for all chronic HSD significantly reduced the overall injury risk (RR=0.47, 95% CI 0.25 to 0.9, p=0.02).

Accelerations.

The risk of contact injury was significantly increased when the ACWR was ≥1.77 (very high) (RR=4.98, 95% CI 1.30 to 18.99, p=0.02). Low ACWR (0–0.33) reduced overall injury risk, for low chronic ACC (<1856) (RR=0.29, 95% CI 0.09 to 0.91, p=0.03).

Total load.

Moderate–high ACWR increased non-contact injury risk (0.88–1.32) (RR=1.87, 95% CI 1.12 to 3.12, p=0.02). Moderate–low ACWR (0.44–0.88) increased contact injury risk (RR=1.92, 95% CI 1.07 to 3.45, p=0.03). Table 14 summarises the risk of contact, non-contact and overall injury for all ACWRs.

Table 14. *Injury risks associated with (A) acute:chronic workload ratios overall, (B) acute:chronic workload ratios combined with low chronic workloads, (C) acute:chronic workload ratios combined with high chronic workloads.*

No. Of Weeks Accumulated		A			B			C		
		NC	C	Overall	NC	C	Overall	NC	C	Overall
TD (m)	Low	1.50	0.37	1.00	0.29	0.26	0.28*	1.19	0.62	0.91
	Mod-Low	0.96	1.72	1.25	1.12	2.12	1.43	0.62	1.47	0.98
	Mod- High	1.45	0.44	0.97	1.43	0.44	0.97	1.53	0.91	1.19
	High	1.05	1.22	1.13	1.28	2.80	1.76	1.51	0.91	1.21
	Very High	0.00	4.98*	2.09	-	-	-	-	3.79	1.80
HSD (m)	Low	0.60	0.32	0.47*	0.63	0.24	0.47	1.20	1.91	1.52
	Mod-Low	0.88	1.45	1.10	0.88	0.82	0.86	0.81	1.52	1.11
	Mod- High	1.33	1.32	1.32	0.85	2.55	1.30	2.09*	0.69	1.27
	High	1.39	0.49	0.98	2.55*	0.85	1.82	0.47	0.54	0.50
	Very High	-	2.28	0.95	-	-	-	-	3.62	1.63
ACC (no.)	Low	1.22	0.39	0.85	0.31	0.25	0.29*	1.37	-	0.71
	Mod-Low	0.81	1.75	1.16	1.32	1.79	1.49	0.63	1.66	1.04
	Mod- High	1.52	0.79	1.15	1.23	0.59	0.94	1.49	1.03	1.25
	High	1.41	1.47	1.44	1.30	2.48	1.70	1.54	0.64	1.10
	Very High	-	4.98*	2.09	-	-	-	-	5.91	2.71
TL (AU)	Low	1.20	0.38	0.84	0.50	0.21	0.37	0.98	0.60	0.81
	Mod-Low	0.84	1.92*	1.15	0.84	1.64	1.15	0.79	1.97	1.22
	Mod- High	1.87*	0.87	1.34	1.55	0.77	1.16	1.93	0.86	1.34
	High	0.87	1.20	1.01	1.16	2.28	1.59	0.53	0.32	0.43
	Very High	-	2.74	1.17	-	-	-	-	6.12	2.67

Note: TD = total distance in metres (m), HSD = high speed distance in metres (m), ACC = number of accelerations (no.), TL = total load in arbitrary units (AU), NC = Non-Contact, C = Contact. *p<0.05 and **p<0.001.

4.05 Discussion

This is the first study to examine the relationship of accumulated GPS- and accelerometer-derived workloads and ACWRs with contact and non-contact injury incidence in elite youth football. In line with other studies examining workload and injury in sport (e.g. Piggott, et al., 2009; Gabbett & Ullah, 2012; Colby, et al., 2014; Ehrmann, et al., 2016; Gabbett, Jenkins, & Abernethy, 2012), many variables were found to be significantly related to injury risk. Three-weekly accelerations >9254 were the strongest indicator of overall (RR=3.84) and non-contact (RR=5.11) injury risk. These findings provide empirical support for monitoring accumulated workloads over 3 weeks, and correspond with those of Colby, et al., (2014) who found various 3-weekly workloads to have the strongest association with injury risk in Australian football during preseason and in season.

High 4-weekly TD (112 244–143–917 m) and 1-weekly TL (474–647 AU) also significantly increased the risk of overall and non-contact injuries (RR=1.64 and 1.65, respectively) similar to previous literature, where higher workloads resulted in a greater injury incidence (Piggott, et al., 2009; Gabbett & Ullah, 2012). Conversely, for HSD, a moderate–high workload over one (856–1448 m) and four (3502–5122 m) weeks resulted in higher overall (RR=1.73) and non-contact (RR=2.14) injury incidence, respectively, compared to lower and higher HSD. Workload classification by z-scores in this study means that the greatest risk of non-contact injury was associated with the most commonly performed high-speed running distances. Non-contact injury risk was also significantly augmented for a moderate–high TL ACWR (ACWR=0.88–1.31, RR=1.87) and a moderate–high HSD ACWR combined with high chronic HSD only (>938 m)

(ACWR=0.91–1.33, RR=2.09). Thus, when the acute and chronic stimuli are similar, the incidence of injury is increased. In addition, a high ACWR combined with low chronic HSD (<938 m) showed a significantly increased risk of non-contact injury incidence (ACWR=1.41–1.96, RR=2.55), which was not evident when combined with high chronic HSD (ACWR=1.34–1.77, RR=0.47). This may be indicative of under-preparedness, similar to that reported by Hulin, et al. (2016) where the previous 4-week chronic HSD exposure was insufficient to prepare the player for high acute bouts. The combination of these findings would suggest that optimal HSD and TL exposure should be periodised to fluctuate across a 4-week period, with the achievement of high and low workloads. In addition, the chronic exposure of HSD should be high enough to prepare the players for the necessary spikes in the ACWR. Ultimately, a certain level of training must be achieved to develop the physical capacities needed to withstand the demands of the sport (Gabbett, 2016). Furthermore, players who can safely train harder may develop a greater resilience and tolerance for the progressively increasing intensity and fatigue of competition.

The majority of studies that assess workloads and injury risk focus solely on non-contact, soft tissue injury, as these are considered largely preventable, whereas contact injuries are considered mostly unavoidable (Rogalski, et al., 2013). However, Gabbett, et al. (2012) found higher workloads to be strongly correlated with contact injuries in professional rugby. Consistent with their findings, the present study demonstrated that very high 1-weekly TL (≥648 AU) and very high ACWR for TD and ACC (≥1.76 and ≥1.77, respectively) were significantly related to a higher risk of contact injury (TL: RR=4.84, TD and ACC:

RR=4.98). Calvert, et al., (1976) reported acute workload as an estimate of an athlete's 'fatigue' and chronic workload as 'fitness'. In the context of this study, a larger discrepancy between acute workload ('fatigue') and chronic workload ('fitness') resulted in a greater contact injury risk than when the ratio was moderate or low (the measure of 'fitness' was similar to or higher than that of 'fatigue'). Furthermore, the ratios above which a significant risk of contact injury was recorded were higher than those for non-contact injury in this study, and previous work within Australian football, cricket and rugby league (>1.5) (Gabbett, 2016). This suggests that a higher level of fatigue (acute workload) relates to contact injury than non-contact injury. Ultimately, by increasing fitness levels and limiting fatigue, players may be able to respond more quickly to avoid the rapid, unpredictable movements preceding contact injury (Wong & Hong, 2005). The only exception to this was a significant risk of contact injury for a moderate–low ACWR of TL (0.44– 0.87). Gabbett (2016) found a 'sweet spot' for the ACWR between 0.8 and 1.3 to maximise fitness and performance while reducing injury risk. Therefore, under-preparedness, or low tolerance to workload, may also be a factor in the occurrence of contact injury. These findings demonstrate the multifactorial nature of injury and highlight the need for future research, specifically into contact injuries.

Total injury incidence (12.1/1000 hours) and also training (7.9/1000 hours) and match (33.5/1000 hours) incidences were similar to those recorded in the UEFA injury study involving 23 top European clubs over seven seasons (Ekstrand, et al., 2011). However, in this study, the large prevalence of contact injuries in competition goes further to highlight the importance of monitoring the

ACWRs, particularly during fixture congested periods, when ensuring adequate recovery between games, while maintaining optimum workloads is a challenge.

Although low accumulated workloads and ACWRs demonstrated a significantly reduced injury risk across all metrics, the authors do not recommend regular training at these workloads. Football players cover ~10 000 m during a match; therefore, low (≤8812 m) weekly distances may result in the players being underprepared for the physical demands of the game, and ultimately may increase their risk of injury. Although there is no doubt that higher workloads are related to a heightened injury risk, when correctly prescribed, higher workloads can also produce positive adaptations that build tolerance and resilience to fatigue and injury (Gabbett, 2016).

This was the first study to monitor injury risk using GPS from training and competition in football, providing comprehensive external workload analysis. The inclusion of match data accounted for match-to-match variability that has been a limitation of previous studies using estimated data (Ehrmann, et al., 2016). However, the players participated in a variety of other conditioning workloads as well as the on-field sessions that could not be quantified by GPS/accelerometer workloads (Colby, et al., 2014). Ultimately, the incorporation of RPE values, as a measure of internal workload, may provide a more complete insight into the likelihood of injury, as well as taking into consideration the athlete’s response to a given workload (Hulin, et al., 2014).

The greater sampling frequency (10 Hz) and integrated accelerometers of the GPS units used in this study allowed for valid and reliable assessment of high intensity activity and injury risk (Varley, et al., 2012) that was not possible in previous studies using lower sampling devices (1 and 5 Hz) (Hulin, et al., 2016). However, measurement error has been found to increase with speed, regardless of sampling rate and therefore caution must still be taken when interpreting the data (Coutts & Duffield, 2010).

While GPS outcomes may be considered modifiable injury risk factors, non-modifiable factors such as age and injury history were not taken into account, despite being associated with future injury incidence (Gabbe, Bennell, Finch, Wajswlner, & Orchard, 2006). Furthermore, the sample size did not permit the analysis of position-specific workloads and injury risk.

Another limitation of the sample size is that the number of injury cases recorded was enough to detect moderate to strong associations between workload and injury, but too small to detect small to moderate associations (Bahr & Holme, 2003). Future research combining data from multiple clubs would solve this issue; however, due to the competitive nature of elite sport, it may prove difficult.

4.06 Conclusion

Accumulated GPS/accelerometer workloads and ACWRs were significantly related to non-contact and contact injury risk in elite youth football players. In general, the higher workloads were associated with the greater injury risks, corresponding to previous literature. Three-weekly ACC ≥9254 was the strongest predictor of overall and non-contact injury risk and should therefore be monitored in practice for injury prevention purposes. In addition, the results suggest that low chronic HSD underprepare the players for the risk of high acute workloads, compared to high chronic HSD. As shown in previous research (Gabbett, 2016), it may not necessarily be higher workloads that augment injury risk but the prescription of these higher workloads. Spikes in non-contact injury risk, when the acute and chronic workloads were similar, highlight the need for systematic variation in the training programme. Ultimately, high, excessive, accumulated and acute workloads were related to a greater injury risk. However, progressive chronic exposure to higher workloads, including appropriate fluctuations to allow for adaptation and recovery (Seyle, 1946), may protect the players from injury by developing their physical capacities. The findings of this study provide initial guidelines for optimal workloads in elite youth football to reduce injury occurrence. However, caution should be applied when generalising these data to different teams and sports due to the specific nature of the physical demands.

CHAPTER 5. SPIKES IN ACUTE:CHRONIC WORKLOAD RATIO (ACWR) ASSOCIATED WITH A 5–7 TIMES GREATER INJURY RATE IN ENGLISH PREMIER LEAGUE FOOTBALL PLAYERS: A COMPREHENSIVE 3-YEAR STUDY

5.01 Abstract

The relationship between GPS-derived workloads and injury in EPL football players (n=33) was examined. Workload and injury data were collected over three consecutive seasons. Cumulative (1-weekly, 2-weekly, 3-weekly and 4-weekly) workloads in addition to ACWRs were classified into discrete ranges by z-scores. Relative risk (RR) for each range was then calculated between injured and non-injured players using specific GPS variables: total distance, low-intensity distance, high-speed running distance, accelerations and decelerations. The greatest non-contact injury risk was when the chronic exposure to decelerations was low and the ACWR was >2.0 (RR=6.7). Non-contact injury risk was also 5–6 times higher for accelerations and low-intensity distance when the chronic workloads were categorised as low and the ACWR was >2.0 (RR=5.4–6.6), compared with ACWRs below this. When all chronic workloads were included, an ACWR >2.0 was associated with a significant but lesser injury risk for the same metrics, plus total distance (RR=3.7–3.9). It is recommended that practitioners involved in planning training for performance and injury prevention monitor the ACWR, increase chronic exposure to workload and avoid ACWR spikes that approach or exceed 2.0.

5.02 Introduction

Typically, EPL football players sustain two injuries per season, resulting in 50 injuries within a squad of 25 players (Ekstrand, et al., 2011). During the 2016/2017 football season, £177million was paid out in wages to injured EPL players, with the average wage per injury being over £248,000 (Barnard, et al., 2018). Consequently, throughout a season, clubs could be expected to pay around £12.4million in wages alone, not including additional treatment costs, to players who are unavailable due to injury. In addition, across 24 European clubs, player availability was positively related to team success, defined by league ranking, and points per match (Hagglund, et al., 2013).

All injuries occur when an athlete is exposed to a given workload (Windt & Gabbett, 2017). Thus, each training or competition bout performed has the potential for athletic injury, indicating that inappropriate workload exposure can increase injury risk. An elevated risk of injury (RR=5.1) with a very high 3-weekly accumulation of accelerations (ACC) (>9254) has been demonstrated in elite youth football players (Chapter 4). More recently, a greater absolute and relative exposure in the 3 weeks prior to injury was reported in professional football players (Lu, et al., 2017). In contrast, other work in elite football found that gradually increasing the exposure to moderate-high workloads produced a smaller association to injury risk than exposure to lower workloads (Malone, Owen, et al., 2017). Therefore, workloads should be monitored over longer periods of time, specifically, how much is performed and how they are prescribed.

Due to the increasing physical demands of the EPL (Barnes, et al., 2014), and the congested fixture schedule at the top level, players are required to repeatedly perform high workloads. Therefore, appropriate workloads that produce adaptations to enhance their fitness levels and tolerance to physical stress are required (Seyle, 1946). In this case, higher workloads would appear to be protective, while lower workloads may be insufficient to induce adaptations or result in detraining thereby increasing the risk of injury. Consequently, research over the last few years has focused on relative workload monitoring, that is, how much workload can a player physically tolerate? This has been estimated using the ACWR to give a workload index between what the player is currently doing (acute workload) versus what they have been prepared for (chronic workload) (Hulin, et al., 2016).

Acute workload spikes have been associated with increased injury risk in football, with metres per minute prior to injury being significantly higher than the season average (Ehrmann, et al., 2016). However, only 16 injuries were analysed, match data were not recorded and the ACWR was not calculated, therefore warranting further research. Consequently, Chapter 4 of this thesis investigated the relationship between the ACWR and injury risk in elite youth football players. A significantly increased risk of injury (RR=2.6) was reported with high ACWR (1.4–1.9) for high speed distance when the chronic workload was low (<938m). While these findings cannot be generalised, they suggest that monitoring the ACWR in professional football may be a key injury prevention strategy.

Furthermore, most studies regarding workload–injury relationships have excluded contact injuries as they are assumed to be unavoidable. However, our previous work in youth football players found very high ACWR to be associated with contact injury risk across several workload measures (RR=4.8–5.0) (Chapter 4). It was concluded that by increasing fitness levels and limiting fatigue (ie, reducing the ACWR), players may be able to respond more quickly to avoid the rapid, unpredictable movements preceding contact injury. Therefore, the inclusion of contact injuries may provide additional insight into workload–injury relationships.

Understanding the workload–injury relationship is fundamental to optimising performance and maximising player availability. Yet, there is very limited research exploring the relationships between workloads and injury in professional football. Furthermore, despite its growing popularity as a workload monitoring method, the ACWR and the associated injury risks require further exploration. Therefore, we aimed to examine the relationships of accumulated workloads, the ACWR and injury risk in EPL football across three seasons.

5.03 Method

5.03.1 Participants.

Data were collected from football players (n=33) from one EPL club (age: 25.4±3.1years, stature: 182.0±6.9cm, body mass: 79.9±7.7kg). All players trained on a full-time basis and played competitive fixtures within the EPL during the 2014–2015, 2015–2016 and 2016– 2017 seasons. Ten (30%) participants competed in all three seasons, 8 (24%) participants competed in two seasons and the remaining 15 competed in one season, resulting in 61 individual football seasons, analysed as independent data points. Goalkeepers were excluded from the study due to the different nature of their activity.

5.03.2 Quantifying workload.

GPS was used to quantify workload data collected from all on-pitch training sessions and friendly matches. The GPS units (Viper 2, StatSports, Ireland), were placed between the scapulae of the players in bespoke vests. These units sampled at 10Hz and the accelerometers at 100Hz. Following each session, the data were downloaded into the specialised analysis software (Viper, 2.1.3.0). Competitive match data were recorded using SACS (TRACAB; ChyronHego, New York, USA) provided, as standard by the EPL. The raw data files were then imported into the GPS software and analysed in an identical manner. The validity and reliability of both GPS and SACS for quantifying the physical demands of team sports has been demonstrated by numerous studies. The interchangeability of the two systems has also been established (Buchheit, et al., 2014). In addition, in Chapter 2, the validity, reliability and interchangeability of both systems used in this study were tested, producing positive results.

For sessions when data were unavailable for a participant (n=1149 of 10221; 11%) as a result of them not wearing a unit, not having match data, not completing the entire session or the data being deemed unreliable due to intermittent satellite signal, estimations were made as follows: Main training session data: estimated by calculating squad averages for drills completed (n=607 of 10221; 6%). International data: estimated by calculating the squad average of the other international players during the period of the international breaks (Buchheit, 2017) (n=306 of 10211; 3%). Game data: matches were only monitored using SACS from 2015/2016 onwards. Prior to this, match data were estimated using individual season game averages (from a minimum of three matches) from the data collected in 2015/2016 and 2016/2017. For players where this was not available (n=6), estimations were made based on friendly matches in which GPS was worn. Game averages were extrapolated according to individual game time, as per previous work (Ehrmann, et al., 2012) (n=236 of 10221; 2%). The variables defined in Table 15 were selected for use in this study due to their relevance to running workloads (and potential injury). All variables were taken from the StatSports software (Viper).

5.03.3 Definition of injury.

Injury information was classified by the club doctor and senior chartered physiotherapists. A recordable injury was defined as one that caused any absence from future football participation, that is, a time loss injury (Fuller, et al., 2006). Injuries were classified as being either minimal (1-3 days of football activity missed), moderate (1-4 weeks of football activity missed), or severe (4+ weeks of football activity missed) (Fuller, et al., 2006). Injuries were also categorised by injury type and body site. The mechanism in which a participant acquired an injury was also classified as being non-contact or contact in nature.

Table 15. *Definition of workload variables.*

Variable	Definition
Total Distance (TD)	Total distance covered (m): this includes walking, jogging, fast running and sprinting
Low Intensity Distance (LID)	Total distance covered (m) below 14.4km/h
High Speed Running Distance (HSD)	Total distance covered (m) between 19.8km/h and 25.2km/h
Accelerations (Acc)	An increase in GPS speed data for at least half a second with maximum acceleration in the period at least 0.5m/s/s
Decelerations (Dec)	A decrease in GPS speed data for at least half a second with maximum deceleration in the period at least 0.5m/s/s

5.03.4 Data analyses.

Data were categorised in weekly blocks from Monday to Sunday. Every time a player participated in a training session or match, data were analysed in two ways. First, the previous 1-weekly, 2-weekly, 3-weekly and 4-weekly workloads were calculated. The workloads were then classified into discrete ranges from very low through to very high using z-scores (Wang & Chen, 2012) (Table 16). The relationships between these weekly cumulative workloads and subsequent injury were investigated. Injuries that occurred within the next 7 days were included for analysis (Piggott, et al., 2009).

Second, the acute workload for the current week was calculated as the 1-week workload and chronic workload as the previous 4-week rolling average acute workload. The acute and chronic workloads were uncoupled to prevent them being falsely correlated. The ACWR was calculated by dividing the acute workload by the chronic workload (Hulin, et al., 2014). Only acute workloads that were preceded by four complete weeks were included in the ratio calculations. A value of greater than 1 represents an acute workload greater than the chronic workload. Chronic workloads were also separated into high and low categories by the median score for each variable (Hulin, et al., 2016). From this, workload–injury relationships between ACWR ratios combined with high and low chronic workloads were analysed. As with accumulated workloads, the ratios were categorised based on z-scores (Table 17). Only conditions that contained 20 or more injuries were included in the statistical analysis to allow for moderate to strong associations to be made (Bahr & Holme, 2003). Consequently, data were excluded for incidences when the chronic workloads were high for both non-contact and contact injuries. This was also the case for contact injuries when the chronic workloads were low.

5.03.5 Statistical analyses.

The analysis was performed in a similar manner to the previous work of Hulin, et al. (2014). Injury incidence was determined by dividing total number of injuries by the ‘on-legs’ exposure time and reported as rates per 1000hours. Injury risks were calculated as the number of injuries sustained relative to the number of exposures to each workload classification (Hulin, et al., 2014). Exposure data were recorded as per the procedures outlined by the Fédération de Football Association Medical Assessment Research Centre (Fuller, et al., 2006). A binary logistic regression model was used to compare workloads between injured and non-injured players for all workload variables independently. Accumulated workload and ACWR were independently modelled as predictor variables. RR was then calculated using to determine the magnitude of the injury risk above and below given workloads or ratios (MedCalc Software, Ostend, Belgium). When a RR was greater than 1.00, an increased risk of injury was reported (ie, RR=1.50 is indicative of a 50% increased risk) and vice versa. For a RR to be significant, 95% CIs did not contain the null RR of 1.00. Data were analysed using IBM SPSS Statistics V.25.0 and reported as means and 95%CI. Significance was accepted at $p<0.05$.

Table 16. *Workload classifications and boundaries for accumulated workloads over 1 to 4 weeks.*

			No. of Weeks Accumulated			
	Classification	Z-Score	1	2	3	4
TD (m)	Very Low	≤-2.00	11,150	24,858	37,202	45,843
	Low	-1.99 to -1.00	11,151-17,539	24,859-35,785	37,203-52,504	45,844-67,519
	Low-Mod	-0.99 to 0.00	17,540-24,041	35,786-46,733	52,505-68,677	67,520-89,707
	Mod-High	0.00 to 0.99	24,042-30,549	46,734-57,697	68,678-84,830	89,708-111,863
	High	1.00 to 1.99	30,550-37,065	57,698-68,685	84,831-101,176	111,864-134,050
	Very High	≥2.00	37,066	68,686	101,177	134,051
LID (m)	Very Low	≤-2.00	9,179	20,347	30,002	37,324
	Low	-1.99 to -1.00	9,180-14,627	20,348-29,653	30,003-43,487	37,325-56,070
	Low-Mod	-0.99 to 0.00	14,628-20,108	29,654-39,026	43,488-57279	56,071-74,824
	Mod-High	0.00 to 0.99	20,109-25,644	39,027-48,423	57,280-71,110	74,825-93,845
	High	1.00 to 1.99	25,645-31,160	48,424-57,886	71,111-85,119	93,846-112,896
	Very High	≥2.00	31,161	57,887	85,120	112,897
HSD (m)	Very Low	≤-2.00	110	509	904	1,251
	Low	-1.99 to -1.00	111-542	510-1,215	905-1,861	1,252-2,464
	Low-Mod	-0.99 to 0.00	543-979	1,216-1,916	1,862-2,827	2,464-3,702
	Mod-High	0.00 to 0.99	980-1,418	1,917-2,624	2,828-3,791	3,703-4,941
	High	1.00 to 1.99	1,419-1,853	2,625-3,326	3,792-4,778	4,942-6,176
	Very High	≥2.00	1,854	3,327	4,779	6,177
Acc (no.)	Very Low	≤-2.00	862	1,945	2,832	3,510
	Low	-1.99 to -1.00	863-1,397	1,946-2,851	2,833-4,166	3,511-5,352
	Low-Mod	-0.99 to 0.00	1,398-1,936	2,852-3,753	4,166-5,510	5,353-7,193
	Mod-High	0.00 to 0.99	1,937-2,472	3,754-4,662	5,511-6,855	7,194-9,042
	High	1.00 to 1.99	2,473-3,010	4,663-5,576	6,856-8,200	9,043-10,902
	Very High	≥2.00	3,011	5,577	8,201	10,903
Dec (no.)	Very Low	≤-2.00	794	1,795	2,625	3,242
	Low	-1.99 to -1.00	795-1,287	1,796-2,625	2,626-3,842	3,243-4,933

Low-Mod	-0.99 to 0.00	1,288-1,782	2,626-3,457	3,843-5,073	4,934-6,625
Mod-High	0.00 to 0.99	1,783-2,277	3,458-4,292	5,074-6,308	6,626-8,323
High	1.00 to 1.99	2,278-2,771	4,293-5,131	6,309-7,459	8,324-10,015
Very High	≥2.00	2,772	5,132	7,460	10,016

Note: TD = total distance in metres (m), LID = low intensity distance in metres (m), HSD = high speed distance in metres (m), Acc = number of accelerations (no.), Dec = number of decelerations (no.).

Table 17. *Workload classifications and boundaries for: (A) acute:chronic workload ratios overall, (B) acute:chronic workload ratios combined with high chronic workloads and (C) acute:chronic workload ratios combined with low chronic workloads.*

	Classification	Z-Score	A	B	C
TD (m)				≥22,325	<22,325
	Very Low	≤-2.00	0.39	0.49	0.43
	Low	-1.99 to -1.00	0.40-0.70	0.50-0.72	0.44-0.77
	Low-Mod	-0.99 to 0.00	0.71-1.08	0.73-0.95	0.78-1.22
	Mod-High	0.00 to 0.99	1.09-1.47	0.96-1.18	1.23-1.67
	High	1.00 to 1.99	1.48-1.86	1.19-1.42	1.68-2.13
	Very High	≥2.00	1.87	1.43	2.14
LID (m)				≥19,322	<19,322
	Very Low	≤-2.00	0.35	0.43	0.40
	Low	-1.99 to -1.00	0.36-0.68	0.44-0.72	0.41-0.68
	Low-Mod	-0.99 to 0.00	0.69-1.09	0.73-1.02	0.69-1.17
	Mod-High	0.00 to 0.99	1.10-1.50	1.03-1.32	1.18-1.66
	High	1.00 to 1.99	1.51-1.97	1.33-1.67	1.67-2.14
	Very High	≥2.00	1.98	1.68	2.15
HSD (m)				≥946	<946
	Very Low	≤-2.00	0.09	0.20	0.09
	Low	-1.99 to -1.00	0.10-0.54	0.21-0.55	0.10-0.55
	Low-Mod	-0.99 to 0.00	0.55-1.08	0.56-0.93	0.56-1.17
	Mod-High	0.00 to 0.99	1.09-1.62	0.94-1.30	1.18-1.80
	High	1.00 to 1.99	1.63-2.16	1.31-1.68	1.81-2.47
	Very High	≥2.00	2.17	1.69	2.48
Acc (no.)				≥1,881	<1,881
	Very Low	≤-2.00	0.32	0.46	0.34
	Low	-1.99 to -1.00	0.33-0.67	0.47-0.71	0.35-0.73
	Low-Mod	-0.99 to 0.00	0.68-1.10	0.72-0.96	0.74-1.25
	Mod-High	0.00 to 0.99	1.11-1.54	0.97-1.21	1.26-1.77
	High	1.00 to 1.99	1.55-1.97	1.22-1.47	1.78-2.29
	Very High	≥2.00	1.98	1.48	2.30
Dec (no.)				≥1,731	<1,731
	Very Low	≤-2.00	0.33	0.45	0.37
	Low	-1.99 to -1.00	0.34-0.67	0.46-0.70	0.38-0.73
	Low-Mod	-0.99 to 0.00	0.68-1.10	0.71-0.95	0.74-1.26
	Mod-High	0.00 to 0.99	1.11-1.54	0.96-1.20	1.27-1.78
	High	1.00 to 1.99	1.55-1.98	1.21-1.45	1.79-2.31
	Very High	≥2.00	1.99	1.46	2.32

Note: TD = total distance in metres (m), LID = low intensity distance in metres (m), HSD = high speed distance in metres (m), Acc = number of accelerations (no.), Dec = number of decelerations (no.).

5.04 Results

5.04.1 Injury incidence.

For the duration of the study, 132 injuries (13.3/1000hours 'on-legs' exposure time) were recorded (2014–2015 season, 17.6/1000hours; 2015–2016 season, 10.2/1000hours; 2016–2017 season, 12.4/1000hours), including contact and non-contact injuries (Appendix B). The knee was the most common site of injury across the three seasons (2.9/1000hours), 69% of which were non-contact injuries (2.0/1000hours), predominantly meniscal or cartilage lesions and ligament sprains (0.9 and 0.7/1000hours, respectively). The ankle was the most common site of contact injury (1.9/1000hours), with the most common type being ligament sprains (1.6/1000hours). The injury incidence in competition was over five times that of training (33.7/1000hours vs 5.8/1000hours). In particular, contact injuries were considerably greater in competition than in training (16.9/1000hours vs 1.3/1000hours). Despite a lower exposure to competition, 80% of contact injuries occurred in matches. The total number of days missed through injury was 4,820 (36.5±62.7 [mean±SD] days per injury).

5.04.2 Overall injuries.

A low chronic workload of accelerations (ACC; <1,881), decelerations (DEC; <1,731) and low intensity distance (LID; <19,222m) combined with a very high ACWR (>2.0) elicited the greatest overall injury risk (RR=3.2, 95% CI=1.3-7.6, p=0.01, RR=3.5, 95% CI=1.5-8.2, p=0.01 and RR=2.76, 95% CI=1.2-6.6, p=0.02, respectively). The risk was also significant for very high ACWR of the same metrics, plus total distance (TD), combined with all chronic workloads (RR= 2.4-2.6) (Table 19). Conversely, a low ACWR of TD (0.4-0.7) for all chronic workloads was associated with a decreased injury risk (RR=0.2, 95% CI=0.1-0.8, p=0.02).

5.04.3 Non-contact injuries.

Low chronic workloads combined with very high ACWRs for TD (>2.14), LID (>2.15), ACC (>2.30) and DEC (>2.32) resulted in a non-contact injury risk 5-7 times greater than ACWRs below this (RR=4.5 (TD) – 6.6 (DEC), p<0.05). Additionally, a low amount of TD accumulated over 4 weeks (45,844-67,519m) also resulted in an increased risk (RR=2.2, 95% CI=1.0-4.6, p=0.04) (Table 18). Significant risks were also found for TD, ACC, DEC and LID for all chronic workloads when the ACWR was very high (RR=3.7-3.9) (Table 19).

5.04.4 Contact injuries.

Mod-high ACWR (1.1-1.5) for TD, DEC and LID produced the largest contact injury risk (RR=2.0, 95% CI=1.0-4.0, p=0.04, RR=2.0, 95% CI=1.0-4.0, p=0.04 and RR=2.6, 95% CI=1.3-5.2, p=0.01, respectively). A mod-high amount of TD (24,042-30,549m) and a low-mod amount of DEC (1,288-1,782) accumulated over a week also showed a heightened risk of contact injury (RR=2.1, 95% CI=1.1-4.0, p=0.03 and RR=2.0, 95% CI=1.1-3.9, p=0.03, respectively).

Table 18. *Injury risk associated with accumulated workloads over 1-4 weeks.*

No. Weeks Accumulated		1			2			3			4		
		NC	C	Overall	NC	C	Overall	NC	C	Overall	NC	C	Overall
TD (m)	Very Low	0.49	0.67	0.28	1.38	0.94	1.19	1.55	2.17	1.81	0.92	1.28	1.07
	Low	0.94	0.16	0.59	1.11	1.01	1.07	1.26	0.32	0.84	2.18*	0.66	1.49
	Low-Mod	1.51	0.85	1.20	1.03	0.86	0.95	1.00	0.69	0.86	0.97	0.63	0.82
	Mod- High	0.80	2.09*	1.22	1.10	1.73	1.33	0.96	1.55	1.18	0.81	1.79	1.13
	High	0.84	0.93	0.88	0.57	0.18	0.40*	0.66	0.68	0.67	0.92	0.48	0.73
	Very High	1.01	1.39	1.17	1.29	1.78	1.50	1.52	2.11	1.77	0.86	2.57	1.07
LID (m)	Very Low	0.40	0.55	0.23	1.32	0.89	1.14	0.51	2.23	1.20	0.91	1.26	1.06
	Low	0.81	0.34	0.60	1.15	1.34	1.23	1.55	0.32	1.00	1.27	0.66	1.00
	Low-Mod	1.17	1.11	1.15	0.98	1.19	1.06	1.06	0.88	0.98	1.36	0.95	1.18
	Mod- High	1.14	1.65	1.34	1.15	1.13	1.14	0.77	1.30	0.97	0.70	1.32	0.93
	High	0.84	0.93	0.88	0.58	0.38	0.49	1.02	0.92	0.98	1.07	0.70	0.91
	Very High	1.01	0.65	0.58	1.18	0.76	0.68	2.63	0.83	1.50	0.86	1.18	0.50
HSD (m)	Very Low	2.61	3.57	1.52	3.23	1.01	1.83	0.44	0.60	0.25	1.43	0.97	1.23
	Low	1.15	0.17	0.70	1.46	0.59	1.07	1.52	0.85	1.22	1.49	0.70	1.14
	Low-Mod	0.86	1.07	0.94	0.92	1.58	1.16	0.99	1.36	1.34	0.87	1.00	0.92
	Mod- High	1.16	1.33	1.23	0.89	0.99	0.93	0.74	079	0.76	0.98	0.82	0.91
	High	1.33	1.61	1.44	0.76	0.40	0.60	1.59	0.89	1.28	0.65	1.46	1.19
	Very High	0.24	0.68	0.28	0.78	2.22	1.37	0.36	2.18	0.89	0.49	2.45	1.00
Acc (no.)	Very Low	0.45	0.61	0.26	1.18	0.80	1.02	0.48	2.10	1.13	1.28	1.16	1.23
	Low	0.93	0.33	0.67	1.18	1.06	1.13	1.50	0.64	1.12	1.06	0.71	0.91
	Low-Mod	1.08	1.62	1.29	1.31	1.89	1.53*	1.10	0.92	1.02	0.99	1.00	0.99
	Mod- High	1.28	0.74	1.03	0.85	0.68	0.78	0.81	1.10	0.92	1.04	1.41	1.18
	High	0.70	1.45	0.99	0.56	0.37	0.48	1.02	0.67	0.87	0.85	0.22	0.57

	Very High	1.12	1.54	1.30	1.71	2.36	1.98	2.14	2.96	2.48	1.39	4.24	1.76
Dec (no.)	Very Low	0.50	0.69	0.29	1.32	0.89	1.14	0.48	0.72	1.15	1.39	1.17	0.98
	Low	1.04	0.32	0.71	0.91	1.61	1.19	1.40	0.60	1.05	1.09	0.73	0.94
	Low-Mod	0.89	2.04*	1.29	1.11	1.34	1.20	1.21	0.92	1.08	1.03	1.08	1.05
	Mod- High	1.31	0.55	0.94	1.13	0.79	0.97	0.69	1.14	0.86	1.08	1.31	1.17
	High	0.84	1.46	1.09	0.55	0.37	0.47	1.18	0.65	0.95	0.84	0.22	0.56
	Very High	1.06	1.47	1.23	1.64	2.27	1.91	2.04	2.82	2.37	1.30	3.96	1.64

Note: TD = total distance in metres (m), LID = low intensity distance in metres (m), HSD = high speed distance in metres (m), Acc = number of accelerations (no.), Dec = number of decelerations (no.), *=p<0.05, **p<0.001.

Table 19. *Injury risks associated with (A) acute:chronic workload ratios overall, (B) acute:chronic workload ratios combined with high chronic workloads, (C) acute chronic workload ratios combined with low chronic workloads.*

		A			B			C		
		NC	C	Overall	NC	C	Overall	NC	C	Overall
TD (m)	Very Low						2.04			
	Low	0.35	0.11	0.19*			0.16	0.59		0.35
	Low-Mod	1.32	0.69	1.01			1.01	1.56		1.22
	Mod-High	0.91	2.03*	1.31			1.18	0.48		0.90
	High	0.29	1.72	0.87			1.86	0.50		0.96
	Very High	3.67*	0.88	2.40*			0.80	4.50*		2.61
LID (m)	Very Low						2.79			
	Low	0.39	0.25	0.33			0.30	0.25		0.16
	Low-Mod	0.83	0.48	0.66			0.80	1.15		1.00
	Mod-High	1.52	2.60*	1.91*			2.08*	0.85		1.13
	High	0.16	1.40	0.57			0.59	0.23		0.58
	Very High	3.93*	0.94	2.56*				5.39*		2.76*
HSD (m)	Very Low									
	Low	1.35	0.26	0.85			0.80	1.67		0.97
	Low-Mod	0.92	1.64	1.18			0.84	1.73		1.78
	Mod-High	1.20	0.80	1.02			1.36	0.70		0.72
	High	0.52	1.07	0.75			1.36	0.39		0.48
	Very High	0.66	0.88	0.76			0.38	0.39		0.51
Acc (no.)	Very Low						3.50			
	Low	0.42	0.27	0.35			0.35	0.18		0.11
	Low-Mod	0.79	0.80	0.79			0.84	1.54		1.49
	Mod-High	1.40	1.81	1.57*			1.37	0.60		0.75

	High	0.33	0.90	0.57			1.27	0.28		0.71
	Very High	3.86*	0.92	2.52*			1.12	5.90**		3.18*
Dec (no.)	Very Low						3.59			
	Low	0.44	0.28	0.37			0.18	0.16		0.09
	Low-Mod	0.88	0.80	0.85			0.98	1.41		140
	Mod-High	1.23	1.99*	1.52			1.31	0.71		0.86
	High	0.34	0.45	0.39			1.29	0.25		0.64
	Very High	3.73*	0.89	2.44*			0.88	6.58**		3.47*

Note: TD = total distance in metres (m), LID = low intensity distance in metres (m), HSD = high speed distance in metres (m), Acc = number of accelerations (no.), Dec = number of decelerations (no.), *=p<0.05, **p<0.001.

5.05 Discussion

This is the first study to explore the relationship of both accumulated GPS-derived workloads and ACWR with contact and non-contact injury risk at an EPL football club. This extends our previous work (Chapter 4) and that of others (Malone, Owen, et al., 2017; Hulin, et al., 2014; Hulin, et al., 2016; Fanchini, et al., 2018; Hulin, Gabbett, Caputi, Lawson, & Sampson, 2016) showing that a number of GPS-derived workloads were associated with injury risk.

A very high ACWR combined with low chronic workload categories demonstrated the greatest non-contact injury risk for most metrics (except HSD) with DEC being most strongly associated with RR (ACWR >2.3, RR=6.6). When all chronic workloads were analysed, a very high ACWR demonstrated a lesser but still significant risk for the same metrics (RR=3.7–3.9). These findings are in line with studies in cricket (Hulin, et al., 2014) rugby (Hulin, et al., 2016; Hulin, Gabbett, Caputi, et al., 2016), Australian football (Stares, et al., 2018) Gaelic football (Malone, Roe, et al., 2017) and football (Chapter 4) where high ACWR, referred to as ‘spikes’ in workload, have been associated with heightened injury risk. Due to the inevitable increased exposure to risk with greater workloads, previous research has focused on the higher workload–higher injury risk relationship (Malone, Roe, et al., 2017; Gabbett & Jenkins, 2011). However, the above findings, alongside the lack of significant risks associated with high accumulated workloads in this study, support a growing body of literature suggesting that acute, excessive, rapid increases in workloads may be responsible for a large proportion of non-contact injuries, rather than chronic exposure to higher workloads (Gabbett, 2016).

The protective effect of high chronic workloads versus low chronic workloads has been reported in rugby (Hulin, et al., 2016). They concluded that the players who were capable of achieving high exposure had the enhanced physical attributes needed for decreased injury risk. This theory has recently been demonstrated in hurling, where players with well-developed lower body strength, repeated sprint ability and speed tolerated higher workloads and had a reduced risk of injury compared with lower performance groups (Malone, et al., 2018). In youth football, a high ACWR combined with low chronic HSD workload showed a significantly increased risk of non-contact injury (ACWR=1.4–2.0, RR=2.6), which was not evident when combined with high chronic HSD (ACWR=1.3– 1.8, RR=0.5) (Chapter 4).

In the current study, there were not enough injuries when the chronic workloads were high to determine the RRs of non-contact injury, further indicating a potential protective effect. Ultimately, training at higher workloads may cause players to develop a greater tolerance for the increasing intensity and fatigue of competition (Gabbett, 2016). Concurrently, reducing workloads, while lowering a player’s exposure to risk, may also have a negative effect on fitness and physical preparedness, potentially increasing the risk. Therefore, as per the training–injury prevention paradox model (Gabbett, 2016), optimal workload management to minimise injury risk should involve appropriate, progressive exposure to higher workloads while avoiding workload spikes that the player is not prepared for.

Very little research has investigated the relationship between contact injuries and workload, despite early workload–injury research suggesting that players with better developed physical capacity may be at less risk of contact injury (Gabbett, 2010). In the current study, 80% of all contact injuries occurred in matches, similar to previous injury incidence reports (Hawkins & Fuller, 1999). This may be due to the high speed and intensity of play, resulting in more body contact such as sliding and tackling (Wong & Hong, 2005). The risk of contact injury was greatest when the ACWR was moderate to high for TD, LID and DEC (RR range=2.0–2.6), meaning the acute workload was very similar to the chronic workload.

Also, as workload was categorised by z-scores, contact risk was highest for the most commonly occurring ratios (z=0.0– 1.0). Players who are regularly in the team, and therefore more at risk of contact injury, typically have a lack of variation in their workload due to a large proportion of the weekly workload being attained from matches. Therefore, when the match workload was constant, variations in the workload produced very little fluctuation in the total acute workload (Stares, et al., 2018). Thus, it would appear that in the current study, contact injury is most likely to be related to match exposure, rather than the prescribed workload. The lack of association of the ACWR to contact injuries is highlighted further by the large RR of non-contact injury following an acute spike compared with overall injury. This suggests that including contact injuries reduces the association of the ACWR with injury risk. Consequently, these injuries should be analysed separately when establishing workload-injury relationships and determining uniform injury definitions across research (Hulin, 2017).

Previous studies have highlighted the limitations of using estimated match data, as it does not account for match to match variability (Buchheit, 2017). This study has attempted to improve on this by including match data for the 2015/2016 and 2016/2017 seasons. However, for the 2014/2015 season, TRACAB data were not available, resulting in estimations being calculated as per previous work (Ehrmann, et al., 2016), emulating the aforementioned limitation. Additionally, as the match data for the latter two seasons were collected using a different system than training, the precision and sensitivity of the data may be decreased, despite it being calibrated to maximise between system agreements (Buchheit, et al., 2014). With technological advancements, and the recent admittance of GPS in league matches, future research should aim to use a single monitoring system for both competition and training.

One potential explanation for the lack of significant non-contact injury risk for very high acute HSD, despite all other metrics reporting otherwise, may be the use of absolute speed thresholds in this study. Buchheit (2017) recently stated that the use of fixed thresholds may reduce the sensitivity of the ACWR due to the varying locomotor profiles between players, particularly as subtle differences in speed at high intensity have been found to have important implications on injury risk. Future research could consider the use of individualised thresholds, although caution must be taken when anchoring all locomotor categories to one fitness measure (Hunter, et al., 2015).

The present study only examined external workload; however, the incorporation of the RPE values, as a measure of internal workload, may provide a more complete insight into the likelihood of injury, as well as taking into consideration the athlete’s response to a given workload (Piggott, et al., 2009). Fanchini, et al. (2018) recently analysed the ACWR in relation to injury risk in elite football using RPE as their workload measure. Similar to the current study and the findings of Chapter 4, they demonstrated a heightened injury risk with acute ‘spikes’. A combination of both methods may give a more complete assessment of workload-related risk, while also considering the validity and specificity of the chosen metrics to the sport and the individual (Blanch & Gabbett, 2016).

Calculating the ACWR using rolling averages is evidence based and supported by a large body of literature. However, future research may consider using exponentially weighted moving averages, which consider the decaying nature of fitness and fatigue over time. This method has recently been shown to have a greater sensitivity to increases in injury risk at higher ACWRs (Murray, et al., 2017).

The statistical power of this study was not calculated prospectively. As retrospective power analysis calculations are not appropriate (Zumbo & Hubley, 1998), the power analysis was not included. However, this study included 81 injury cases, which is enough to make moderate to strong associations regarding injury risk factors (Bahr & Holme, 2003). Future studies should ensure prospective power analysis for inclusion. Furthermore, as commonly recommended in elite sport research, future work involving multiple clubs would enhance the ability to generalise these findings, advance the statistical analysis and detect small to moderate associations (+200injury cases).

5.06 Conclusions

In summary, ACWR had a stronger association to non-contact injury risk in this cohort of EPL football players than accumulated workloads. This suggests the rapid increase in workload is more indicative of injury than the cumulative amount of workload performed. Specifically, very high acute spikes when the chronic workloads were low corresponded to the greatest non-contact injury risk. We recommend that training programmes should involve progressive exposure to higher workloads to enhance physical capacities while minimising the risks associated with rapid, excessive spikes. Due to the majority of contact injuries occurring during competition, which is both inevitable and relatively non-modifiable by practitioners, it is unlikely that they were associated with a given workload. While this study provides an initial insight into the relationships between workload an injury risk, care should be taken when applying the findings beyond the studied population.

CHAPTER 6. USING THE ACWR IN PRACTICE AUGMENTS WORKLOAD CAPACITY IN ENGLISH PREMIER LEAGUE FOOTBALL PLAYERS

6.01 Abstract

There is a growing body of research into the relationship of the ACWR to injury risk. However, very little research has examined its application as an injury prevention strategy once the risks associated with given workloads has been identified. Using the findings of our previous studies on workload and injury, the aim of this study was to ascertain the effectiveness of ACWR monitoring in elite football practice for injury prevention. GPS-derived workload and injury data were collected for an entire season. ACWRs were used to monitor and programme workloads. Relative risks (RR), based on the findings of Chapter 5, were calculated for the ACWRs, and analysed between injured and non-injured players. Differences in acute and chronic workloads were also assessed between the current season (2017-18) and the previous three seasons (prior to the use of ACWR monitoring). There were no differences in ACWRs or RR between injured and non-injured players in the current study for any GPS metric ($p>0.05$). Acute and chronic workloads were higher in the current season compared to the previous three seasons across all metrics, whilst the ACWRs were lower ($p<0.05$). Using the ACWR as a monitoring tool in practice appears to augment workload tolerance, as players were able to train harder with no increase in injury incidence. However, the lack of difference in ACWRs between injured and non-injured players suggests that the ACWR is not sensitive enough as an isolated injury prevention tool in an elite football setting.

6.02 Introduction

There has been a rapid increase in workload, performance and injury research growing from 9 papers in 2000 to 145 papers in 2017 (Gabbett, 2018). Earlier studies reported a positive relationship between workload and injury suggesting that the harder athletes train, the more likely they are to sustain an injury (Colby, et al., 2014; Gabbett & Jenkins, 2011; Gabbett, 2004). However, other cohorts have found that higher workloads induce physiological adaptations such as aerobic capacity, strength, optimal body composition and repeated-sprint ability, which are vital for performance and may also increase an athlete's tolerance to injury risk (Tønnessen, et al., 2011; Gabbett, 2005). Thus, workloads that are too low may result in inferior physical capacity and reduced performance, suggesting an inverse or U-shaped relationship between workload and injury (Straker, et al., 2018).

The majority of research finding a positive relationship have utilised an absolute acute workload measure, whilst more recent work describing an inverse or U-shaped relationship have used chronic measures of workload (Eckard, Padua, Hearn, Pexa, & Frank, 2018). These contrasting findings have resulted in growing support for relative workload monitoring, primarily the ACWR. Studies investigating the relationship of ACWR with injury risk have demonstrated that excessive, acute 'spikes' in workload heighten injury risk, whilst chronic exposure to high workloads produces physical adaptation for performance as well as being protective against injury (Gabbett 2016; Hulin, et al., 2016). This has also been demonstrated in Chapters 4 and 5, concluding that progressive chronic exposure to higher workloads improves tolerance to high acute workloads and consequently resilience to injury in both elite youth and senior football players.

However, a disconnect has been highlighted between the evidence-based workloads recommended for optimal performance with minimal injury risk, and actual workloads prescribed (Gabbett, 2018). Sub-optimal integration with coaches and insufficient human resources were highlighted as two main factors limiting the impact of workload monitoring in elite sport environments (Akenhead & Nassis, 2016). Consequently, coach philosophy has largely dictated where a team sits on the cost-reward equilibrium of workload implementation (Gabbett, et al., 2016). Some coaches have wanted to maximise performance gains through higher workloads, accepting that this may cause more frequent injuries. However, other coaches have wished to avoid injuries and the associated cost, at the potential sacrifice to performance (Gabbett, et al., 2016). However, effective communication, supported by the growing body of ACWR empirical evidence, may facilitate the relationship between coach and practitioner, increasing the chances of monitoring having an impact on practice (Gabbett & Blanch, 2018). Ultimately, by using a combination of experience and science it should be possible to estimate the ideal cost-reward ratio which ensures the players are prepared for the demands of the game whilst minimising injury risk.

Despite the growing body of research into the relationship of the ACWR to injury risk using retrospective data, very little research has examined its success as an injury prevention and performance enhancement tool prospectively, once the risks associated with given workloads have been identified. Therefore, this chapter applies our previous findings on workload and injury (Chapters 4 & 5) to the current daily practices of the same football club. The aim is to ascertain the effectiveness of informed workload modification via ACWRs for injury prevention and workload tolerance.

6.03 Method

6.03.1 Participants.

During one season, data were collected and analysed from 25 football players (age: 25.1±3.0years; mass: 81.1±7.7kg; height: 182.2±7.4cm) from one EPL club. All players trained full time and competed in EPL fixtures during the 2017-18 season. These data were compared to the data and findings from Chapter 5 which analysed 33 football players from the same club over three seasons (2014-15, 2015-16 and 2016-17 seasons). Of the 25 players in the current study, 18 (72%) were also participants during some or all of the previous study (2014-15 to 2016-17 seasons). Eight players were participants during every season across the two studies. Goalkeepers were excluded from the study due to the different nature of their activity.

6.03.2 Quantifying workload.

External workload during all on-pitch training sessions and friendly matches was quantified using augmented 18Hz GPS units (Apex, StatSports, Ireland). The data were streamed and monitored live during the sessions using the Apex app and downloaded post session using the specialised analysis software (Apex, 3.0.08211). SACS (Tracab, ChyronHego, New York, USA) was used to record workload during competitive matches, as standard throughout the EPL. The raw data files were then imported into the GPS software in an identical manner. In Chapter 2, we demonstrated the interchangeability between the two monitoring systems, as well as their validity and reliability for monitoring workload in football. For sessions where data were missing for a participant (n=204; 4%), estimations were made as per Chapter 5. The variables outlined in Table 20 were selected in line with Chapter 5 and due to their relevance to running demands (and therefore injury) in football. All variables were taken from the GPS software.

Table 20. *Definition of workload variables.*

Variable	Definition
Total Distance (TD)	Total distance covered (m): this includes walking, jogging, fast running and sprinting
Low Intensity Distance (LID)	Total distance covered (m) below 14.4km/h
High Speed Running Distance (HSD)	Total distance covered (m) between 19.8km/h and 25.2km/h
Accelerations (Acc)	An increase in GPS speed data for at least half a second with maximum acceleration in the period at least 0.5m/s/s
Decelerations (Dec)	A decrease in GPS speed data for at least half a second with maximum deceleration in the period at least 0.5m/s/s

6.03.3 Definition of injury.

A recordable injury was defined as any injury which resulted in time loss from football participation (Fuller, et al., 2006). Injuries were categorised as:

minimal (1–3 days of football activity missed), mild (4–7 days of football activity missed), moderate (1–4 weeks of football activity missed) or severe (4+ weeks of football activity missed) (Fuller, et al., 2006). Injury incidence was determined by dividing total number of injuries by the 'on-legs' exposure time and reported as rates per 1000 hours. Exposure data were recorded as per the procedures outlined by the Fédération de Football Association Medical Assessment Research Centre (Fuller, et al., 2006). For the description of injury incidence only, injuries were also classified by injury type, body site and contact or non-contact. For workload-injury analysis, only non-contact injuries were considered, due to their being no association between contact injuries and workload in Chapter 5.

6.03.4 Data analyses.

Every time a player participated in training or competition during the 2017-18 season, the ACWR was calculated as per Chapters 4 & 5. However, chronic workloads were not sub-categorised into low or high due to there not being enough injuries for statistical analysis (Bahr & Holme, 2003). For each ACWR, the associated relative risk (RR) of injury based on the findings of Chapter 5 was calculated (i.e. an ACWR >1.87 for total distance was associated with a RR of 3.67 in Chapter 5, therefore this risk was applied to all ACWR for total distance >1.87 in the current study). Injuries that occurred within the next seven days were included in the analysis. The differences in ACWRs and RR between injured and non-injured players were then investigated.

During the 2014-15, 2015-16 and 2016-17 seasons ACWR monitoring was not used to inform the prescription of workloads in practice. However, by applying the findings of Chapters 4 & 5, this process was used to inform practice during the 2017-18 season (current study). Therefore, for all metrics the differences in acute and chronic workloads, as well as ACWRs between the previous three seasons (prior to the implementation of ACWR monitoring in practice) and the current season were analysed. Injury incidence (no. injuries/1000h) was also compared between the seasons. The eight players who completed all four seasons studied were included in the analysis, and also analysed separately.

6.03.5 Practical application of the ACWR.

In line with the consensus statement on monitoring athlete workloads (Bourdon, et al., 2017), coach and player education was carried out at the start of pre-season. This highlighted the key metrics used, the basic principles of the ACWR and its role in the prescription of workload for performance enhancement and injury prevention. Coach support for monitoring the ACWR was augmented due to the use of this PhD research using club data to set workload thresholds.

At the start of each week, a presentation to coaches, sport science and medical practitioners summarised the workload completed in the previous week and recommended workload targets for the preceding week. Based on coach feedback, a report was designed, detailing the basic workload completed in each training session or match. Each morning, before training, there was a multi-disciplinary team meeting involving the relevant key stakeholders to discuss training content based on the technical, tactical and physical workload aims. Modifications in workload were made throughout the week to ensure, where possible, planned workloads were adhered to. For example, four days before the game, training was typically intensive, involving small pitch sizes and short high intensity drills. An example focus of an intensive session is quick movement of the ball (technical) and pressing the opponent (tactical). These sessions accumulated many accelerations and decelerations because of the small areas and high player contacts. If the session outputs for these actions were greater than planned, the drills would be adapted on the following day, to reduce further accumulation beyond weekly recommendations. Three days before the game was usually extensive, with larger pitch sizes, and physical outputs closer to game activity. To reduce accelerations and decelerations based on the previous day, drills were modified by increasing pitch area per player, or shortening total session duration.

By applying the findings and learnings from Chapters 4 & 5, a training programme was implemented during the 2017-18 season which aimed to progressively increase workloads (avoiding acute workloading spikes) to achieve moderate-high chronic exposure (Figure 9). Training at consistently high chronic workloads may result in stress-related injuries (Drew, Raysmith, & Charlton, 2017) and therefore a workload 'ceiling' was set. The players may have two games within a week maximum, interspersed with light training. Thus, the equivalent of three games worth of work a week was used as the workload ceiling, as this was considered worst-case scenario. In addition to the progressive increases in workload, workload was periodised in three-week blocks (based on the accumulated workload results of Chapter 4), involving a de-load week, a maintenance week and an overload week (Figure 9). The ACWR thresholds for each of these weeks were at ~0.85 for a de-load, ~1.0-1.2 for a moderate week and ~1.4-1.7 for a high week, based on the results of Chapter 5. Players who did not regularly play in matches or were returning from injury, were provided with top-up conditioning across the required metrics to maintain sufficient acute and chronic workloads.

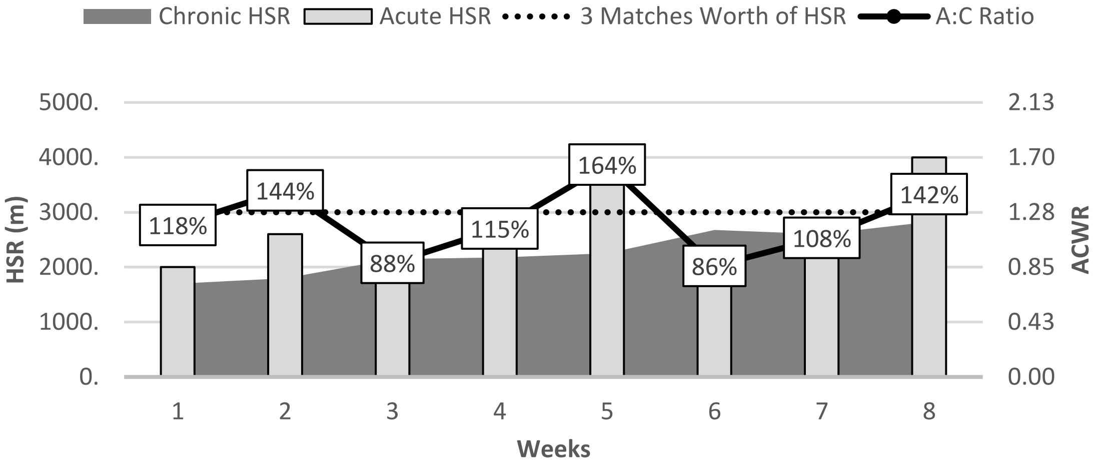

Figure 9. Graphical representation of the progressive increase of a player's chronic high speed running over the course of 8 weeks. The player begins with a chronic workload of 1700 m representing a 2-match workload and is trained with the goal of progressively increasing his chronic workload to the equivalent of 3 matches per week. The periodisation model used a 3-weekly cycle including a maintenance week with an acute:chronic workload ratio (ACWR) of ~1.0-1.2, an overload week (~1.4-1.7), followed by a de-load (~0.85). Adapted from "Recommendations for hamstring injury prevention in elite football: translating research into practice" by M. Buckthorpe et al., 2018, *British Journal of Sports Medicine,* doi: 10.1136/bjsports-2018-099616.

6.03.6 Statistical analyses.

Independent samples T-tests were used to compare ACWR and RR (based on Chapter 5 results) between injured and non-injured players during the 2017-18 season. RR was calculated in Chapter 5 to determine the magnitude of the injury risk above and below given workloads or ratios (MedCalc Software, Ostend, Belgium). When an RR was greater than 1.00, an increased risk of injury was reported (ie, RR=1.50 is indicative of a 50% increased risk) and vice versa. For an RR to be significant, 95% CIs did not contain the null RR of 1.00. One Way ANOVA tests were used to examine differences in workload and injury incidence between the current season and the previous three seasons. Data were analysed using IBM SPSS Statistics V.25.0 and reported as means ± standard deviations. Significance was accepted at $p<0.05$. Magnitude based inferences were also used to determine the practical meaningfulness of the differences between groups and seasons. These were reported as Cohen's effect sizes (d) with d ± 95% CI described as < 0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, 2.0–4.0 very large (Hopkins, 2002).The likelihoods that the true values of the effect represented meaningful differences were assigned the following qualitative terms: <75% trivial, >75% likely, 95% very likely, >99.5% almost certainly that the effect size exceeded 0.20 (Batterham & Hopkins, 2006). The magnitudes of differences between groups were considered practically meaningful when the likelihood was ≥75% (Batterham & Hopkins, 2006). An effect where there was >5% chance of the change being positive or negative was deemed as unclear.

6.04 Results

6.04.1 Injury incidence.

During the 2017-18 season there were 42 injuries (7.0 injuries/1,000h) (Appendix C) compared to (13.3/1000h) across the previous 3 seasons (2014-15 season, 17.6/1000h; 2015-16 season, 10.2/1000h; 2016-17 season, 12.4/1000h). The posterior thigh was the most common site of injury (1.8/1000h), all of which were non-contact muscle injuries. The ankle was the most common site of contact injury (0.7/1000hours), which were either ligament sprains or synovitis/effusions. The injury incidence in competition was almost six times that of training (23.4/1000hours vs 3.6/1000hours). Despite a lower exposure to competition, 83% of contact injuries and 43% of non-contact injuries occurred in matches. The total number of days missed through injury was 545 (13.0±19.0 [mean±SD] days per injury). There were no statistically significant differences in non-contact injury incidence between the 2017-18 season (3.3/1000h) and the previous three seasons (2014-15; 7.6/1000h, 2015-16; 4.6/1000h, 2016-17; 4.5/1000h). However, magnitude-based inferences revealed a moderate effect that is likely to be positive (F(3,82)= 1.56, p=0.20, d=1.6±2.4, 81%, likely +ve).

6.04.2 ACWR and RR between injured and non-injured players.

There were no statistical or practically meaningful differences in the ACWR or the RR of injury, between injured and non-injured players during the 2017-18 season (Table 21).

Table 21. *The differences in acute:chronic workload ratios and relative risk of injury (based on the findings of Chapter 5) between injured and non-injured players using t-tests.*

	Non-Injured		**Injured**				
ACWR	*Mean*	*SD*	*Mean*	*SD*	*t*	*p*	*Qualitative Inference*
TD	1.03	0.27	1.03	0.30	-0.08	0.94	*trivial*
LID	1.04	0.30	1.02	0.34	0.24	0.81	*trivial*
HSD	1.03	0.39	1.01	0.29	0.28	0.78	*trivial*
ACC	1.03	0.28	1.07	0.33	-0.57	0.57	*trivial*

DEC	1.03	0.27	1.07	0.33	-0.69	0.49	*trivial*
RR							
TD	1.09	0.42	1.17	0.27	-0.81	0.42	*trivial*
LID	1.02	0.50	1.00	0.38	0.18	0.86	*trivial*
HSD	1.01	0.21	1.07	0.15	-1.13	0.26	*trivial*
ACC	0.98	0.42	0.98	0.33	-0.04	0.97	*trivial*
DEC	0.96	0.33	0.98	0.23	-0.18	0.86	*trivial*

Note: TD=total distance covered, LID=low intensity distance, HSD=high speed distance, ACC=accelerations, DEC=decelerations, ACWR=acute:chronic workload ratio, RR=relative risk.

6.04.3 Acute workloads in current study vs previous study.

The 2017-18 season had significantly higher acute workloads for all measured variables compared to the previous three seasons (Table 22). When analysed as individual seasons, all variables were significantly different across the four seasons (Figure 10). Post-hoc analysis revealed that the 2017-18 season had significantly higher ACC (F(3,80)=34.26, p=0.000) and DEC (F(3,80)=59.81, p=0.00) workloads compared to all other seasons. For HSD (F(3,80)=10.69), 2017-18 was significantly higher than both 2014-15 and 2015-16 (p=0.00). TD (F(3,80)=8.61) was higher in 2017-18 than the 2015-16 season (p=0.00). LID during the 2017-18 season was significantly greater than during the 2015-16 (p=0.00) and 2016-17 (p-0.01) seasons.

6.04.4 Chronic workloads in current study vs previous study.

The chronic workloads during the 2017-18 season were higher across all GPS-derived metrics than the previous three seasons (Table 22). All metrics were also significantly different when the seasons were analysed individually

(Figure 11). The 2017-18 season had greater chronic TD (F(3,80)=9.68), LID (F(3,80)=13.44), ACC (F(3,80)=33.43) and DEC (F(3,80)=57.57) compared to all other seasons (p<0.05). For HSD (F(3,80)=13.57), 2017-18 had significantly higher distances than both 2014-15 and 2015-16 (p=0.00). Despite the mean outputs being higher during 2017-18 season there were no significant differences in HSD with the 2016-17 season (p=0.35).

6.04.5 ACWRs in current study vs previous study.

The ACWRs during the 2017-18 season were significantly lower across all metrics than the previous three seasons (Table 23). All metrics were significantly different across the four seasons (p<0.05) (Figure 12).

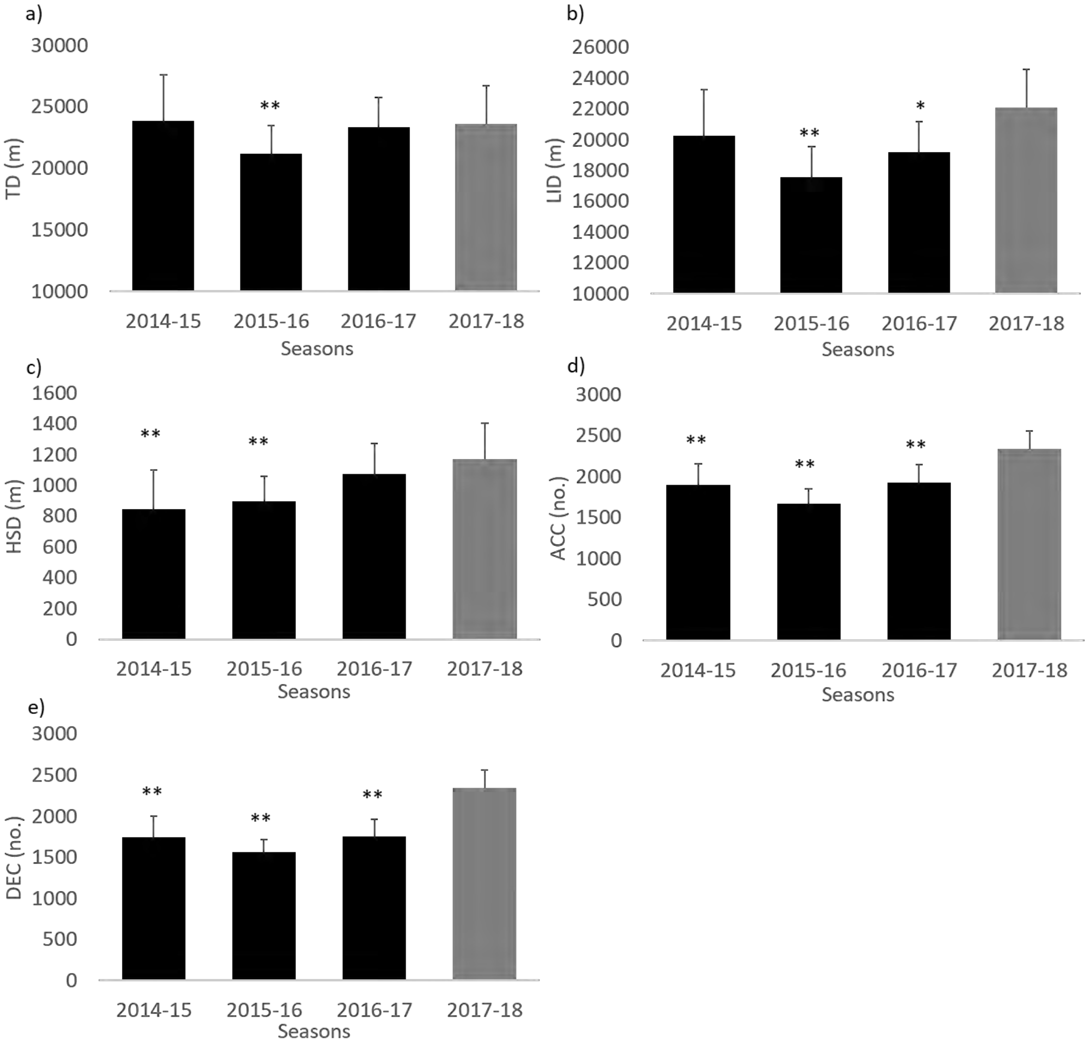

Figure 10. Differences in acute workloads during 2017-18 season compared to the three previous seasons, across various GPS-derived metrics: a) total distance (TD), b) low intensity distance (LID), c) high speed distance (HSD), d) accelerations (ACC), e) decelerations (DEC). *p<0.05, **p<0.001.

Post-hoc analysis revealed that the 2017-18 season had significantly lower ACWRs than the 2014-15 season for all GPS variables. There were no significant differences in ACWRs between the 2017-18 season with the 2015-16 season or the 2016-17 season, despite having lower mean outputs.

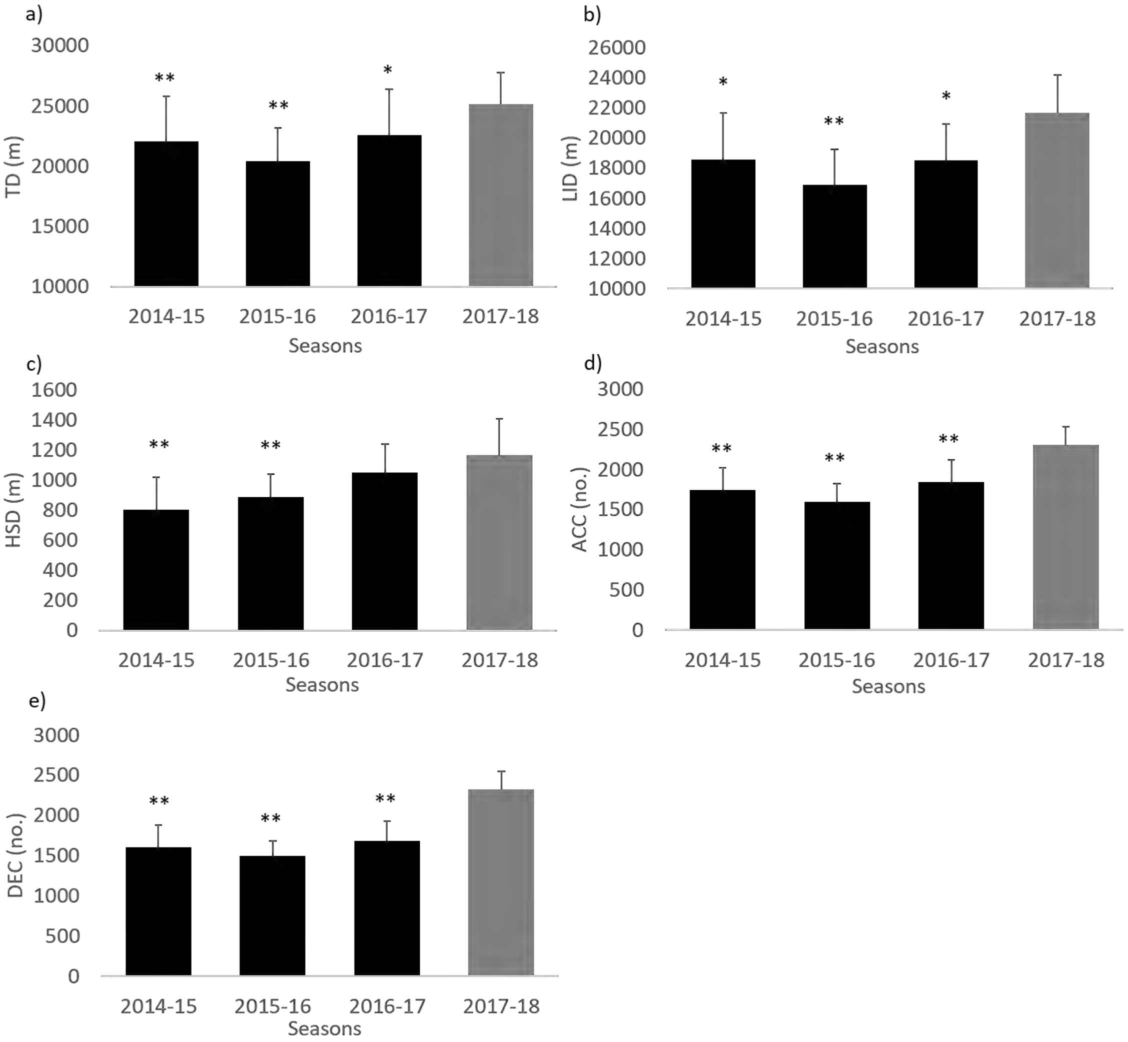

Figure 11. Differences in chronic workloads during 2017-18 season compared to the 3 previous seasons, across various GPS metrics: a) total distance (TD), b) low intensity distance (LID), c) high speed distance (HSD), d) accelerations (ACC), e) decelerations (DEC). *p<0.05, **p<0.001.

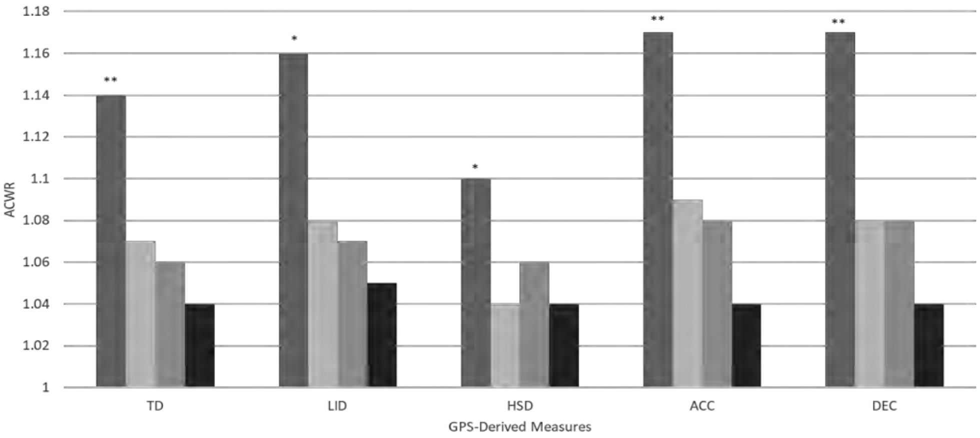

Figure 12. Differences in ACWR during 2017-18 season compared to the 3 previous seasons, across various GPS metrics: a) total distance (TD), b) low intensity distance (LID), c) high speed distance (HSD), d) accelerations (ACC), e) decelerations (DEC). *p<0.05, **p<0.001.

Table 22. *The differences in acute and chronic workloads and acute: chronic workload ratios (ACWR) between 2017-18 season and the previous three seasons using t-tests.*

	Current Season		**Previous 3 Seasons**		
Acute	*Mean*	*SD*	*Mean*	*SD*	*t*
TD (m)	25,414	2,496	22,804	3,059	-3.77**
LID(m)	22,077	2,506	19,012	2,545	-5.07**
HSD (m)	1,170	234	942	226	-4.17**
ACC (no.)	2,330	223	1,831	249	-8.67**
DEC (no.)	2,344	220	1,691	223	-12.38**
Chronic					
TD (m)	25,154	2,597	21,694	3,212	-4.76**
LID(m)	21,668	2,492	18,001	2,700	-5.82**
HSD (m)	1,164	239	917	211	-4.74**
ACC (no.)	2,301	228	1,731	277	-9.06**
DEC (no.)	2,319	230	1,598	246	-12.85**
ACWR					
TD	1.04	0.04	1.09	0.10	3.37*
LID	1.06	0.05	1.10	0.11	2.92*
HSD	1.04	0.04	1.07	0.09	2.04*
ACC	1.04	0.04	1.11	0.12	4.03**
DEC	1.04	0.04	1.11	0.12	4.18**

Note: TD=total distance covered, LID=low intensity distance, HSD=high speed distance, ACC=accelerations, DEC=decelerations, ACWR=acute:chronic workload ratio, RR=relative risk, *p<0.05, **p<0.001.

6.04.6 Workloads and injury incidence across the four seasons for the eight consistent players.

Acute and chronic workloads were higher in the 2017-18 season for all variables compared to the previous three seasons, as per the whole squad analysis. However, the ACWRs were not significantly different between any seasons for those eight players. Average injury incidence for the eight player is detailed in Table 23.

Table 23. *Injury incidence across 4 seasons for eight players.*

	Injury Incidence (per 1,000h)	
Season	Mean	SD
2014-15	7.7	7.3
2015-16	10.1	5.9
2016-17	7.7	7.4
2017-18	4.8	4.5

6.05 Discussion

This is the first study to examine the effectiveness of using ACWRs in elite football for injury prevention and performance enhancement. ACWRs and RR of injury (based on the findings of Chapter 5) were not different between injured and non-injured players. However, workloads were higher in the current season, with fewer acute workload spikes, than previous seasons where ACWR monitoring was not utilised. In addition, whilst not statistically significant, injury incidence was almost halved in the current season compared to the previous 3 seasons, demonstrating a 81% likely positive meaningful effect.

Chapter 4 and 5 advocated the implementation of gradual, progressive workloads to enhance fitness, whilst providing enough recovery between overloads to allow the negative effects of fatigue to subside (Meeusen, et al., 2013). Consequently, in the 2017-18 season, the training programme aims were to push players' chronic exposure to workload, via measured increments in acute workloads. Training was periodised into 3-weekly blocks of overload, de-load then maintenance in reference to the ACWRs. This allowed the players to train harder than they previously had (acute workload >chronic workload), followed by a de-load (chronic workload > acute workload) to aid recovery and adaptation (Figure 13). The ACWR approach to workload monitoring resulted in an increase in both acute and chronic workloads, as well as a reduction in ACWRs or workload ‘spikes’ in the current season, compared to the previous three seasons when the focus of monitoring was the absolute accumulation of workload.

Research in both rugby and football has demonstrated the protective effect of high chronic workload exposure on injury risk (Bowen, et al., 2017; Bowen, Gross, Gimpel, Bruce-Low, & Li,, 2019; Hulin et al., 2016). One possible explanation is that athletes who can achieve high exposure have the enhanced physical attributes needed for decreased injury risk (Malone, et al., 2016). Additionally, by gradually increasing their acute workloads, athletes can develop the physical attributes required to perform and cope with demands (Tønnessen, et al., 2011). Thus, the augmentation of both acute and chronic workloads in the current study is interdependent. It is likely that correctly programmed higher acute workloads have developed the players’ physical capacities for high chronic workloads, which in turn, has allowed coaches to push the acute workloads higher, due to the players’ increased workload tolerance.

Despite training harder, and potentially being more physically robust, there were no differences in total non-contact injury incidence between the current season and the previous three seasons. However, although large individual variations prevented significance, the mean injury incidence for the current season was almost half that of the previous 3 seasons (7.0/1000h vs 13.3/1000h). Magnitude based inferences confirmed a 81% likely positive effect of season on injury incidence. Therefore, despite not being statistically significant, the findings are practically meaningful.

Furthermore, as the total number of injuries was similar (42 per season vs 44 per season), this means injuries occurred less frequently, i.e. the players trained for more often, for longer durations (and harder) without increasing the risk of injury.

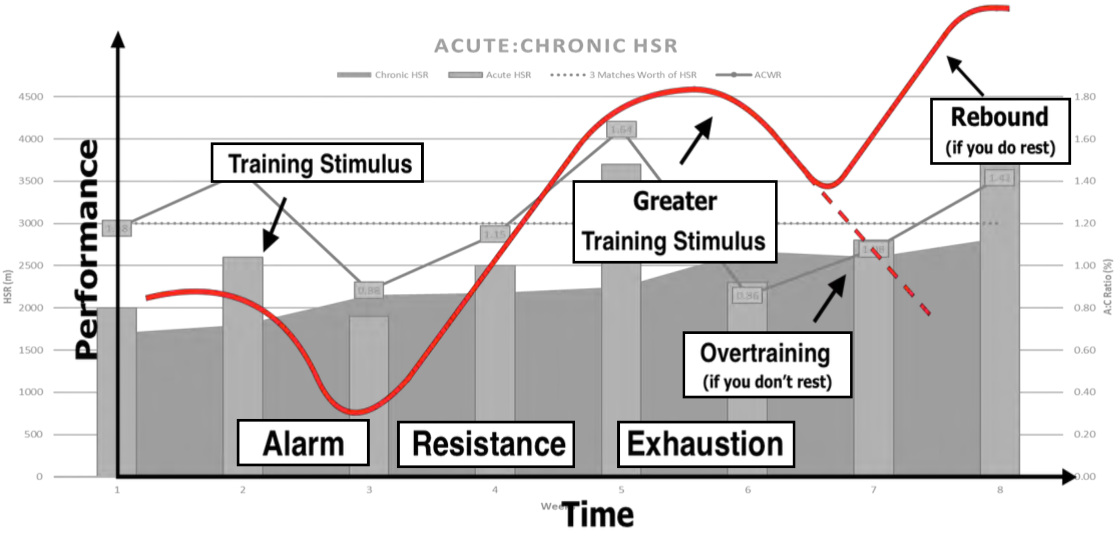

Figure 13. Graphical representation of the three-weekly training periodisation in conjunction with Seyle's General Adaptation Syndrome (Seyle, 1946). Adapted from "Recommendations for hamstring injury prevention in elite football: translating research into practice" by M. Buckthorpe et al., 2018, *British Journal of Sports Medicine,* doi: 10.1136/bjsports-2018-099616, and "Progressing as a Derby City athlete" by Slater Coe, https://derbycitycf.com/progressing-as-a-derby-city-athlete/.

Furthermore, there were no differences in ACWR or RR of injury based on the findings of Chapter 5, between injured and non-injured players during the 2017-18 season. Recently, a number of studies have concluded that whilst the ACWR is associated with injury, it cannot be used as a diagnostic tool to predict injury risk for individual players (Fanchini et al., 2018; Delecroix et al., 2018; Lu, et al. 2017). The multi-factorial nature of injury provides an obvious explanation for the lack of predictive ability of ACWR monitoring. Within the current study many of the internal and external risk factors detailed in the workload-injury aetiology model may have contributed to the injury incidence, alongside workload, although future research is required to confirm this (Windt & Gabbett, 2017).

One external factor that may have contributed to the injury incidence is the change in manager. Leadership style and the interaction with sport science and medical practitioners has been found to be correlated with injury risk across 36 elite football teams (Ekstrand, et al., 2018). Throughout the duration of the four seasons, the team worked under four managers from four different countries and backgrounds, with varying leadership styles. Coach support and coach philosophy have both been found to affect the success of injury prevention strategies in sport (Akenhead & Nassis, 2016; Gabbett, et al., 2016). Within the current study, the relationship and communication between coaches and practitioners was subjectively open and effective, allowing the successful implementation of the ACWR model (reflected in the increased workloads). However, whilst it can only be speculated within the constraints of the study methodology, the different coaching philosophies of the two managers throughout the current season may have influenced injury incidence.

The change in management may also have influenced the workload completed due to differences in technical and tactical aspects. As it was not an aim of this study to determine the effect of management change on workload, it was not originally included in the data analysis. However, to exclude it as a confounding factor, the differences in workload between the two managers was assessed post-study (Appendix D), finding no significant change. Future research should analyse the coaching philosophies and related injury incidence within a football club. With the large turn-over in managers common to the EPL now (Bell, Brooks, & Markham, 2013), it should be possible to maintain a similar cohort but analyse multiple managers.

The greatest cause of time-loss throughout this study was hamstring injuries, where in the previous seasons knee injuries had been most prevalent. Hamstring injuries have increased annually in football, despite the increase in preventative research and practice (Ekstrand, et al., 2016). This has been attributed to the increase in the intensity of physical demands at the elite level (Barnes, et al., 2014). Supporting this, hamstring injuries have recently been associated with an increase from a player's two yearly average exposure to high speed running (Duhig, et al., 2016). Within the current study, 91% of the hamstring injuries occurred in players over the age of 27 years. The odds of suffering a hamstring injury increased by 1.78 for every 1-year increase in age in EPL football players (Henderson, Barnes, & Portas, 2010). Many other internal factors have been identified as predisposing an athlete to hamstring injury including previous injury, strength, psycho-social factors, somatotype, flexibility etc. (Buckthorpe, et al., 2019). Whilst it was beyond the scope of this study to analyse all the contributing factors to injury, the augmented workloads in the current study may not have been effective at protecting the players who were predisposed to a heightened risk of hamstring injury. Thus, ACWR monitoring alone is not effective as an injury prevention method. Consequently, we have recently published an education review detailing our five-point hamstring injury prevention that was developed based on the literature and our learnings as a multi-disciplinary sport science and medicine team over the last few years (Buckthorpe, et al., 2019). Future research should detail and assess the effectiveness of holistic injury prevention strategies specific to football.

6.06. Conclusions

In conclusion, using the ACWR method to monitor and programme workloads was effective in improving workload tolerance, with players training harder in the current season, than previous seasons, without an increase in injury incidence. However, the lack of change in injury incidence and no change in ACWR between injured and non-injured players, suggests that ACWR monitoring alone cannot be used as an effective injury prevention method. However, using the ACWR to increase the players' physical capacity and robustness, in conjunction with other injury prevention strategies addressing other risk factors, may provide a best practice approach. This study provides an insight into the implementation and effectiveness of ACWR monitoring in practice, however caution must be taken when applying these findings to populations outside the studied cohort.

CHAPTER 7. GENERAL DISCUSSION

7.01 Overview

Within an elite football environment, sport scientists will typically prescribe high workloads which are aimed at enhancing athletic performance through physiological adaptation to stress. Conversely, the medical staff advocate lower workloads with the aim of reducing the risk of injury (Ekstrand, et al., 2019). Both approaches have equal importance in maximising team success, however, workloads must be planned in synergy in order to be effective (Gabbett & Whiteley, 2017).

The introduction of GPS for the quantification of workloads has allowed practitioners to more accurately prescribe the work performed (Borresen & Lambert, 2009), however overall injury rates in elite football remain unchanged, and hamstring injuries have risen (Ekstrand, et al., 2016). Hence, there appears to be a lack of understanding as to the optimal amount of work to prescribe, which enhances physical capacity without unduly increasing injury risk.

The primary purpose of this thesis was to identify and understand the relationships between GPS-derived workload and injury within an EPL football club. The enhanced understanding of workloads and the associated risks gained from completing this research was then implemented into practice at the same club. Thus, a secondary aim was to determine the effectiveness of informed workload prescription as an injury prevention method in elite football.

This chapter (Chapter 7) will be structured into three parts:

- Firstly, a discussion around the key learnings of this thesis, both as individual chapters and as a collective. Within this, the importance of these finding to current theory and practice are considered.
- Secondly, the constraints of undertaking this applied research in elite football are addressed.
- Finally, the limitations, areas for future research and main conclusions are presented.

7.02 Main Discussion

7.02.1 Validity, reliability and inter-changeability of GPS and SACS.

Throughout this thesis, GPS was used to quantify external workload. For the academy players (U18 and U21), GPS devices were worn in both training and matches. However, for the senior players, from the 2015-16 season onwards, GPS was used in training, whilst SACS was used during match play. The aim of Chapter 2 was to assess the reliability and validity of SACS and GPS and to determine any discrepancy between these systems in both a football-specific circuit and during match play. The key findings were that both systems showed good validity and reliability during the circuit, although this was decreased with tasks involving multi-directional movements and decelerations, as previously found (Jennings, et al., 2010). In match-play, GPS and SACS were comparable for distances covered at all speeds except sprint distance. Consequently, sprint distance was not used to establish workload-injury relationships within this thesis. However, repeated sprint ability is essential to football performance success (Delaney, et al., 2017), as well as being a substantial physical stress. Therefore, the exclusion of this metric may have resulted in the effect of high intensity efforts on injury occurrence being underestimated. Since the start of this thesis, GPS technology has developed and rule changes have permitted their use in competition. Thus, future research with heightened accuracy should now be possible exploring the relationships between sprint distance and injury risk.

7.02.2 Youth vs senior football.

To achieve the UEFA ruling of eight home-grown players per 25-man squad (UEFA, 2014), youth academies are part of and funded by professional clubs. At Southampton FC, the development of youth players is a main strategic focus, as they do not have the budget to compete with the top teams who can buy large numbers of talented players. As a consequence, injury prevention strategies are applied club-wide to maximise player availability at the top level, and to maximise player progression at the youth level. Hence, this thesis explored workload and injury relationships in both youth and senior players, to inform practice throughout.

Chapter 3 served to quantify the differences in workload between the studied squads (U18s, U21s and seniors). The key finding was that whilst the match outputs did not vary significantly, the training demands were different for each squad. This was attributed to the different technical and tactical requirements of the three squads, with the main focus shifting from development to performance as they progress to the senior level. Despite injury incidence being higher in matches (Ekstrand, et al., 2011), training exposure was typically 5-6 times higher than match exposure (Bengtsson, 2017), constituting a large proportion of the workload. Moreover, this study highlighted that findings from youth players cannot be generalised to adult players or vice versa. Consequently, the youth and senior players were analysed separately when determining workload-injury relationships.

7.02.3 Workload and injury relationships.

The difference in youth and adult training focus may explain the variance in results between Chapters 4 and 5, most notably regarding contact injuries. Chapter 4 assessed workload and injury relationships within the U18 and U21 squads, whilst Chapter 5 assessed the same relationships in senior players. The U18 and U21 players had a higher risk of contact injury when the ACWRs for TD and ACC were very high. This could potentially be explained by greater levels of fatigue preventing players from responding to the rapid, unpredictable movements preceding contact injury. However, these findings were not reflected in the senior players. Over 80% of the contact injuries recorded at the elite level occurred during competition, where workload is non-modifiable, limiting the association between workload prescription and contact injury risk. In contrast, only 44% of the contact injuries at the youth level occurred in competition. One possible explanation for the higher number of contact injuries in youth football training is the different definitions of success for each squad. For youth players, success is progression into the senior team, whereas for the senior players, success is based on match outcomes (Vaeyens, Coutts & Philppaerts, 2005). Thus, there is a greater level of pressure to exceed as an individual rather than as part of a team for youth players (Pfirrmann et al., 2016). As a result, youth players are less likely to modify the intensity of their tackles on their teammates during training. Conversely, at the elite level, players may self-manage contact situations during training, as their focus is on their team performance on a match day, resulting in lower numbers of contact injuries in training. Nevertheless, the increased pressure to succeed in competition at the senior level may explain why overall contact injury incidence (4.3-5.9/1000h) was similar to the youth players (4.7-5.6/1000h). Regardless, the findings would indicate that general fatigue management and player education may reduce contact injuries in the youth players. Furthermore, workload prescription has little to no effect on contact injury incidence, especially in senior players.

Conversely, workload prescription was found to be a key factor in the incidence of non-contact injury for both youth and adult players. In the youth players, a high ACWR (1.41-1.96), coupled with a low chronic workload for HSD (<938m), showed a significant risk of non-contact injury. However, when the chronic workload was categorised as high, this injury risk was no longer significant. Similarly, in the adult players, a very high ACWR combined with a low chronic workload only, showed the greatest non-contact injury risk for most metrics (except HSD). When all chronic workloads were analysed, a very high ACWR demonstrated a lesser but still significant risk for the same metrics. These findings are in line with studies in cricket (Hulin, et al., 2014), rugby (Hulin, et al., 2016; Hulin, Gabbett, Caputi, et al., 2016), Australian football (Stares, et al., 2018) and Gaelic football (Malone, Roe, et al., 2017) where high ACWR, referred to as 'spikes' in workload, have been associated with heightened injury risk. Thus, the findings of this thesis support the growing body of literature suggesting that acute, excessive, rapid increases in workloads are associated with a large proportion of non-contact injuries, whilst exposure to higher chronic workloads may have a protective effect (Gabbett, 2016).

Interestingly, HSD had strong associations with injury risk in youth players, with high chronic workloads demonstrating the aforementioned protective effect. However, it was the only GPS metric not to have any association with injury risk in adult players. One explanation for this may be the use of arbitrary speed thresholds, across all squads, which did not account for the individual and potentially faster speeds the senior players could achieve, making it easier to perform HSD; Players with a max speed of 10m/s find it easier to reach the HSD arbitrary threshold of 5.5m/s, as it is 55% of their maximum, compared to players who have a max speed of 8.5m/s making this 65% of their maximum. This is supported by the greater maximum speeds of senior players compared to U18 players in Chapter 3. Therefore, HSD may underestimate the intensity of performance and the risk of injury for the older players.

Conversely, Chapter 3 also found similar HSD performed by U18, U21 and senior squads across a week. Furthermore, the HSDs analysed for Chapter 3 and Chapter 5 were similar (medians: 938m vs 946m). Therefore, it may be that the senior players studied had the enhanced physical qualities required to tolerate HSD, reducing the association with injury risk. Supporting this, at high chronic HSD workloads (>938m), youth players were at heightened risk of injury when the ACWR were moderate-high (i.e. the acute workloads were similar to the chronic workloads). This suggests that youth players cannot maintain high HSD workloads, regardless of chronic condition, and must be given appropriate de-loads after a high stimulus to reduce risk. Similarly, previous research has found that extended playing experience and higher 2-year exposure reduced the associated hamstring injury risks associated with acute bouts of HSD (Duhig, et al., 2016). Thus, youth players should be prescribed HSD workloads which fluctuate to provide both stimulus and recovery, whilst gradually increasing the chronic workloads to meet the requirements of the senior level. In addition, more research is needed regarding the effect of training history on the injury risks associated with ACWRs, not just in terms of duration, but exposure to workloads.

Contrary to the findings of this thesis, previous research has found an increased risk of injury with acute spikes of HSD in senior football (Malone, et al., 2018). One explanation for this may be the different training philosophy of Southampton FC compared to other clubs studied in the literature. Within the current thesis, the average senior player covered 950-1200m of high speed running per week with no significant injury risk. However, Malone, et al. (2018) had a moderate high speed running group covering 201-350m, with the high reference group covering 350-525m. Therefore, the players in this thesis regularly cover considerably greater distances at high speeds, which may have developed their physical tolerance to these workloads.

The augmented workload capacity of the senior players may also explain why injury risks occurred at higher ACWR for adult players (>2.0) than for youth players (>1.5). The heightened risk of injury at lower workloads for youth players may be because they have not had the chronic exposure to increase their tolerance to greater workloads. Furthermore, it is the more physically robust youth players who typically make it through to seniors (Mills, et al., 2012), who can tolerate higher workloads whilst remaining injury free. Therefore, at senior level, players should have had chronic exposure to the positive adaptations that result from training hard, increasing their workload capacity, whilst the less robust players may have been released or had to retire due to injury (Windt & Gabbett, 2017). This explanation is supported by work in rugby (Hulin, Caputi, et al., 2016), which concluded that the players who were capable of achieving higher workloads had the enhanced physical attributes needed for decreased injury risk.

Hence, there appears to be a positive feedback loop between workload capacity and physical attributes. That is, workload develops physical qualities, which in turn, increase tolerance to workload (Gabbett, et al., 2019). This thesis provides support for previous speculation that individual and appropriate workload management solves the problem of “which comes first?” to create a robust athlete (Gabbett, et al., 2019). Ultimately, gradually progressing the chronic workload, whilst avoiding acute ‘spikes’ may improve physical qualities, which in turn improves the players’ workload capacity (Chapter 1, Figure 6). Future research which encompasses valid measurements of all the physical qualities required for performance, alongside ACWRs, to assess associations with injury risk is required.

7.02.4 Workload prescription for injury prevention.

This thesis demonstrates that in elite football, high workloads are not injurious provided they are prescribed correctly and appropriately. Chapters 4 and 5 recommend initial guidelines for workload prescription in elite football without increasing the chance of injury have been proposed. The secondary aim of this thesis was to determine whether these guidelines were effective as an injury prevention strategy in practice. The transfer of research into practice in this field has previously been poor (Akenhead & Nassis, 2016). This has been attributed to the research not directly answering the performance question or not being specific to the target population (Bishop, 2008). The performance question asked of this thesis from the coaches was "How hard can the players at Southampton FC work without increasing their risk of injury?". Having answered this retrospectively in Chapters 4 and 5, Chapter 6 used those initial guidelines to prescribe workloads prospectively (in the following season after Chapter 5) in the senior squad at Southampton FC. The effectiveness of informed workload prescription as an injury prevention tool in practice was then assessed.

The key finding of this applied study was that using the ACWR method to monitor workloads appears to allow players to work harder without increasing the risk of injury. Specifically, by using the ACWR guidelines set out in Chapter 5, acute and chronic workloads were higher in the most recently studied season (Chapter 6; 2017-18), despite no increase in non-contact injury incidence. Although there was no significance, mean injury incidence was almost halved in the 2017-18 season, compared to the previous three seasons (7.0/1000hours vs 13.3/1000hours). Magnitude based statistics found this difference to be practically meaningful, showing a positively 81% likely effect. This was also the case when injury incidence was only considered for the eight players who remained consistent from the 2014-15 season to the 2017-18 season. These players recorded a mean injury incidence of 4.8/1000hours in 2017-18 vs

8.5/1000hours in the previous 3 seasons. As the number of injuries remained similar across the seasons, this was a result of the players training more often and for longer durations without any additional injuries. This can be demonstrated by displaying injury rate, as injuries per 100km of HSR, as opposed to the traditional method of injuries per thousand hours; In the 3 previous seasons there were 3.2 injuries 100km compared to 1.4 injuries per 100km of HSR in the current season. Hence there were less injuries per metre ran in the current season, than the previous three seasons.

Therefore, whilst ACWR did not reduce injury occurrence, it did contribute to the players being able to train harder and longer without increasing the risk. It seems possible that if the same players continued to achieve higher (appropriate) workloads, over time, their physical robustness would increase and injury rates may improve. Future research exploring the long term effects of optimal workload prescription would therefore enhance the current body of research. In addition, chronic workloads cannot increase indefinitely; thus, research exploring the optimal, achievable limits to this progression would be of value.

However, it must be acknowledged that workload monitoring cannot be used as an injury prevention tool in isolation. As discussed in Chapter 1, workloads are merely a vehicle by which injury occurs. There must still be an inciting event, in combination with numerous modifiable and non-modifiable risk factors which contribute to injury incidence (Windt & Gabbett, 2017). Hence, to prevent injuries effectively, all risk factors relevant to each individual must be addressed. However, using the ACWR to increase the players' physical capacity and robustness, in conjunction with other injury prevention strategies addressing other risk factors, may provide a best practice approach.

Within research, thousands of cases would be required to statistically determine the effect of a combination of strategies on injury prevention. Within practice, the number of cases required are almost always impossible, if not at least improbable to attain. Case studies and education reviews may provide a practical solution to enhancing the knowledge and understanding of the wider population. As hamstrings were the most common site of non-contact injury reported in Chapter 6, the medical and sport science staff at Southampton FC recently developed a five-point hamstring injury prevention strategy. This is based on the literature, the findings of this thesis, and the learnings of the staff over the last few years (Buckthorpe, et al., 2019). Whilst this is a start, more injury prevention strategies are required addressing multiple risk factors. In addition, it would be interesting and useful to assess the effectiveness of these strategies in practice.

7.03 Research Constraints Within a Practical Elite Football Environment

The research presented in this thesis was completed in an applied setting, and the findings have been used to inform and influence daily practices at Southampton FC. To ensure optimal and accurate transfer of this research to practice, the workload and injury relationships were assessed within the dynamic environment, rather than trying to reduce or ignore the uncontrollable elements. Thus, the main environment-driven confounding factors for this research were player transfers in and out of the club, management changes, external factors affecting weekly workload and coach/player understanding. These four barriers are discussed below.

7.03.1 Player transfers.

The movement of players in and out of the football club happens in two periods throughout the season, during the summer transfer window (May-August) and the winter transfer window (January). Therefore, in Chapters 5 and 6, there was not a consistent set of players studied throughout the three seasons. In order to account for this as best as possible, Chapter 6 assessed the workloads of the eight players who remained consistent throughout the study period. Additionally, in Chapter 4, only 63% of the players were present in both seasons, with the others either being released from the club or progressing to the senior team. To increase scientific rigour, the same participants would have been used throughout the thesis. A sample size of eight however is not enough to run comprehensive statistics (Bahr & Holme, 2003). Furthermore, player transfers are part of normal practice within a football team and therefore workload monitoring strategies and practitioner understanding must be adaptable to this. Despite the large turnover of players, the significant findings throughout this thesis suggest that relative workload monitoring using ACWR can be applied across different players.

7.03.2 Management changes.

As presented in the discussion section of Chapter 6, a change in the manager may have implications for workload monitoring. Management change has been associated with injury risk within 34 elite football teams (Ekstrand, et al., 2018). Furthermore, leadership style, philosophy and coach support have all been found to affect workload monitoring as an injury prevention strategy (Akenhead & Nassis, 2016). Within the senior team, the manager changed four times throughout the study period, each with different philosophies of the game. All managers operated a typical Saturday to Saturday periodisation (with match days usually on a Saturday). The ACWR used throughout was 7:28 days to fit in with this structure. Therefore, the effect of variation in workload prescription on monitoring between managers was minimal during this thesis (Figure 14). Additionally, Chapter 6 demonstrated that workloads did not significantly vary between the two managers throughout the 2017-18 season. Ideally, the manager of each team would have remained consistent throughout the thesis, however management turnover is high in the EPL (Bell, et al., 2013), and must therefore be accepted as a confounding factor. The significant findings of this thesis suggest that as with player transfers, ACWR is sensitive to injury risk, regardless of manager. Future research should explore the direct effect of management change on injury incidence within the same cohort over a period of time.

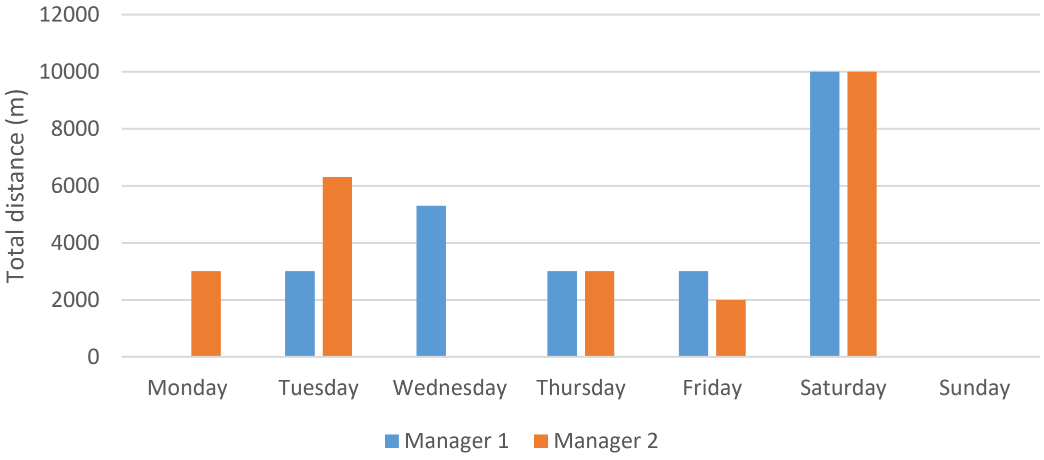

Figure 14. Differences in total distance workload and periodisation between the two managers during the 2017-18 season.

703.3 External factors affecting workload.

Elite football is a fast-paced, ever changing environment, where numerous factors outside of the game can affect workload and performance. For example, travel to and from away games disrupts the regular training structures, with additional recovery required for longer journeys. Furthermore, the weather, media commitments, international team commitments, cup competitions, coaching decisions and player absences have all interrupted a typical training week, and therefore workloads, throughout this thesis.

International breaks present one of the biggest challenges for workload monitoring, as each national team either uses different monitoring systems to that of the club, different systems to each other, or do not use monitoring systems at all (Buchheit, 2017). Consequently, for the ~50% of the squad, data is often estimated based on their club session averages for 8-10-day periods at a time, 3-4 times a season, whilst they are on international duty. In the case of international breaks, using a 7:28 day ratio means that if one week of data is missed, it will be another four weeks before the ACWR is no longer compromised, which very often coincides with another international break (Buchheit, 2017). To avoid artificial spikes or drops in workload, any event which resulted in data being missed was replaced with an average (either individual or session depending on the event), in each chapter. Whilst estimations create a level of inaccuracy, they provide an acceptable alternative to no data at all, and allow continuous workload monitoring. Collaborative research between club and country teams is required to provide a complete workload profile of international players, and to enhance sport science and medical practice.

Coach decisions and player absences have only highlighted the flexibility of ACWRs for use in practice. Within a given week, a coach may decide to change the session content based on specific tactics they wish to work on, increase/decrease the number of sessions or durations, or add/ remove physical conditioning. In addition, the sudden absence of a player (e.g. through illness) may increase or decrease the workload for other players, particularly during small sided games if there is an odd number of players (Praca, Custodio, & Greco, 2015). However, the clarity of the ACWR in terms of calculating how much a player had been prepared to do (chronic workload), meant that throughout Chapter 6, modifications could be made for the next 7 days, to ensure the recommended workloads were still adhered to. This adherence was accentuated by the information supplied by Chapter 5, as well as the supportive and receptive relationship the sport science staff had with the coaching team (Ekstrand, et al., 2019).

7.03.4 Coach and player understanding.

Coach and player understanding have been highlighted as key factors in increasing the effectiveness of workload monitoring for injury prevention (Akenhead & Nassis, 2016). From a player perspective, this is beneficial to ensure the GPS devices are consistently worn and that prescribed workloads are adhered to. From a coach perspective, this helps with the prescription of appropriate workloads, and increases the likelihood of recommended workloads being carried out in practice. To increase this understanding, with the full support of the club’s sport science staff, coach and player education was carried out at the start of pre-season. This defined what the key metrics were and their relevance to practice, as well as the basic principles of the ACWR and its role in the prescription of workload for performance enhancement and injury prevention. The use of club data within this research also helped improve coach support, due to its relevance to practice. In addition, coaches were informed weekly of any monitoring ‘headlines’, and players were often given performance feedback to increase interest and understanding. Despite this, as achieving the appropriate workloads for injury prevention is not the primary purpose of football, there were times throughout this thesis when the recommended workloads were not adhered to, due to an alternative being deemed more beneficial to performance. As elite sporting environments are performance focused, in those instances it is the role of the sport science and medical staff to ensure the players are prepared as best as possible for the required demands. As mentioned in the above section, the flexibility of the ACWRs used in this thesis allowed for the majority of these disruptions.

7.04 Limitations and Future Research

The work presented in this thesis provides novel insights to both research and practice in elite football. Predominantly due to the highly ecologically valid and therefore uncontrollable environment, each study within this thesis has highlighted a number of limitations.

In addition to those already presented, a main limitation which has emerged through the use of these findings in practice is the generic application of ACWRs to all individuals. In Chapters, 4, 5 and 6 the relative risk associated with a given ACWR was assumed to be the same for each individual. However, each individual has different moderating factors which modify their ability to tolerate workload (Windt & Gabbett, 2017). Subjectively, it appears that there are general trends amongst certain players with similar moderating factors. For example, when the senior players were ranked by maximum speed, the 6 slowest players did not receive a non-contact injury throughout the course of this thesis (Figure 15). Whilst the two players with the highest injury occurrence were in the top 5, the player with the highest maximum speed also suffered no injuries. Therefore, future research is necessary to understand the relationship of maximum speed, and the associated physiological qualities, with injury risk. Ideally, the influence of all measurable moderating factors combined on injury risk should be analysed in detail, providing direction to injury prevention strategies.

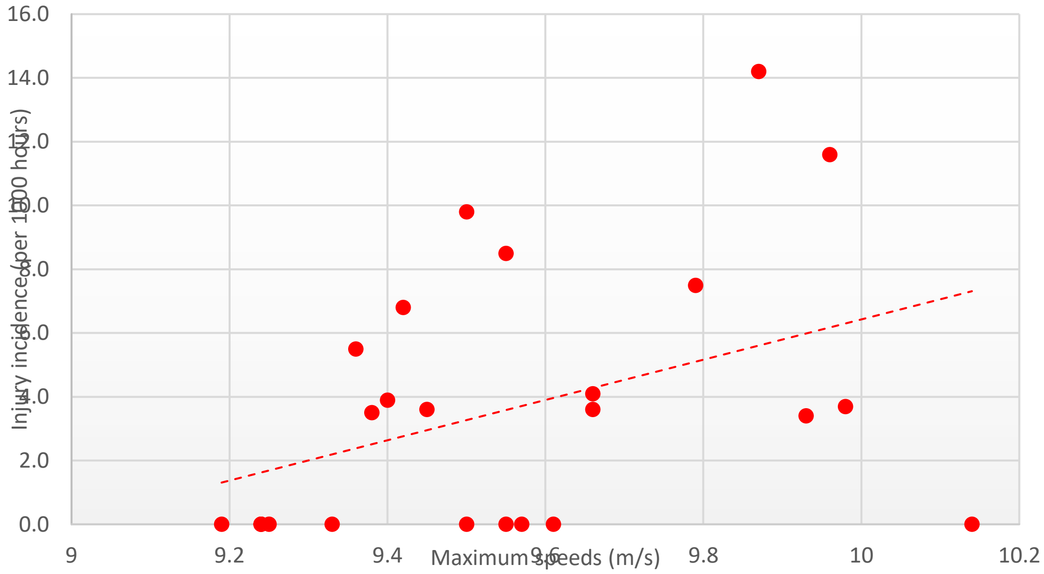

Figure 15. Injury incidence and maximum speeds for the players studied in Chapter 6.

Furthermore, case-studies should be carried out, to allow a greater depth of understanding about individual workload-injury relationships. Whilst the group approach used in this thesis allows for statistical analysis, case studies structured as narratives permit a more complex, multi-disciplinary and individualised approach to workload monitoring (Halperin, 2018). Additionally, coach understanding is likely to be approved using this structure, as the information will be easier to comprehend (Halperin, 2018). The benefit of a group approach in team sports is undeniable, as prescribing different ACWR for every player is impractical. However, the combination of case studies with a group study design would provide additional understanding of individual variances within a group.

7.05 Conclusions

In conclusion, this thesis has explored and enhanced the understanding of the workload-injury relationships in elite youth and senior football. The findings have provided guidelines for optimal workload prescription which does not unduly increase injury risk. Subsequently, the recommended guidelines were then implemented into practice, and used to inform workload prescription. In addition, it has demonstrated that workload monitoring, specifically using the ACWR, is sensitive enough to changes in injury risk within an ever-changing, unpredictable and challenging environment. This research provides only a foundation for the exploration of workload and injury relationships in professional football. However, the importance and benefit of informed workload prescription is highlighted throughout. Furthermore, this PhD was completed as part of a sport science role within a football club, allowing for maximal transfer of research to practice. In addition, through collaboration and learning, practice has also informed the research questions addressed, augmenting the relevance and impact of the findings to Southampton FC. Due to this collaboration, the findings of this thesis have been both applied and tested in practice, creating a complete research loop (Bishop, 2008). Particularly in elite sport, the opportunity to utilise research to impact performance is rare, making this thesis a unique addition to the literature.

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APPENDICES

Appendix A. *Chapter 4: Classification of Injuries per 1,000h*.

	2013-14		*2014-15*		*Total*	
(per 1,000h)	Non-Contact (8.2)	Contact (5.6)	Non-Contact (5.4)	Contact (4.7)	Non-Contact (6.9)	Contact (5.2)
Site						
Ankle/foot	2.8	3.3	1.3	1.9	2.1	2.6
Knee	1.3	0.7	0.9	0.6	1.1	0.6
Hip/Groin	1.8	0.5	0.7	0.0	1.3	0.3
Quadriceps	0.2	1.1	0.4	0.2	0.3	0.7
Hamstring	0.2	0.0	1.5	0.2	0.8	0.1
Forearm/wrist/hand	0.3	0.5	0.4	0.2	0.3	0.3
Head/neck	0.0	0.5	0.0	0.6	0.0	0.5
Abdomen/Lower Back	0.0	0.0	0.9	0.0	0.4	0.0
Lower leg	0.2	0.2	0.2	0.4	0.2	0.2
Shoulder/arm/elbow	0.0	0.2	0.0	0.0	0.0	0.1
Sternum/ribs/upper back	0.0	0.2	0.0	0.0	0.0	0.1
Injury Type						
Haematoma/contusion	0.0	5.1	0.4	2.4	0.2	3.8
Ligament sprain	2.6	1.1	1.5	0.9	2.1	1.0
Muscle strain	1.8	0.0	2.1	0.0	1.9	0.0
Fracture	0.3	0.2	0.6	0.6	0.4	0.3
Other	0.7	0.0	0.7	0.0	0.7	0.0
Tendinosis	0.7	0.0	0.6	0.0	0.6	0.0
Joint injury	0.7	0.2	0.2	0.0	0.4	0.1
Concussion	0.0	0.2	0.2	0.2	0.0	0.2
Laceration	0.0	0.3	0.0	0.0	0.0	0.2
Severity						
Minimal	1.5	2.5	1.1	0.6	1.3	1.6
Mild	1.8	1.5	0.9	1.5	1.4	1.5
Moderate	2.5	2.3	1.5	1.5	2.0	1.9
Severe	1.3	0.5	1.5	1.5	1.4	1.0
Activity performed						
Game	7.9	22.6	12.5	24.2	9.9	24.2
Training	6.3	3.7	4.8	2.3	5.6	2.3

Appendix B. *Chapter 5: Classification of injuries per 1,000 hours.*

	2014-15		2015-16		2016-17	
(Per 1000 hours)	Non Contact (11.8)	Contact (5.9)	Non Contact (5.8)	Contact (4.3)	Non Contact (6.9)	Contact (4.6)
Site						
Abdomen	1.6	0.0	0.0	0.0	0.0	0.0
Ankle	0.3	3.0	0.3	1.2	0.5	1.5
Ant Thigh	0.7	0.3	0.3	0.6	0.5	0.3
Foot/Toe	0.3	0.3	0.3	0.3	0.3	0.3
Hand/Finger/Thumb	0.0	0.0	0.3	0.0	0.0	0.0
Head/Face	0.0	0.7	0.0	0.3	0.0	0.8
Hip/Groin	2.6	0.0	0.9	0.0	1.3	0.0
Knee	2.0	0.7	1.8	1.5	2.1	0.5
Low back/sacrum/pelvis	0.7	0.0	0.6	0.0	0.3	0.0
Lower Leg/Achilles Tendon	1.3	0.3	0.0	0.3	0.0	0.0
Neck/cervical spine	0.3	0.0	0.0	0.0	0.0	0.0
Post Thigh	2.0	0.3	1.2	0.0	2.1	0.8
Shoulder/clavicula	0.0	0.0	0.0	0.0	0.0	0.3
Sternum/ribs/upper back	0.0	0.3	0.0	0.0	0.0	0.0
Upper Arm	0.0	0.0	0.0	0.0	0.0	0.3
Injury Type						
Concussion	0.0	0.3	0.0	0.3	0.0	0.5
Dislocation/Subluxation	0.0	0.0	0.3	0.0	0.0	0.3
Fracture	0.0	0.7	0.0	0.3	0.0	0.5
Haematoma/contusion/bruise	0.3	1.0	0.0	1.2	0.8	0.3
Laceration	0.0	0.3	0.0	0.6	0.0	0.0
Lesion of Meniscus/Cartilage	1.0	0.3	0.6	0.0	0.8	0.3
Muscle rupture/strain/tear/cramp	4.3	0.7	1.2	0.0	2.6	0.8
Nerve Injury	0.0	0.0	0.3	0.0	0.3	0.0
Other	6.2	0.3	1.8	0.0	3.3	0.0
Other Bone Injury	0.7	0.3	0.3	0.0	0.3	0.0
Sprain/Ligament	1.0	1.6	0.6	1.5	0.8	1.5
Synovitis/Effusion	1.0	0.3	0.3	0.3	0.3	0.3
Tendon injury/rupture/tendinosis/bursitis	0.3	0.0	0.0	0.0	0.8	0.3
Severity						
Minimal	5.6	0.3	0.6	0.0	2.8	0.3

Mild	3.3	2.0	1.2	1.8	2.3	1.3
Moderate	3.3	2.3	1.5	1.2	3.1	1.5
Severe	2.6	1.3	2.1	1.2	2.3	1.5
Activity Performed						
Game	6.2	5.3	2.1	3.4	3.6	3.3
Training	5.6	0.7	3.7	0.9	3.3	1.3

Appendix C. Chapter 6: *Injury incidence per 1000h during the 2017-18 season.*

(Per 1000 hours)	Non Contact (4.9)	Contact (2.0)
Site		
Abdomen	0.0	0.0
Ankle	0.0	0.7
Ant Thigh	0.0	0.3
Foot/Toe	0.3	0.0
Glut	0.2	0.0
Hand/Finger/Thumb	0.0	0.0
Head/Face	0.0	0.2
Hip/Groin	1.0	0.0
Knee	0.7	0.3
Low back/sacrum/pelvis	0.3	0.2
Lower Leg/Achilles Tendon	0.7	0.2
Neck/cervical spine	0.3	0.0
Post Thigh	1.8	0.0
Shoulder/clavicula	0.0	0.2
Sternum/ribs/upper back	0.0	0.0
Upper Arm	0.0	0.0
Injury Type		
Concussion	0.0	0.2
Dislocation/Subluxation	0.0	0.0
Fracture	0.0	0.0
Haematoma/contusion/bruise	0.0	0.7
Laceration	0.0	0.0
Lesion of Meniscus/Cartilage	0.3	0.0
Muscle rupture/strain/tear/cramp	3.3	0.2
Nerve Injury	0.3	0.0
Other	0.0	0.2

Other Bone Injury	0.2	0.0
Sprain/Ligament	0.2	0.5
Synovitis/Effusion	0.5	0.3
Tendon injury/rupture/tendinosis/bursitis	0.2	0.0
Severity		
Minimal	0.7	0.8
Mild	1.8	0.3
Moderate	1.6	0.7
Severe	0.2	0.8
Activity Performed		
Game	13.2	9.2
Training	3.3	0.4

Appendix D. Chapter 6: *Difference in workload between the two managers during the 2017-18 season.*

	Manager 1		**Manager 2**		
Weekly Workload	*Mean*	*SD*	*Mean*	*SD*	*t*
TD (m)	24,233	6,888	24,331	6,973	-0.20
LID(m)	20,390	6,066	20,667	5,995	0.87
HSD (m)	1,040	468	1028	473	0.72
ACC (no.)	2,012	619	2,009	605	0.62
DEC (no.)	1,904	616	1,880	596	0.46

Note: TD=total distance covered, LID=low intensity distance, HSD=high speed distance, ACC=accelerations, DEC=decelerations.