

**A new way of using accelerometers in
Australian rules football: Assessing external
loads**

Submitted by

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ABSTRACT

This thesis aimed to assess an accelerometer system (Player load) for measuring the external load of Australian football. Study one established the reliability of a triaxial accelerometer (MinimaxX 2.5) in a laboratory and sports-specific field setting. Repeat trials on a mechanical shaker revealed that MinimaxX were reliable in a controlled laboratory setting ($CV = <1.05\%$). Field testing during Australian football activity also indicated that MinimaxX were reliable ($CV = <2.80\%$). The measurement error of the MinimaxX was less than the smallest practically important difference, deeming these devices to be sensitive for detecting differences in Australian football activity. Study two assessed concurrent validity by measuring relationships between Player load and locomotor load, internal responses, perceptual responses, and physical performance tests, during small-sided Australian football games. Player load had very large relationships with total locomotor distance ($r = 0.63$ to 0.76) and moderate relationships with myoglobin concentration ($r = 0.40$). These measures were also compared between two small-sided games conditions, one with physical contact activity and the other without. Player load did not differ between the two conditions, however when locomotor distance was accounted for, contact had higher external load. Higher levels of fatigue (54 to 57.1%), soreness (44.4 to 69.8%) and myoglobin (27.6%) following non-contact were also shown. This may be a bi-product of higher locomotor distance from the non-contact condition. In study three Player load was measured during Australian football matches and training. Differences between playing positions, playing levels, and from matches to training were discovered. Player load was higher in elite compared to sub-elite matches, with midfielders higher than all other positions. Small-sided games were the only training modality that elicited similar external load to matches. Accelerometers are a reliable and sensitive measure of external load capable of differentiating

between different types of Australian football activity. They also have the potential to be a proxy measure of locomotor distance. Further research is required to develop accelerometer systems capable of detecting isolated activities that are currently misrepresented by other measures of external load.

STUDENT DECLARATION

“I, Luke Boyd, declare that the PhD thesis entitled ‘A new way of using accelerometers in Australian rules football: Assessing external loads’ is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work. A section of this thesis (Study 2; Chapter 4) was part of a larger collaborative investigation assessing recovery strategies in Australian football, conducted by Emma Gallaher. Dr Robert Aughey and Dr Kevin Ball were involved in the planning of this research, and some of the testing procedures. Dr Robert Aughey, Dr Nigel Stepto, and Dr Christos Stathis provided guidance during the blood and saliva analysis. Blood sampling was performed by qualified medical personnel. Associate Professor Vincent Rouillard and Adam Hunter assisted with mechanical testing procedures.

Signature:

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ABBREVIATIONS

GENERAL:

AF	Australian football
RPE	Rating of perceived exertion
EMG	Electromyography
au	arbitrary units
TRIMPS	Training impulse
SSG	Small-sided games
SS	Steady state
INT	Intermittent
AFL	Australian football league
WAFL	Western Australian football league
s	Seconds
min	Minutes
mm	Millimetres
° C	Degrees Celsius

LOCOMOTOR ANALYSIS:

UNITS

CBT	Computer-based tracking	
GPS	Global position system	
HVR	High velocity running	
Acc	Acceleration	
m	metres	
km	kilometres	
	metres per minute	m.min ⁻¹
	kilometres per hour	km.h ⁻¹

metres per second	m.s^{-1}
efforts per minute	efforts.min^{-1}
sprints per minute	sprints.min^{-1}
accelerations per minute	acc.min^{-1}

PHYSICAL ACTIVITY:**UNITS**

EE	Energy expenditure	kcal.hr^{-1}
METS	Metabolic equivalent	
<i>g</i>	'g' force	
VM	Vector magnitude	au
	Accelerometer derived VM	load.min^{-1}
		PL.min^{-1}
	accelerometer counts per minute	counts.min^{-1}
	collisions per minute	$\text{collisions.min}^{-1}$

STATISTICAL:

<i>SD</i>	Standard deviation
<i>TE</i>	Technical error
<i>CV%</i>	Co-efficient of variation
<i>SEE%</i>	Standard error of the estimate
<i>r</i>	Pearson's correlation co-efficient
<i>ICC</i>	Intra-class correlation coefficient
<i>SWD</i>	Smallest worthwhile difference

ELECTROLYTES		UNITS
Da	Daltons (molecular mass)	
[Lac-]		
(BLa)	Lactate anion concentration	mmol.l ⁻¹
CK	Creatine kinase	U/L ⁻¹
LDH	Lactate dehydrogenase	U/L ⁻¹
Mb	Myoglobin	μg.l ⁻¹ ; μg.ml ⁻¹ ; ng.ml ⁻¹
Cortisol		μg.dL ⁻¹ ; nmol.L ⁻¹
Testosterone		pg.mL ⁻¹
T:C	Testosterone to cortisol ratio	

CARDIOVASCULAR		UNITS
HR	Heart rate	beats.min ⁻¹
HRmax	Maximum heart rate	beats.min ⁻¹
HRreserve	Heart rate reserve	beats.min ⁻¹
ECG	Electrocardiography	
VO ₂	Oxygen consumption	l.min ⁻¹
VO _{2max}	Maximum relative oxygen consumption	ml.kg ⁻¹ .min ⁻¹
VO _{2peak}	Peak relative oxygen consumption	ml.kg ⁻¹ .min ⁻¹

PUBLICATIONS

The following publications are presented in support of this thesis:

Publications arising directly from this thesis:

1. Boyd, L.J., Ball, K. & Aughey, R.J. (2011). The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *International Journal of Sports Physiology and Performance*. Vol 6, pp 311-321. (Study 1; Chapter 3)
2. Boyd, L.J., Ball, K. & Aughey, R. (2011). Comparison of external loads in Australian football matches and training using accelerometers. (*International Journal of Sports Physiology & Performance*. Accepted, In press) (Study 3; Chapter 5)

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CHAPTER 1. INTRODUCTION

Since its official introduction in the mid 1800's, Australian football has provided society with an enjoyable modality of physical activity, and a spectacle that draws large crowds of spectators each week. Participation rates are growing across a broad spectrum that ranges from local junior competition, to an elite professional league spanning the country.

Official matches are played over four quarters equating to approximately 120 minutes (min), which is substantially greater than other field sports (rugby: 80 min; soccer: 90 min; basketball: 48 min; hockey: 70 min). A total of 44 players (22 per team) compete in a match, with 36 (18 per team) permitted on the field at one time and 8 (4 per team) used as interchange or substitute players. The area of an Australian football ground ranges from 15,000 to 18,000 square metres (m²) (436-516 m² per person) compared to 8,250 m² (375 m² per player) in soccer and 7,000 m² (233 m² per player) for rugby codes (Ball, 2006).

As a consequence of larger playing fields and longer match durations, locomotor loads of Australian football (~12,000 to 16,000 m) (Gray & Jenkins, 2010) are greater than other football codes such as soccer (~9,000 to 12,000 m) (Carling *et al.*, 2008), rugby league (~8,000 to 10,000 m) (Gabbett, 2005), and rugby union (~4,000 to 6,000 m) (Duthie *et al.*, 2003a) with maximal velocities of ~9.0 m.s⁻¹ achieved regularly (Coutts *et al.*, 2009a; Wisbey *et al.*, 2009; Aughey, 2010; Brewer *et al.*, 2010). Lower-velocity evasive actions such as cutting and lateral shuffling are also performed regularly in confined spaces. They are often accompanied by episodes of physical contact, which unlike other invasion team sports such as basketball, soccer and hockey, is permitted in Australian football. These contact-based activities such as tackling, bumping, blocking, and contested situations when the ball is in dispute on

the ground and in the air, occur up to 127 times per match (Dawson *et al.*, 2004b), causing collisions and impacts between players and the playing surface. Although not as frequent in Australian football (0.51 collisions.min⁻¹) (Dawson *et al.*, 2004b), compared to rugby league (0.64 collisions.min⁻¹) (Gabbett *et al.*, 2010), and of significantly less force (Gray & Jenkins, 2010), the combination of high locomotor volumes and frequent episodes of physical contact provides a demanding stimulus that is unlike any other team sport.

As with the majority of elite-level team sports, Australian football training and competition schedules are highly demanding on a week to week basis, over an extended period of up to 11 months. Monitoring the exercise stimulus is of the highest priority to ensure that an optimal, but not excessive exercise load is prescribed. There are external and internal forms of exercise load (Impellizzeri *et al.*, 2005; Coutts *et al.*, 2007). External load, which includes whole body mechanical movements such as running, sprinting, jumping and tackling determine the internal load or physiological stress placed on the body (Impellizzeri *et al.*, 2005).

Various systems of quantifying exercise load currently exist. External measures of load, such as time-motion analysis provided valuable information relating to locomotor activity, however currently are unable to accurately quantify movement in confined spaces, fail to measure contact-based activities, and are unavailable indoors. Numerous physiological measures such as heart rate, and blood and saliva sampling are proposed as indicators of internal load. These measures can be highly variable, have poor validity during intermittent activity such as team sports, and are difficult to implement during contact-team sports such as Australian football. Perceptual measures of load (i.e. rating of perceived exertion) are proposed as a universal measure incorporating both external and internal loads. Despite this, the system is

based on a subjective rating that may be mis-interpreted or manipulated by individuals.

Recent innovations from sport micro-technology companies include the introduction of accelerometry technology as part of the current global-positioning system devices used in team sports. Tri-axial accelerometers are a highly responsive inertial sensor that is designed to measure acceleration in three dimensions. Although unable to quantify internal loads, accelerometers have the potential to measure external forms of load from whole body mechanical movement. Accelerometers are also non-invasive, and data collection is available indoors. Studies of basketball (Coe & Pivarnik, 2001; Montgomery *et al.*, 2010) and rugby union (Cunniffe *et al.*, 2009) have used accelerometers to measure external load in the absence of time-motion analysis. However the findings from these studies are difficult to transfer and apply to Australian football as the physical requirements are so unique. A system capable of measuring all forms of external load is required. This thesis investigated the application of an accelerometer-based system for measuring external load in Australian football activity.

CHAPTER 2. REVIEW OF LITERATURE

The following section reviews the current research methods used to profile the external and internal loads of team sports activity. This review focused primarily on methods used in Australian football, however some additional methods utilised in other team sports were also discussed.

2.1 Locomotor time-motion analysis in team sports

Time-motion analysis is frequently employed to quantify locomotor movement during team sports training and competition. Various analysis methods have been developed to assess the frequency, duration (time and distance), and intensity (Eg. walking, jogging, striding, sprinting) of locomotor movement (Dobson & Keogh, 2007). As with the majority of team sports research, soccer has the most extensive body of work, dating back to the 1980's across a range of playing standards (Ekblom, 1986; Stroyer *et al.*, 2004; Di Salvo *et al.*, 2006a). This may be a result of the large participation and greater number of research groups across many countries compared to other sports. Rugby codes (Duthie *et al.*, 2005; Deutsch *et al.*, 2007), hockey (Lothian & Farrally, 1994; Spencer *et al.*, 2002; Johnston *et al.*, 2004; Spencer *et al.*, 2004), basketball (Abdelkrim *et al.*, 2007), cricket (Duffield & Drinkwater, 2008) and Australian football (Dawson *et al.*, 2004b, a; Farrow *et al.*, 2008; Coutts *et al.*, 2009a; Wisbey *et al.*, 2009; Aughey, 2010; Brewer *et al.*, 2010; Aughey, 2011a) have also utilised time-motion analysis to characterise sports specific locomotor movement. The information provided by time-motion analysis can facilitate the development and management of the physical preparation program by enabling replication of match loads in training. Further, individuals can be monitored and managed to provide the correct training stimulus.

2.1.1 Manual tracking systems

Early methods of analysis used manual tracking to observe individual athlete movement patterns (Reilly & Thomas, 1976; Hahn *et al.*, 1979). Common practice required the field dimensions to be scaled down onto paper to subsequently sketch and track movement. A grid of known distance intervals was overlaid so that the observer had reference points for the sketching (Veale *et al.*, 2007). Different styles of lines were used to determine intensities such as walk, jog, run, and sprint. Once an individual's movement was recorded, variables such as the distance, intensity and frequency of efforts were calculated post-hoc.

2.1.1.1 Reliability

The reliability of manual tracking using the grid sketching method was assessed during Australian football matches (Veale *et al.*, 2007). This research used one observer, therefore only intra-observer analysis was performed. Two observations of three separate matches displayed high reliability ($r = 0.98$) (Veale *et al.*, 2007). Despite minimal variation from the observer, the validity of this method was not determined. In addition, the use of correlation analysis between observations may not be a true measure of reliability.

2.1.1.2 Validity

Validation of a manual tracking system in soccer was carried out by comparing the observers' grid sketchings to a pre-determined criterion measure of distance (Reilly & Thomas, 1976). Correlations within each intensity zone (walking, jogging, cruising, sprinting, and backwards movement) were high ($r = 0.91$ to 0.97) (Reilly & Thomas, 1976). Despite these positive outcomes, this method only allows researchers to observe one athlete at a time, with the post-hoc analysis being time consuming.

2.1.2 Video tracking systems

The manual analysis concept was developed further with the addition of video systems intending to enhance the quality of the information (Dawson *et al.*, 2004b, a; Dobson & Keogh, 2007). This method allowed the observer to record movement and analyse the information later with greater accuracy. Movement patterns and intensities could be recorded with greater precision by stopping and starting the video. The methodology for video time-motion analysis includes single camera analysis following one player, and multi-camera protocols designed to capture the entire playing area. Using multiple cameras allowed the observer to track more than one player. Despite this, the process is labour intensive and requires consistent filming and analysis techniques (Dobson & Keogh, 2007). In addition, video tracking does not facilitate real-time analysis, minimising the influence of the information during actual matches (Mohr *et al.*, 2003; Deutsch *et al.*, 2007). Various video analysis techniques exist, some simply recording the time and frequency of efforts (McInnes *et al.*, 1995), whereas others have attempted to estimate the distance covered by an individual player (Deutsch *et al.*, 1998; Dawson *et al.*, 2004b, a). Commonly used measures include total movement distance, distance and time in various intensity zones (Spencer *et al.*, 2002; Dawson *et al.*, 2004b, a; Duthie *et al.*, 2005; Burgess *et al.*, 2006; Deutsch *et al.*, 2007), length, time and frequency of efforts (Bangsbo *et al.*, 1991; Duthie *et al.*, 2005; Deutsch *et al.*, 2007), and work to rest ratios including time between maximal efforts (Dawson *et al.*, 2004b, a; Spencer *et al.*, 2004).

2.1.2.1 Reliability

The reliability of video tracking has been established across multiple team sports. In most cases researchers determine their own reliability statistic as part of the studies methodology. Intra and inter-observer reliability assessments are common practice as

human testers are required to collect and analyse data. In one study, video-based TMA was utilised to track the movement patterns of Australian football players in matches (Dawson *et al.*, 2004b). Only one observer was used to view and analyse the video footage, therefore only intra-observer reliability was calculated. The frequency and total time of movements and match related activities were assessed for reliability. Pearson's correlation coefficient (r) was used to display relationships between trial, and the coefficient of variation ($CV\%$), which is the technical error of measurement expressed as a percentage, was used to display the magnitude of variation (Dawson *et al.*, 2004b, a). The variables incorporated into the reliability testing included movement intensities zones (standing, walking, jogging, fast running, and sprinting), changes of direction whilst sprinting, and various game based activities such as kicking, handballing and marking. No significant differences from trial one to two were found, whilst relationships were strong ($r = >0.96$). The $CV\%$ which represents the magnitude of difference was $<4\%$ for frequency, and between 7 and 11% for total time of the various movements and activities (Appleby & Dawson, 2002; Dawson *et al.*, 2004b, a). The error associated with this data collection method is high in relative terms as an underestimation of up to 11% could have an impact on the interpretation of the information.

Rugby union and hockey research displayed similar intra-observer reliability statistics for total time and frequency of movements in various intensity zones (Duthie *et al.*, 2003b; Spencer *et al.*, 2004). Rugby analysis displayed moderate reliability for total time and frequency of low intensity movements such as walking ($CV= 8.7$ & 7.2%), jogging ($CV= 5.8$ & 4.3%) and striding ($CV= 7.4$ & 6.9%) whereas sprinting ($CV= 10.9$ & 10.3%) was harder to replicate. Interestingly, the recognition of stationary or resting ($CV= 11.1$ & 13.6%) periods by observers showed a larger $CV\%$, this may

have a significant effect on the time and frequency of work bouts during a match (Duthie *et al.*, 2003b). Similarly, hockey analysis from matches showed that stationary or resting ($CV= 9.4$ & 9.8%) periods were more difficult to repeatedly observe compared to low intensity movement (Walk: $CV= 5.9$ & 5.7% ; Jogging: $CV= 5.4$ & 8.8%). Sprinting ($CV= 8.1$ & 7.3%) still showed a substantial error, but not to the extent of the previous study (Spencer *et al.*, 2004). Rugby and hockey fields are standardised across all competitions with multiple line markings at pre-determined intervals. With reference points for the observers to utilise, it could have been assumed that reliability would be higher than an oval playing field, however, this was not the case.

Basketball time-motion analysis research also determined intra-observer reliability as part of the testing protocol (McInnes *et al.*, 1995). The magnitude of difference between trials was determined using the $CV\%$. Similarly, the percentage of time in lower intensity activity (Walk/Jog: $CV= 4.1$ to 4.9%) was easier to replicate compared to running and sprinting ($CV= 8.8$ and 5.6% , respectively) (McInnes *et al.*, 1995). The reliability of timing individual efforts decreased as intensity increased. These efforts are often shorter in duration and difficult to time accurately. Frequency analysis showed high reliability, aside from the running category, which can be difficult to isolate from jogging and sprinting as the action often appears similar. Basketball specific movements such as lateral shuffling were slightly less reliable than common locomotor categories, as various techniques are used and distances are often shorter and difficult to categorise (McInnes *et al.*, 1995). The variation in movement type between sports, along with different field dimensions and game styles emphasises the need for specific reliability assessments of each sport. (Duthie *et al.*, 2003b).

Records of inter-observer reliability are less frequent as most investigations use one observer, possibly to eliminate the inter-observer variation. One investigation, during rugby union activity displayed an inter-observer reliability of $CV = <8.7\%$ for frequency of efforts, total time, and the mean duration of efforts in each intensity zone from one observer to another (Deutsch *et al.*, 2007). Soccer research displayed higher inter-observer reliability for measuring the frequency of efforts, and mean duration in various intensity zones ($CV = <4\%$) (Bangsbo *et al.*, 1991). Unfortunately these investigations did not provide statistics for each individual intensity zone.

2.1.2.2 Validity

Validation studies of video time-motion analysis are limited, as a criterion measure of locomotor activity in matches was difficult to obtain. Researchers from one study developed a video of rugby match play where the distances travelled by an individual was known (Deutsch *et al.*, 1998). The observers predicted distance was compared to the known distance to calculate the validity of this specific time-motion analysis method (Deutsch *et al.*, 1998). The error associated with this method was $CV = <4.94\%$ ($r = 0.73$ to 0.93). The main source of error was associated with alternative movements such as lateral and backward running (Deutsch *et al.*, 1998). Alternative methods such as the frequency and time length of efforts were not validated.

2.1.3 Computer-based tracking systems

The introduction of computer-based tracking systems enabled researchers to analyse data more efficiently post match. These systems usually required a mouse or mousepen to trace individual movements using a scaled down model of the playing pitch on a computer (Burgess *et al.*, 2006; Edgecomb & Norton, 2006). Additionally, computerised key activation systems, and software packages that detect movement based on video recordings from matches also exist (Abdelkrim *et al.*, 2007; Duffield

& Drinkwater, 2008). Although the information gained from these systems is similar to video tracking, the data can be entered into a computer system for automated analysis and considerably less manual labour.

2.1.3.1 Reliability

The reliability of various CBT systems has been assessed in isolated research (Edgecomb & Norton, 2006), and as part of the methodology in a number of studies (Burgess *et al.*, 2006; Abdelkrim *et al.*, 2007). One time-motion analysis study of soccer players assessed the intra- and inter-observer reliability of the computer tracing method (Trak Performance Software [SportsTec Pty Ltd., Sydney]) (Burgess *et al.*, 2006). Variations of $CV= 4.6\%$ for the same observer were calculated over 5 halves of match play on two separate occasions. The inter-observer reliability was calculated with Pearson's correlation ($r = 0.98$), instead of the previously mentioned $CV\%$. Both these measure were assessed only for total distance covered, intensity zones and frequencies were not tested (Burgess *et al.*, 2006). Soon after, an isolated study designed to establish the reliability of the same computer tracking method was conducted (Edgecomb & Norton, 2006). Australian football players were tracked over multiple courses of known measurement, and during actual matches (Edgecomb & Norton, 2006). A sample of four observers displayed intra-observer reliability of $CV= <3.3\%$ and 4.7% , for the known courses and in actual matches, respectively (Edgecomb & Norton, 2006). Inter-observer reliability was assessed by tracking the same player by two separate observers, again using a known course and in actual matches. These results indicated that a difference of $CV= 6.1\%$ between observers in analysing matches, and $CV= 4.4\%$ for the known course (Edgecomb & Norton, 2006). Another system designed to track basketball players (PC foot 4.0) used a computer-based program to analyse video recording of the entire playing area (Abdelkrim *et al.*,

2007). This system differed from the other methods in that the computer used statistical modelling to determine the change of position of each player from frame to frame (0.04 s). It was stated in the methodology that intra- and inter-observer reliability would be determined; however results were not expressed separately. The sprinting ($CV \leq 3.6\%$) and sports specific high intensity movements such as shuffling ($CV \leq 3.9\%$) displayed the highest error (Abdelkrim *et al.*, 2007). The lower intensity activity of walking ($CV \leq 2.9\%$), jogging ($CV \leq 2.6\%$), and low-specific movements ($CV \leq 2.9\%$) displayed slightly less error. These results align with video TMA reliability, suggesting that as the speed of movement increases so does the measurement error (Duthie *et al.*, 2003; Spencer *et al.*, 2004). The measures assessed for reliability were the frequency of efforts at various intensities, average time of the efforts, and the percentage of live time, which is the time spent by the player whilst the clock was running. The live time measure was the most difficult to replicate with the error being between $CV= 2.7$ to 3.8% .

2.1.3.2 Validity

As part of the previously described reliability study (Section 2.1.3.1), validity was also determined by comparing the predicted distance of four observers, to the known distance of multiple course measured out using a calibrated trundle wheel (Edgecomb & Norton, 2006). Over 176 trials, observers overestimated distance by $CV= 5.8\%$. As the distance of the known courses increased the error decreased (Edgecomb & Norton, 2006) (Figure 2.1). It was concluded that overestimations may result from slight sideways movements of the mouse or mouse pen. This is more likely to occur at lower velocities.

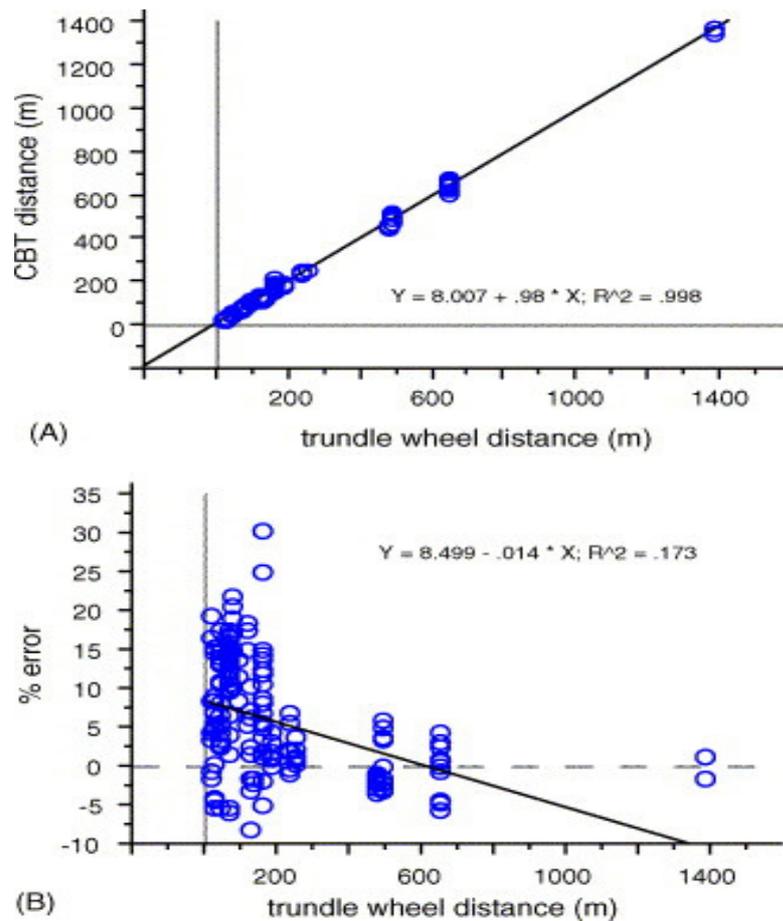


Figure 2.1. Tracking distances for CBT vs. actual distances are shown. In panel (A) there was a significant correlation between distances measured using both systems. Panel (B) illustrates that there was a systematic error as a function of actual distance (slope is different from zero, $p < 0.0001$). That is, the mean relative error decreased across actual distances. Also, the absolute error is greater over shorter distances when compared to those over longer distances. The relative error in panel (B) was calculated as $((\text{CBT distance} - \text{trundle wheel distance}) / \text{trundle wheel distance}) \times 100$. Reproduced from (Edgercomb & Norton, 2006).

2.1.4 Multi-camera computerised tracking systems

Further development of computer and video methods saw the introduction of semi-automated tracking systems (Prozone Sports Ltd®, Leeds, UK; & Amisco Pro, Sport-Universal Process, Nice, France). Reliability, validity and applied research using the Prozone system is frequent, whereas the literature for the Amisco system is limited. Most commonly used in soccer, these systems were developed to further increase accuracy (sampling rate < 25 Hz), and reduce labour in the recording and analysis

phase. Multiple cameras (6 to 12) are strategically positioned to simultaneously observe the pitch space and all players involved in the activity (Rampinini *et al.*, 2006). Optical character recognition technology picks up cues such as players numbers, and individual gait patterns to distinguish between players. The 'x' and 'y' co-ordinates of each individual is used to calculate movement throughout the video captured space (Carling *et al.*, 2008). This system can capture all players on the pitch in real-time, however operators are required to manage the system during capturing periods (Di Salvo *et al.*, 2006a; Rampinini *et al.*, 2007a).

2.1.4.1 Reliability

Reliability assessments of an automated camera tracking system (Prozone Sports Ltd®, Leeds, UK) were performed by a research group as part of the methodology for two separate studies tracking soccer players during matches (Bradley *et al.*, 2009). As an observer is required to operate the system, both intra- and inter-observer reliability were assessed. Five players were randomly selected from a professional soccer match, and tracked by two trained observers on two separate occasions. Eight cameras were strategically positioned at the height of the stadium roof to ensure that all areas of the playing pitch were captured. Intra-observer reliability for total distance ($CV= 1.0\%$) was high, as was the distances covered in each velocity band ($CV= <1.2\%$). At high velocities the reliability decreased, this was evident for sprinting ($>6.94 \text{ m}\cdot\text{s}^{-1}$) ($CV= 2.4\%$) (Bradley *et al.*, 2009). Inter-observer reliability showed similar trends, with activity $<6.94 \text{ m}\cdot\text{s}^{-1}$ ($CV= 1.2\%$) more reliable, compared to sprinting ($CV= 3.5\%$). Although reliability decreases at higher velocities, this variation is below what is deemed to be an acceptable level for team sports analysis (Cormack *et al.*, 2008c). Comparable reliability research of the Prozone tracking was conducted, again using elite level soccer players during actual matches (Di Salvo *et al.*, 2009). Two skilled

observers assessed the same players on 4 occasions to determine inter-observer reliability. Seven days after the initial assessment, each observer re-assessed the same players from the same matches to determine intra-observer reliability. Inter-observer ($CV= 3.4$ to 3.5%) and intra-observer ($CV= 2.7$ to 3.6%) reliability for both time spent and distance covered in velocity zones were high (Di Salvo *et al.*, 2009). As velocity increased, reliability decreased, which is a similar trend to the previously discussed reliability study (Bradley *et al.*, 2009). However in the current study ($CV= 1.5\%$ to 6.5%) (Di Salvo *et al.*, 2009) reliability values were not as high across all velocity zones compared the previous analysis ($CV= 1.2\%$ to 3.5%) (Bradley *et al.*, 2009).

2.1.4.2 Validity

Validation of the same system (Prozone Sports Ltd®, Leeds, UK) was carried out using six soccer players over a series of runs, of known distance (Di Salvo *et al.*, 2006b). Straight, curved and turning runs were performed at velocities ranging from 1.95 to $6.38 \text{ m}\cdot\text{s}^{-1}$ at different locations on the playing field. Activity was captured using the method explained in the previously discussed reliability paper (Bradley *et al.*, 2009). Velocity measured from the tracking system was compared to the actual velocity based on the time taken to complete each course using timing gates. Pearson's correlation displayed very large relationships across all distances and velocities ($r = 0.92$ to 1.00) (Di Salvo *et al.*, 2006b). Straight line activities were the most accurate, with turning activities being more difficult to measure (Table 1). Sprinting activity ($>25 \text{ km}\cdot\text{h}^{-1}$) as reported in the previous reliability study was not validated. Failure to accurately measure this type of maximal activity may grossly underestimate locomotor demands.

Table 1. Statistical measure of absolute reliability for velocity over 4 different tests. Raw typical error, total error, relationships and typical error as a CV% between velocity from the timing gates and Prozone® were calculated. Reproduced from (Di Salvo et al., 2006b).

Test	Typical Error (Upper and Lower 95% Confidence Intervals)	Total Error (Limits of agreement)	Intraclass Correlation Coefficient	Typical Error as CV%
60 m straight run	0.04 (0.06 - 0.03)	0.05 (0.12)	0.999	0.2
50 m curved run	0.07 (0.11 - 0.05)	0.09 (0.22)	0.999	0.3
15 m straight sprint	0.01 (0.04 - 0.01)	0.02 (0.05)	0.999	0.2
20 m sprint and turn	0.23 (0.58 - 0.15)	0.23 (0.85)	0.950	1.3

2.1.5 Global positioning system tracking

Unlike the previously described methods where data is recorded from an observatory position, global positioning systems (GPS) technology requires the players to wear a device during sports activity. These devices have an inbuilt receiver that communicates with a network of satellites to determine location based on the time taken for the signal to be transferred from the satellite to the device (Macleod *et al.*, 2009). This system automatically tracks and stores the movement patterns of individuals. Multiple players can be tracked at the same time, and data analysis is automated. Various manufacturers have developed these devices with a range of models currently in existence.

The widespread use of GPS technology in team sports was accompanied by numerous reliability and validity investigations. Initial investigations assessed the 1 Hz devices which have been superseded by 5 and 10 Hz systems. As the 10 Hz devices were released in the past year only one letter to the editor exists in the current literature. Reliability and validity investigations for the 1 Hz (Edgecomb & Norton, 2006;

Coutts & Duffield, 2008; Macleod *et al.*, 2009; Portas *et al.*, 2011) and 5 Hz models (Petersen *et al.*, 2009; Aughey & Falloon, 2010; Jennings *et al.*, 2010a; Jennings *et al.*, 2010b; Portas *et al.*, 2011) will be discussed further in the following section. Summary tables for GPS reliability and validity are displayed in appendix 6.

2.1.5.1 1 Hz GPS

2.1.5.1.1 Reliability

On two occasions an oval shaped course has been used to assess the intra-unit reliability of 1 Hz GPS (SPI 10, GPSports Systems, Canberra, Australia). The first of these studies compared the distance travelled (m) around the course. Over multiple trials of the same device at self-selected velocities the technical error of measurement was $CV = 5.5\%$ (Edgercomb & Norton, 2006). The second investigation of the same GPS model (SPI 10; GPSports Systems, Canberra, Australia), assessed reliability over a range of different velocities (Petersen *et al.*, 2009). Results indicated high intra-device reliability for walking ($<2 \text{ m}\cdot\text{s}^{-1}$), jogging (2 to $3.5 \text{ m}\cdot\text{s}^{-1}$), running (3.5 to $4 \text{ m}\cdot\text{s}^{-1}$), and striding (4 to $5 \text{ m}\cdot\text{s}^{-1}$) ($CV = 0.4, 0.4, 1.5$ and 0.5% , respectively). A course incorporating intermittent intensities, with changes of direction is required for more specificity to team sports movement patterns, and may have produced different outcomes.

Similar findings from 1 Hz devices were shown in another reliability study, this time assessing 3 different models from the same manufacturer (SPI 10; SPI Elite; WiSPI; GPSports Systems, Canberra, Australia) (Coutts & Duffield, 2008). This investigation differed, with a specifically designed team sports locomotor circuit (Bishop *et al.*, 2001) incorporating varied intensities of movement used in the assessment (Figure 2.2). Total distance (m), low-intensity activity distance ($<4 \text{ m}\cdot\text{s}^{-1}$), high-intensity running distance ($>4 \text{ m}\cdot\text{s}^{-1}$) and very high-intensity running distance ($>5.5 \text{ m}\cdot\text{s}^{-1}$) were

compared between two devices of the same model and between different models over 6 laps of the course. Intra-model analysis showed that total distance ($CV= 4.0$ to 7.2%) had acceptable reliability, however as the velocity of movement increased, reliability decreased ($>4 \text{ m}\cdot\text{s}^{-1}$: $CV= 11.2$ to 32.4% ; $>5.5 \text{ m}\cdot\text{s}^{-1}$: $CV= 11.5$ to 30.4%) (Coutts & Duffield, 2008). Inter-model analysis followed a similar trend with total distance ($CV\approx 2.4\%$) displaying the highest reliability, followed by low-intensity activity distance ($CV\approx 3.9\%$), high-intensity running distance ($CV\approx 10.8\%$) and very high-intensity running distance ($CV\approx 17.3\%$). Based on these findings, the information collected through different models will substantially vary and make comparisons between data sets difficult. The reliability of data may be increased if devices were allocated to individual athletes.

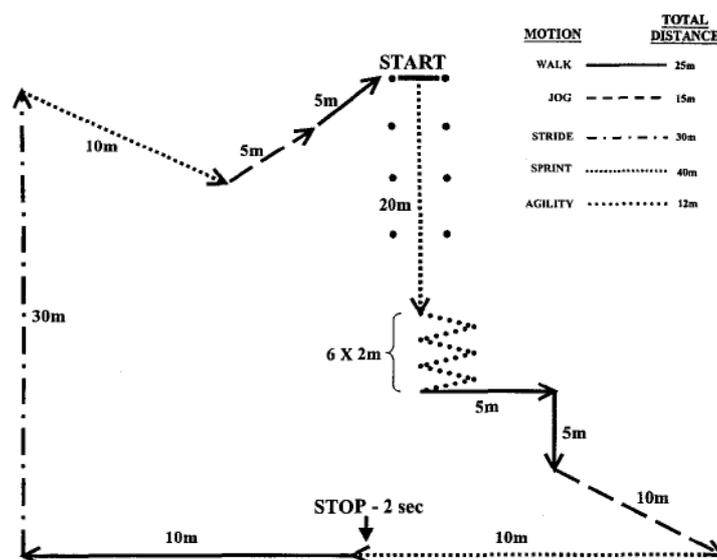


Figure 2.2. Diagram of specifically designed team sports locomotor circuit. Reproduced from (Bishop *et al.*, 2001).

High intensity activity was the focus of a recent study addressing the intra-unit reliability of GPS devices (SPI Elite; GPSports Systems, Canberra, Australia) (Barbero-Alvarez *et al.*, 2009). A repeated sprint protocol (7 x 30 m) was carried out on two occasions one week apart. Unlike previous research, a feature of this paper

was the high velocities ($\sim 6.9 \text{ m}\cdot\text{s}^{-1}$) achieved by the participants. Peak velocity and summated peak velocity from each trial compared between the two testing periods displayed high reliability ($CV= 1.2\%$ and 1.7% , respectively). Interestingly this study did not account for difference in the athlete's performance from one testing week to the next. This makes it difficult to determine where the source of error is derived. Is it the GPS devices, or the day to day variability of the athlete that are responsible for the difference? In addition, no distance or average velocity data was presented. Maximal velocities are only attained for a brief period during each effort whereas distance and average velocity may have reflected the entire duration of the efforts.

2.1.5.1.2 Validity

Validity testing of 1 Hz GPS units has indicated varying results. A study of the SPI10 (GPSports Systems, Canberra, Australia) compared the estimated distance from GPS to the known distance around an oval course measured using a trundle wheel (Edgercomb & Norton, 2006). Significant differences between known and estimated distance were displayed with the SPI10 overestimating actual distance by 4.8%. Conversely, in a separate study the same GPS unit (SPI10) was evaluated, this time using the same team sports locomotor circuit described in Figure 2.2 (Bishop *et al.*, 2001) as outlined previously (Coutts & Duffield, 2008). Opposing results were displayed with the GPS underestimating distance ($-4.1\pm 4.6\%$) (Coutts & Duffield, 2008). This suggests that the error relative to actual distance is not systematic as previously stated (Edgercomb & Norton, 2006). Rapid changes of direction may have been underestimated as the 1 Hz sample rate is insufficient in tracking the precise course of an individual when changing direction or velocity rapidly. In this same investigation, two updated models of GPS units from the same manufacturer were assessed. It was concluded that the more recently developed SPI Elite and WiSPI (-

2.0±3.7% and 0.7±0.6%, respectively) had greater accuracy (Coutts & Duffield, 2008).

The validity of 1 Hz GPS (SPI Elite; GPSports Systems, Canberra, Australia) to measure activities of short duration with changes of direction, at high intensities was assessed in a separate investigation (Macleod *et al.*, 2009). Four different sport-based movement patterns were designed from time-motion analysis of hockey matches. The known distance of each course was measured using a trundle wheel, and compared to the estimated distance from the GPS. The inbuilt map that is provided by the analysis software was used to determine the start and end points for each course. The time taken to complete each course using light gates combined with the known distance values were used to calculate average velocity and compare to the estimated average velocity from GPS. The estimated distance from the GPS compared to known distances measured using a calibrated trundle wheel displayed small errors (-0.1 to 2.5 m). However the method used to determine the GPS start and end point of each course was questionable. The inbuilt maps from the analysis software often produce inaccurate traces relative to actual movement, and are yet to be validated. The estimated average velocity differed from the known value by -0.03 and 0.05 m.s⁻¹. Although valid measures were obtained from the GPS, the average velocities (1.5 to 3.6 m.s⁻¹) were relatively low. These outcomes may have differed if higher velocities were achieved.

2.1.5.2 5 Hz GPS

The 5 Hz GPS was developed to improve both validity and reliability. Movement in confined spaces and change of direction, which was previously difficult to measure, may be more accurately reproduced as sampling rates are higher. In most cases the assessments of 5 Hz devices were accompanied by a comparison with 1 Hz data

(Petersen *et al.*, 2009; Jennings *et al.*, 2010a; Portas *et al.*, 2010). In all cases, 5 Hz systems were more valid and reliable than 1 Hz systems but still showed limitations.

2.1.5.2.1 Reliability

As previously cited, research in cricket ran trials of a known distance around an athletics track multiple times, and straight-line movement over 20 to 40 m to assess reliability. This time two different 5 Hz GPS models ([SPI Pro; GPSports Systems, Canberra, Australia] and [MinimaxX 2.0; Catapult Innovations, Melbourne, Australia]) (Petersen *et al.*, 2009) were tested. Intra-unit analysis over 20 trials (600 to 8800 m) of walking, jogging, running, and striding indicated high reliability (SPI Pro: $CV= 0.3$ to 2.9% ; MinimaxX: $CV= 1.2$ to 2.6%). Inter-unit reliability across nine GPS devices tested simultaneously around the same track showed high reliability (MinimaxX: $CV= 1.3\%$; SPI Pro $CV= 1.5\%$) (Petersen *et al.*, 2009). However, in this study straight-line sprints over 20 to 40 m showed poor intra-unit reliability (MinimaxX: $CV= 15.8$ to 30.0% ; SPI Pro: $CV= 2.3$ to 9.3%) (Petersen *et al.*, 2009). Similarly, in research using Australian football players, intra-unit reliability for straight-line movement found that estimates of distance for 10 m were poor ($CV= 22.8$ to 39.5%) compared to 40 m ($CV= 6.6$ to 9.2%) (Jennings *et al.*, 2010a). Sprinting activity ($CV= 9.2$ to 39.5%) was also the most unreliable compared to walking and jogging ($CV= 6.6$ to 23.3%) (Jennings *et al.*, 2010a). Despite poor reliability the 5 Hz models showed improved reliability compared to the 1 Hz equivalent. These findings again suggest that reliability decreases over short distances at high velocities. The inter-unit reliability of the MinimaxX devices were reported in a companion study by the same research group. The same straight line course displayed variability of $CV= 9.9$ to 11.9% (Jennings *et al.*, 2010b). The movement

velocity (walking to sprinting) and distance travelled (10 to 40 m) did not affect the inter-unit reliability.

As part of the same study, the 5 Hz GPS devices were tested for reliability during short duration change of direction locomotion (Jennings *et al.*, 2010a). These types of multi-directional courses have become more popular as they more effectively represent team sports movement patterns. Two 40 m slalom courses, one with gradual and the other with tight turns were developed (Figure 2.3) (Jennings *et al.*, 2010a).

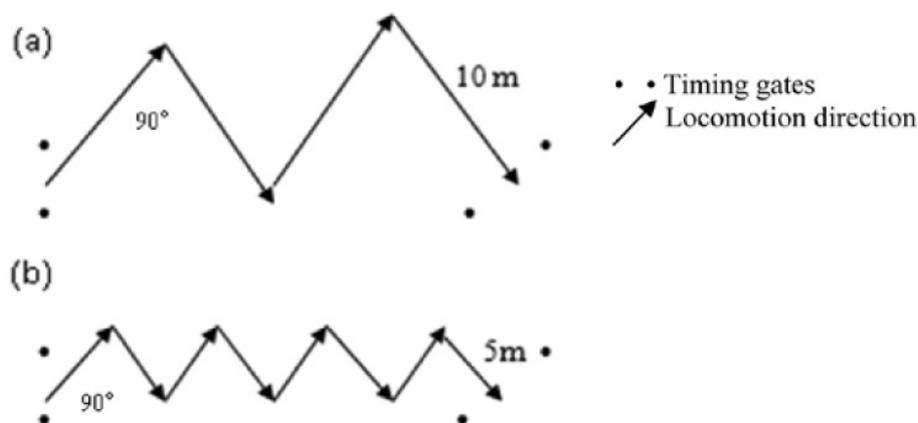


Figure 2.3. Change of direction (COD) course: (a) Gradual 10 m COD. 4 × 10 m straights with 3 × 90° COD (b) Tight 5 m COD. 8 × 5 m straights with 7 × 90° COD. Reproduced from (Jennings *et al.*, 2010a).

Unexpected outcomes showed that jogging, striding and sprinting ($CV= 7.9$ to 10.0%) displayed higher intra-unit reliability compared to walking ($CV= 11.5$ to 15.2%). Additionally, when jogging, striding and sprinting, tight ($CV= 8.6$ to 9.3%) and gradual ($CV= 7.9$ to 10.0%) change of direction patterns had similar intra-unit reliability (Jennings *et al.*, 2010a). Lower average velocities during the change of direction courses compared to straight line sprints may have contributed to the higher reliability. The 5 Hz devices ($CV= 7.9$ to 15.2%) were more reliable than 1 Hz ($CV= 8.6$ to 17.5%) over the change of direction courses. As with the straight-line analysis, inter-unit reliability was consistent across all movement velocities, and similar

between the gradual (9.7 to 10.4%) and tight (9.5 to 10.8%) courses (Jennings *et al.*, 2010b).

A second investigation using six different short duration multi-directional trials were used to assess the intra-unit reliability of 5 Hz GPS devices (MinimaxX 2.5, Catapult Innovations, Melbourne, Australia) (Portas *et al.*, 2010). Courses incorporated 45, 90, and 180° changes of direction (Figure 2.4).

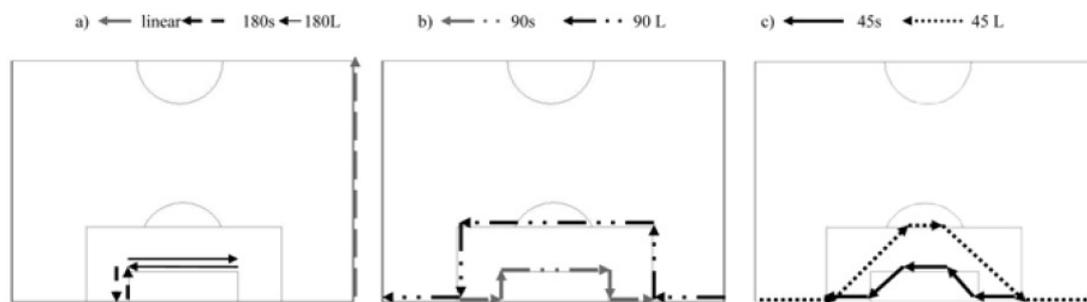


Figure 2.4. Maps of multi-directional trials used to assess GPS reliability and validity. Reproduced from (Portas *et al.*, 2010).

As the courses became more complex, the reliability reduced. The course incorporating 180° changes of direction ($CV= 4.73$ to 7.71%) had the lowest reliability, compared to the 45° ($CV= 3.42$ to 5.85%) and 90° ($CV= 3.08$ to 5.93). The intensity of movement did not affect the reliability (Walk: $CV= 3.42$ to 6.72% ; Run: $CV= 3.71$ to 6.11%). Statistical analysis was not performed between the 1 Hz and 5 Hz sample rate, however it appears that 5 Hz were marginally more reliable.

Three recent studies have utilised simulated sports specific courses as part of GPS reliability and validity research (Jennings *et al.*, 2010a; Jennings *et al.*, 2010b; Portas *et al.*, 2010). These courses are designed to replicate sports movement patterns over longer distances and at varied intensities to match the intermittent nature of team sports compared to the previously discussed change of direction courses. The first of these studies utilised a series of soccer-specific courses designed from locomotor

analysis of soccer matches (Figure 2.5) to assess intra-unit reliability (MinimaxX 2.0, Catapult Innovations, Melbourne, Australia) (Portas *et al.*, 2010). Despite multiple changes of direction at high intensities, the outcomes were positive with reliability ranging from $CV= 2.2$ to 4.5% .

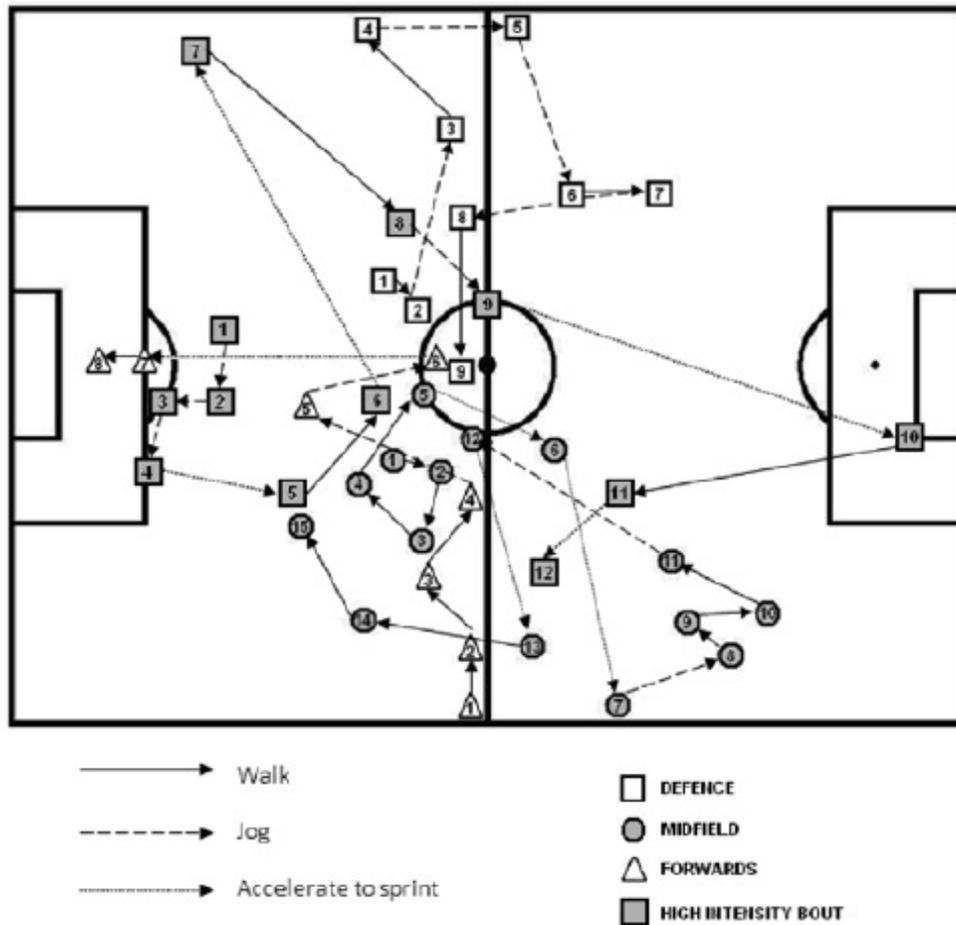


Figure 2.5. Soccer-specific courses designed from locomotor analysis of matches. Reproduced from (Portas *et al.*, 2010).

The second study developed a modified version of the team sports locomotor circuit described in section 2.1.5.1.1. to measure the reliability of the MinimaxX 2.5 (Jennings *et al.*, 2010a; Jennings *et al.*, 2010b). Intra- and inter-unit reliability was $CV= 3.6\%$ and 11.1% respectively (Jennings *et al.*, 2010a). No difference was shown between 5 Hz and 1 Hz. In another study by the same research group, inter-unit reliability was assessed during actual competitive hockey matches by attaching 2

devices to each player (Jennings *et al.*, 2010b). Reliability was poor ($CV= 10.3\%$), suggesting that devices should be allocated to individual players to avoid any differences in measures between devices.

2.1.5.2.2 Validity

Validity assessments of the 5 Hz GPS models have been conducted for measuring distance, and velocity during straight, multi-directional and team sports specific movements at varied intensities (Petersen *et al.*, 2009; Jennings *et al.*, 2010a; Jennings *et al.*, 2010b; Portas *et al.*, 2011).

Estimated movement velocity from two different models (MinimaxX 2.0; SPI-Pro) were compared to the actual velocity calculated with time and distance variable around an athletics track (Petersen *et al.*, 2009). Within models, the MinimaxX 2.0 had lower measurement error during striding movements (standard error of estimate, $SEE= 1.7$ to 1.8%), compared to walking, jogging and running ($SEE= 1.8$ to 3.8%). An overestimation of up to 3.2% was evident across these trials. The SPI-Pro differed with walking ($SEE= 0.5$ to 1.0%) having greater validity compared to jogging, striding and sprinting ($SEE= 0.4$ to 3.7%) (Petersen *et al.*, 2009). The SPI-Pro underestimated distance by up to 3.8% . In the same investigation straight line sprinting was assessed with over 20, 30, and 40 m. Both the MinimaxX 2.0 and SPI-Pro had larger errors in measurement over the 20 m (MinimaxX 2.0: $SEE= 15.2$ to 23.8% ; SPI-Pro: $SEE= 5.5$ to 10.5%) compared to the 40 m (MinimaxX 2.0: $SEE= 14.9$ to 16.1% ; SPI-Pro: $SEE= 2.9$ to 7.7%) (Petersen *et al.*, 2009). Both MinimaxX 2.0 (19.5 to 37.3%) and SPI-Pro (7.4 to 15.3%) underestimated sprinting distance. Parallel validity research assessing the more recent MinimaxX 2.5 during straight line movement over a range of intensities displayed similar outcomes (Jennings *et al.*, 2010a). Across all intensities (walking to sprinting) the MinimaxX 2.0 showed greater

measurement error over 10 m ($SEE= 21.3$ to 30.9%) compared to 40 m ($SEE= 9.8$ to 11.9%). Alternatively, over 10 m the validity decreased as movement intensity increased (Walking: $SEE= 21.3\%$; Sprinting: $SEE= 30.9\%$). Over 20 and 40 m, the validity remained similar, regardless of the movement intensity (Jennings *et al.*, 2010a). As with the reliability statistics, the 5 Hz devices were more valid than the 1 Hz equivalents. The MinimaxX overestimated distance for walking and jogging (2.4 to 7.1%), and underestimated for striding and sprinting (2.2 to -26.0%).

More recent work assessing GPS (MinimaxX 2.5) validity during straight line movement found the measurement error to be substantially less (Walking: $SEE= 3.1\%$; Running: $SEE= 2.9\%$) (Portas *et al.*, 2011). However the devices used were updated models (MinimaxX 2.5), and the course distance was longer (51 m) which may have reduced the error. Unlike previous investigations, the 5 Hz and 1 Hz samples rates displayed similar measurement error for straight line movement. Slight overestimation of criterion distance occurred from both 5 Hz and 1 Hz devices (~1%) (Portas *et al.*, 2011).

Similarly to the previously discussed reliability investigations, validity was assessed on two occasions using the same short duration change of direction, and multi-directional courses (Figure 2.3 & Figure 2.4) (Jennings *et al.*, 2010a; Portas *et al.*, 2011). The first of these studies indicated that the error of measurement for both the gradual and tight courses (Figure 2.3) increased as the intensity of movement increased (Jennings *et al.*, 2010a). Walking ranged from $SEE= 8.9$ to 9.9% error, whereas sprinting was $SEE= 11.5$ to 11.7% . The tight course had slightly higher error in measurement, however error was reduced across both courses for 5 Hz analysis, compared to 1 Hz. Across all intensities over both courses the MinimaxX underestimated the criterion distance (-0.6 to -15.8%) (Jennings *et al.*, 2010a). The

second study assessed the validity of GPS (MinimaxX 2.5) over six multi-directional short duration courses (Figure 2.4) (Portas *et al.*, 2011). Measurement error ranged between $SEE= 2.2$ and 4.4% , however no trends were shown in relation to the angle of direction change or distance of course. There was no systematic under- or over-estimation of criterion distance by the MinimaxX 2.5 with estimations ranging from 2% over- to 11% under-estimation (Portas *et al.*, 2011).

Two investigations assessing the validity of GPS (MinimaxX 2.5) to measure team sports movement over longer distances currently exist (Jennings *et al.*, 2010a; Portas *et al.*, 2011). The first study assessed validity using the same team sports circuit (140 m) as previously described (Jennings *et al.*, 2010a). Validity was high ($SEE= 3.8\%$), with an underestimation of 3.7% found. Minimal differences were found between 5 Hz and 1 Hz systems for the team sport circuit. The second investigation, utilised the soccer-specific courses (121 to 197 m) displayed in figure 2.5. High validity ($SEE= 1.5$ to 2.2%) was again reported with accuracy ranging between 1% over-estimation and 1% underestimation (Portas *et al.*, 2011). The 5 Hz system had slightly greater accuracy. The validity of GPS over these longer team sports movement patterns appears to be higher compared to the previously described short duration movement patterns. Again this suggests that as measuring distances increases so does the accuracy of GPS.

Unlike previous suggestions, the measurement error associated with GPS analysis appears to be unsystematic. Under- and over-estimations have been reported, this varying based on the type and length of movement, and more importantly, the model of GPS device being used. The majority of findings suggest that the 5 Hz systems display higher accuracy and reliability compared to 1 Hz. It also appears that when

movement distance is short and intensity of movement is high, both reliability and validity are compromised.

2.1.6 Summary

As discussed in section 2.1, locomotor time-motion analysis methods have developed greatly since the late 1970's, when manual methods were first reported in the literature. Despite this, a consistent theme remains with measurement error increasing as the intensity of movement rises. Understanding the flaws of the various systems helps to ensure that the information is interpreted correctly to guide effective practice. In addition, these flaws can be utilised to guide the development of new systems of analysis, with the aim of providing reliable, valid and informative data.

2.2 Australian football locomotor activity

The following section will describe how these time-motion analysis methods have been applied to determine the locomotor demands of Australian football.

2.2.1 Locomotor analysis of competitive matches

Table 2 displays a summary of common locomotor parameters used in time-motion analysis research across competitive Australian football matches.

Table 2. Locomotor data from competitive Australian football matches. These data represent a full-length match.

Study	TMA Method	Playing level	Total Distance	No. of work efforts	High velocity running (m)
Veale (2007)	Manual	Junior elite	~9,896 m	157	-
Dawson (2004)	Video	Senior elite	15,653 m	580	~2,234 m
Coutts (2009)	GPS	Senior elite	12,939 m	-	3,885 m
Aughey (2010)	GPS	Senior elite	12,734 m	-	3,334 m
Wisbey (2009)	GPS	Senior elite	11,976 m	-	-
Brewer (2010)	GPS	Senior elite & sub-elite	12,311 m	~264	-

Note. The methodology used to determine the number of working efforts and high velocity running differed between studies.

Broad assessments across the entire match are often the starting point for time-motion analysis research in team sports. A manual system was used to measure locomotor activity in junior Australian football players (Veale *et al.*, 2007). Total distance across all playing positions was ~9,896 m, with ~73% of that activity being jogging, running, and sprinting. Approximately 157 working efforts (at or above jogging intensity) were performed over an average distance of 50 m (Veale *et al.*, 2007). The cross-section of participants in this study did not include all playing positions. Video tracking results from elite senior matches differed greatly with an average distance of 15,653 m covered with only 62% spent jogging, running, and sprinting (Dawson *et al.*, 2004b). The number of working efforts also differed with 580 efforts in this investigation (Dawson *et al.*, 2004b). When semi-automated systems utilising GPS technology were introduced total distances of 12,939 m were recorded in elite senior Australian football matches (Coutts *et al.*, 2009a). This was similar to another GPS study which recorded total distances of 12,311 m (Brewer *et al.*, 2010). These reports were limited to one elite Australian football team per study that at the time of analysis were placed

in the bottom third of the competition standings. Alternatively, in work assessing one elite Australian football team from the top third of competition standings, distances of 12,734 m were found (Aughey, 2010). The minimal differences shown between team of different standards suggests that total distance may not be a key determinant of successful performance.

A multitude of other variables can be obtained through GPS analysis. Some of these descriptors such as high velocity running distance (3880 ± 633 m) (Coutts *et al.*, 2009a) (3334 ± 756 m) (Aughey, 2010), maximum velocity (8.1 ± 0.5 to 8.4 ± 0.5 m.s⁻¹) (Coutts *et al.*, 2009a; Wisbey *et al.*, 2009; Brewer *et al.*, 2010), and mean velocity (1.88 to 2.08 m.s⁻¹) (Wisbey *et al.*, 2009) provide more detail of locomotor movement in competitive matches. Parameters such as the number of high velocity efforts, sprints, and accelerations are also valuable, however velocity and acceleration bands are quite varied across Australian football research, and are difficult to compare. One major limitation of early time-motion analysis research was the failure to account for differences in actual time spent on the ground (playing time) between individuals. Normalising parameters based on playing time are often more effective when comparing within or between individuals. Those that exist include metres per minute which has varied between studies (103 ± 14 to 108 ± 15 m.min⁻¹ (Coutts *et al.*, 2009a); 125 ± 14 to 131 ± 13 m.min⁻¹ (Brewer *et al.*, 2010); 127 ± 17 m.min⁻¹ (Aughey, 2010)), high intensity metre per minute (34 ± 9 m.min⁻¹) (Aughey, 2010), high velocity efforts per minute (2.9 ± 0.6 HV efforts.min⁻¹) (Brewer *et al.*, 2010), sprints per minute (0.8 ± 0.2 sprints.min⁻¹) (Brewer *et al.*, 2010), and maximal accelerations per minute (0.99 ± 0.39 acc.min⁻¹) (Aughey, 2010).

2.2.2 Locomotor changes across a competitive match

Changes in locomotor activity over the course of a match are often used as descriptors of fatigue or variation in game speed and style (Coutts *et al.*, 2009; Aughey, 2010; Brewer *et al.*, 2010). Table 3 displays the changes in various locomotor parameters across a match.

In elite junior Australian football players, there was a decrease in the number of working efforts from quarter one (41.0) to quarter two (37.2), followed by an increase in quarter three (41.2) and subsequent decrease in quarter four (37.5) (Veale *et al.*, 2007) (Table 3). This suggests that fatigue was greater following the smaller breaks in play at quarter and three quarter time (6 min) compared to the longer half time break (20 min) where the players were able to return to first quarter standards (Veale *et al.*, 2007).

A similar quarter by quarter analysis of a competitive match used GPS to determine changes across a game (Coutts *et al.*, 2009a). Data expressed in metres per minute of game time showed that the first quarter ($117 \pm 14 \text{ m} \cdot \text{min}^{-1}$) was the highest, followed by a decrease in the second quarter ($108 \pm 15 \text{ m} \cdot \text{min}^{-1}$), which was maintained in the third quarter ($108 \pm 17 \text{ m} \cdot \text{min}^{-1}$), followed by another decrease in the fourth quarter ($103 \pm 14 \text{ m} \cdot \text{min}^{-1}$). This differed slightly with high velocity running distance (m) ($>4.0 \text{ m} \cdot \text{s}^{-1}$), which showed a decrease each quarter ($1090 \pm 212 \text{ m}$; $980 \pm 219 \text{ m}$; $971 \pm 256 \text{ m}$; $844 \pm 198 \text{ m}$) (Table 3). It appears that the higher velocities were more difficult to maintain regardless of the time between quarters (Coutts *et al.*, 2009a). It was also evident that the elite senior players were unable to return back to 1st quarter standards in the 3rd quarter as the junior elite players did. This may represent a much greater intensity at elite senior levels, therefore making it more difficult to maintain across a match. Similar patterns were found using GPS when periods of play were separated

into first and second halves. Decrements in metres per minute (4.5%), high velocity efforts per minute (10%), and sprints per minute (12.5%) were found in the second half of matches (Brewer *et al.*, 2010) (Table 3).

Table 3. Time-motion analysis data from Australian football matches comparing between periods of play. Data is reproduced from (Veale *et al.*, 2007; Coutts *et al.*, 2009a; Aughey, 2010; Brewer *et al.*, 2010)

Study	TMA Method	Playing level	Parameter	Playing periods							
				1st Half		2nd Half					
Brewer (2010)	GPS	Senior elite & sub-elite	Metres.min ⁻¹	126		119					
			High velocity efforts per min ⁻¹	2.8		2.5					
			Sprints per minute ⁻¹	0.8		0.7					
				1st Quarter	2nd Quarter	3rd Quarter	4th Quarter				
Veale (2007)	Manual	Junior elite	No. of working efforts	41	37.2	41.2	37.5				
Coutts (2009)	GPS	Senior elite	Metres.min ⁻¹	117	108	108	103				
			High velocity running (m)	1090	980	971	844				
				Q1-R1	Q1-R2	Q2-R1	Q2-R2	Q3-R1	Q3-R2	Q4-R1	Q4-R2
Aughey (2010)	GPS	Senior elite	Metres.min ⁻¹	~133	~133	~134	~134	~125	~130	~127	~127
			High velocity running per min ⁻¹ (m)	~34.5	~33.5	~31	~29.5	~33	~31	~29.5	~29.5

TMA = time-motion analysis; GPS = global positioning system; Q = quarter; R = rotation;

Additional work used a ‘high’ and ‘low’ median split technique, to determine changes from the first to second half (Coutts *et al.*, 2009a). Players that worked at higher intensities in the first half, displayed decrements in total distance (m) and high velocity running ($>4.0 \text{ m}\cdot\text{s}^{-1}$) in the second half (Figure 2.6). Interestingly, when players had a lower intensity in the first half, total distance and high velocity running was maintained (Coutts *et al.*, 2009a) (Figure 2.6).

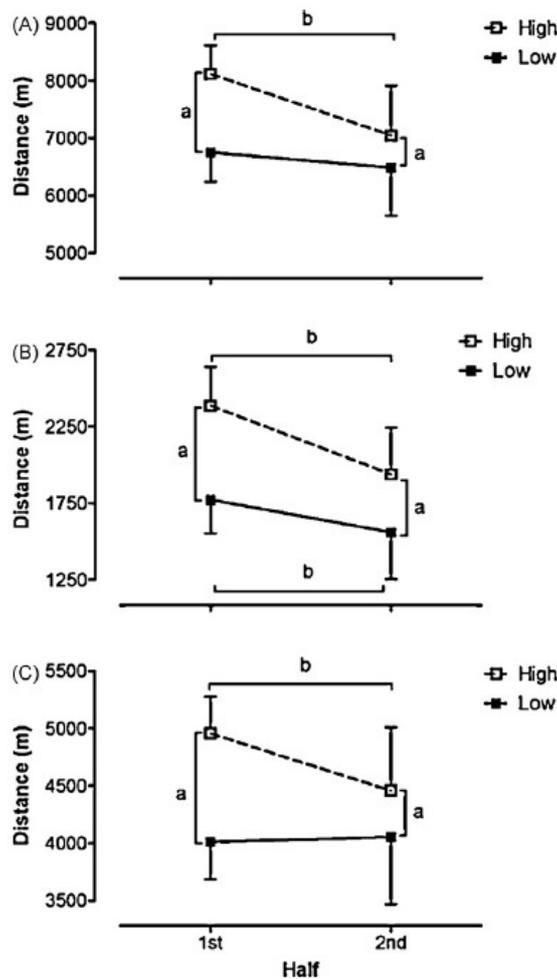


Figure 2.6. Effect of first half exercise intensity on second half exercise intensity ($Mean \pm SD$) for (A) Total distance (m), (B) high-intensity running distance (m); and, (C) low-intensity activity distance (m). High (\square), players that travelled above the median value for the pooled data ($n=32$); Low (\blacksquare), players that travelled below the median value for the pooled data ($n=32$). Interactions were significant for all four variables ($p < 0.001$). a Significantly different between High and Low group ($p < 0.05$) and significantly different between first and second half ($p < 0.05$). Reproduced from (Coutts *et al.*, 2009a).

As part of Australian football rules, players can be interchanged freely over the course of a match. Each period of time spent on the ground in play, is commonly referred to as a rotation. One study of elite Australian football players assessed the change in locomotor activity from one rotation to another (Aughey, 2010) (Table 3). High intensity running per minute and maximal accelerations per minute were highest during the first rotation of a match, and subsequently declined in the majority of other rotations (Aughey, 2010). An exception was during the first rotation following the half time break (20 minutes), where high intensity running but not maximal accelerations, was maintained (Aughey, 2010) (Figure 2.7).

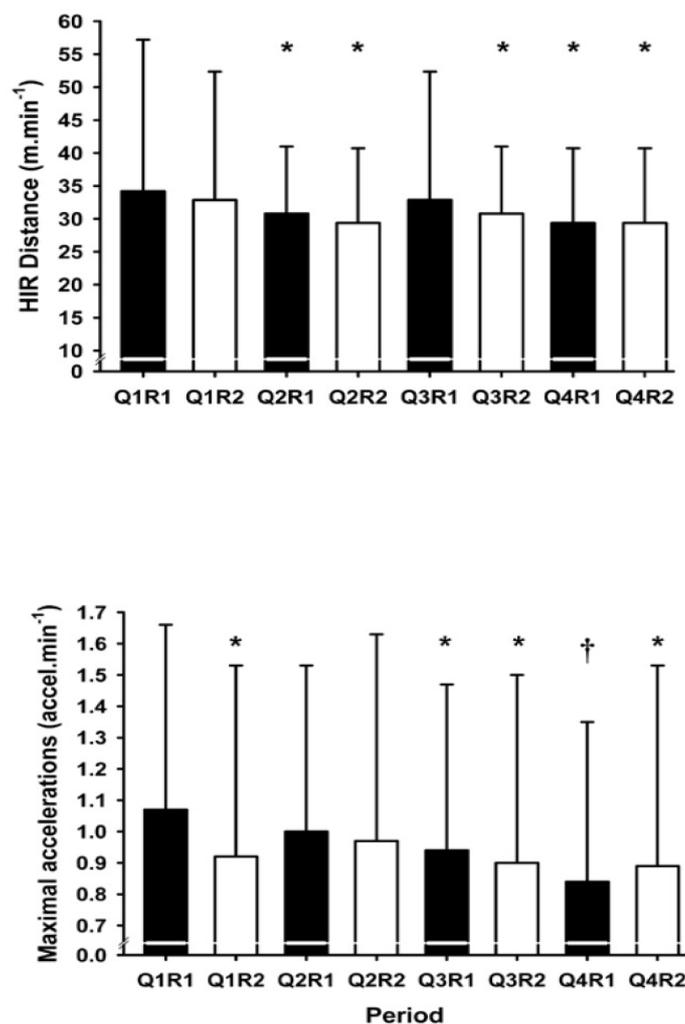


Figure 2.7. High intensity running (HIR) distance in meters and maximal accelerations per rotation expressed per minute of game time (m.min⁻¹; accel.min⁻¹). Periods were named for the quarter of play they occurred in, and the sequential number of the rotation in that quarter (Q1R1; Q1R2; Q2R1; Q2R2; Q3R1; Q3R2; Q4R1; and Q4R2 respectively). Magnitudes of change were classified as a substantial increase or decrease when there was a $\geq 75\%$ likelihood of the effect being equal to or greater than the smallest worthwhile change estimated as $0.2 \times$ between subject standard deviation, and classified as small 0.2 to 0.6; moderate 0.6 to 1.2; large 1.2 to 2.0; and very large 2.0 to 4.0. * Denotes a small reduction from Q1R1. † Denotes a moderate reduction from Q1R1. All data are $Mean \pm SD$, $n = 147$. Reproduced from (Aughey, 2010)

2.2.3 The evolution of Australian football

With GPS research in Australian football only becoming prominent since 2005, longitudinal analysis from year to year is limited. One investigation assessed locomotor activity over a four year period (Wisbey *et al.*, 2009) (Table 4). Changes in

mean velocity were evident with an increase of 8.4%, which is possibly related to a decrease in playing time (9.9%). A decrease in decelerations from a starting velocity of over 2.78 m.s⁻¹ in 2008 (~14%) compared to the previous three years also occurred, which was supported by an increase in steady state running >2.22 m.s⁻¹ (~7%). Although links can be made between some of these measures, the investigation failed to report parameters relative to game time. This may dramatically alter the findings, as time on field can have a significant impact on time-motion variables. Data from this investigation was collected at 1 Hz. As outlined in the previous section (2.1), 1 Hz GPS data has relatively poor reliability and validity. Further, the use of GPS data has not been validated for the detection of acceleration and deceleration activity.

**Table 4. Movement characteristics of AFL football by position in the 2008 (Mean±SD).
Reproduced from (Wisbey *et al.*, 2009).**

Variable	Forward (n= 77)	Nomadic (n= 635)	Defender (n= 87)
Total time (mins)	103:28±14:43	99:02±14:19	104:02±13:12
Total distance (km)	11.7±2.0	12.3±1.9	11.9±1.7
Mean velocity (km.h ⁻¹)	6.8±0.6	7.5±0.6	6.8±0.6
Accelerations over 4 km.h ⁻¹ in 1 s	237±39	248±47	237±40
Surges above 18 km.h ⁻¹	77±16	89±21	77±17
LCT over 20 km.h ⁻¹ (s)	10±2	11±3	11±8
Steady state time above 8 km.h ⁻¹ (min)	20:49±5.20	25:11±5:08	22:22±5.17
Time over 18 km.h ⁻¹ (min)	4:26±1:09	5:29±1:3	4:23±1:10
Rotations (per game)	3.2±1.9	4.3±1.8	3.0±1.9

LCT = longest continuous time.

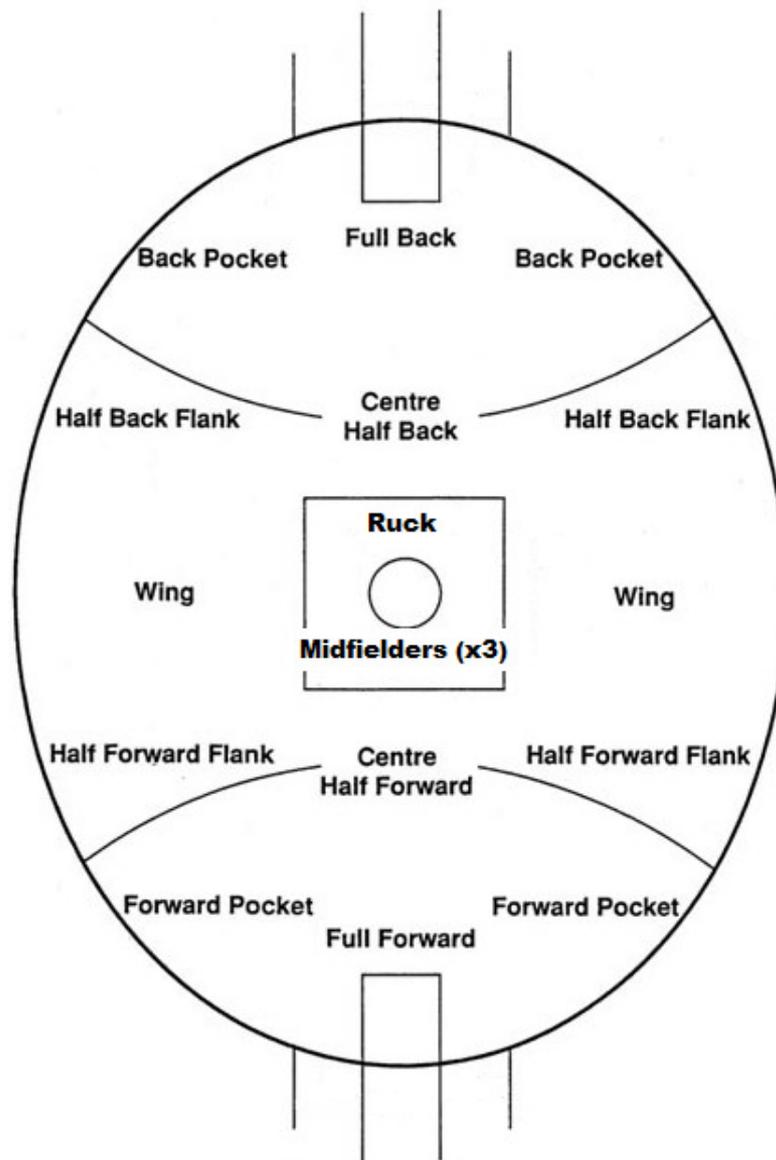
2.2.4 Differences between playing positions

Positional comparisons present information that can be utilised to prepare the athlete specifically to meet the requirements of their role within the team. Table 5 provides a description of each positional role, however it is important to understand that the role may vary from one team to another, depending on preferred structures and the opposition. Figure ___ also provides a visual descriptor of the approximate location of each playing position on a map of the ground.

Table 5. Descriptions of positional roles in Australian football matches.

Playing position	Description
Back pocket & forward pocket	Small and mobile attackers and defenders that tend to play deeper in the attacking and defensive 50 metre area. Midfield player often rest in these positions.
Half forward & back flank	Can be small or medium sized attackers and defenders that push higher up the ground to provide support for the midfielders or rebound from the defensive area.
Centre half forward & back	Mobile and tall attackers and defenders that play inside the 50 metre areas as well as pushing up towards the middle of the ground.
Full forward & back	Tall attackers and defenders that plays deep inside the 50 metre area with the aim of either scoring or defending goals.
Ruckmen	Usually the tallest player on the team, the ruckmen does not play in a set position. They tend to roam around the ground with the aim to be at all stoppages in play to contest the bounce-downs and boundary throw-ins. Ruckmen often play slightly behind the play to provide support to the defenders, or push forward to provide another attacking option.
Midfielders	Mobile players that roam the entire ground. Midfielders are usually present at all stoppages in play. They can also push forward to provide an attacking option, or drop back into defense to provide support.
Nomadics	Players that fulfill a variety of roles for the team across the midfield, defensive and attacking zones.

Figure 2.8. Diagram of playing position location on an Australian football field.



Manual methods used to track junior elite players revealed that the midfield (wings, centres) and running defenders (half back flank) covered the most distance (11,537 m to 11,877 m), in comparison to small deep defenders (back pocket), and rucks (5,319 and 9,203 m, respectively) (Table 6) (Veale *et al.*, 2007). The forwards and key position players were not included in this analysis. Similar trends were shown for work to rest ratios with the midfield and running defenders ranging between 77% and 79% of working activity compared to the small deep defenders (59%), and rucks (72%) (Veale *et al.*, 2007) (Table 6). Interestingly, the rucks, which are commonly

categorised as a midfield player showed lower values compared to the other midfield positions. This may be a consequence of the players' anthropometrical status, as rucks are taller and often less mobile. Additional analysis determined the number and distance of efforts by each playing position. This component established that the running defenders completed the largest number of working efforts (see section 2.2.1) (180), whereas the wing players covered the greatest distance per working effort (58 m). Again the small defenders and rucks were lower in both number, and length of efforts in comparison to the midfield, and running defenders positions (Veale *et al.*, 2007). This suggests that midfield players are required to perform sustained efforts of longer duration compared to the intermittent activity from running defenders. Our knowledge is somewhat limited from this investigation as not all playing positions were assessed. Data was also limited to a maximum sample of three players for each position. Larger sample sizes for each playing position may reduce the influence of factors such as game style, team strategies, and the variability of individual roles. A number of general issues associated with manual tracking also exist, such as the labour-intensive nature of tracking multiple players, and that data is only available post hoc.

A more extensive analysis used video to track the locomotor activity of players from two elite teams over an entire match (Dawson *et al.*, 2004b) (Table 6). This study recorded data from five playing categories which incorporated all playing positions in an Australian football team, however only one match was assessed. The positional analysis was broken down into; full forwards/backs, midfielders, rucks, small forwards/backs, and centre half forwards/backs. Distances were estimated by calculating each individual's regular stride length and stride frequency from video recording of each intensity zones (walking, jogging, fast running and sprinting).

Midfielders recorded the highest total distance (16,976 m), closely followed by the small forwards and defenders (16,278 m), and centre half forwards/backs (16,005 m) and rucks (15,393 m) (Dawson *et al.*, 2004b). Those that played a role deep in the forward or defensive zones (full forward/backs – 13,614 m) again recorded the lowest total distance (Dawson *et al.*, 2004b). High velocity running (fast running and sprinting) was highest for small forwards/backs (3,061 m) followed by midfielders (2,891 m), centre half forwards/backs (2,180 m), rucks (1,911 m) and full forwards/backs (1,127 m) (Dawson *et al.*, 2004a). In addition the full forwards/backs (30) and small forwards/backs (31) performed a higher frequency of sprints compared to other positions (17 to 24) (Table 6). These findings suggest that the high total distance from the midfielders comprises more constant intensities, whereas the small forwards and backs play a more intermittent, high velocity style. It is also interesting to note the much larger total distance covered by the small forwards and backs compared to the full forwards and backs. It appears that the small forwards/backs have a significant role to play further up field, rather than being confined to the forward and defensive zones. Despite this analysis incorporating numerous locomotor parameters across many playing positions, caution must still be taken in interpreting the information, as only one match was assessed.

Table 6. Difference between playing positions from Australian football matches. Data is reproduced from (Dawson *et al.*, 2004b; Veale *et al.*, 2007; Wisbey *et al.*, 2009; Brewer *et al.*, 2010).

Study	TMA Method	Playing level	Variable	Full Forwards / Backs	Centre-half Forwards/Backs	Midfielders	Small Forwards / Backs	Rucks	Half Forward / Back Flankers	
Dawson (2004)	Video	Elite	Total distance (m)	13,614	16,005	16,976	16,278	15,393	-	
			High velocity running (m)	1,127	2,180	2,891	3,061	1,911	-	
			No. of Sprint efforts	30	18	23	31	17	-	
Veale (2007)	Manual	Junior Elite	Total distance (m)	-	-	11,527 to 11,877	N/A	9,203	11,545	
		% of total distance working	-	-	77 to 79	59	72	77		
Brewer (2010)	GPS	Elite	Total distance (m)	11,147	12,130	12,637	12,963	10,811	-	
			Metres per minute (m.min ⁻¹)	119	120	135	127	123	-	
			High velocity efforts/min ⁻¹ (>15 km.h)	226	261	295	292	187	-	
			Sprint efforts per min ⁻¹	0.7	0.8	0.8	0.9	0.5	-	
Wisbey (2009)	GPS	Elite		Forwards			Nomadics		Defenders	
			Total distance (m)	11,700			12,300		11,900	
			Time over 18 km.h ⁻¹ (min)	4:26			5:29		4:23	
			Accelerations (> 4 km.h ⁻¹ in 1s)	237			248		237	

More recent positional comparisons using GPS systems (SPI-10 and SPI-Elite; GPSports, Canberra, Australia) were conducted, this time with a larger cohort of elite senior teams (8) (Wisbey *et al.*, 2009) (Table 6). Nomadic players had significantly higher values for total distance (3.4% >forwards), and time over 18 km/h⁻¹ (23% >forwards & defenders) (Wisbey *et al.*, 2009). The number of moderate accelerations (velocity increased by more than 4 km.h⁻¹ in 1 s) was between 237 and 248 times per match, with no difference found between playing positions. Differences in playing time were not accounted for in this analysis. Interchange rates for each position vary considerably and may influence positional comparisons. In addition to this, the categorisation of players was different to the aforementioned work (Dawson *et al.*, 2004a; Veale *et al.*, 2007), which makes comparing between different studies difficult. The nomadic category was not defined well in the method which makes it difficult to replicate in future research. Midfield players may be better categorised as those who primarily play in the midfield, with an additional category for those who rotate through the midfield from other positions such half forward and half back.

A similar analysis of positional differences (midfielders, full forward/backs, centre half forward/backs, small forward/backs, and rucks) using GPS (SPI-10, GPSports, Canberra, Australia) accounted for the time each players spent on the ground (Brewer *et al.*, 2010) (Table 6). Elite midfielders (135 m.min⁻¹) had higher metres per minute compared to all other positions (119 to 127 m.min⁻¹) (Brewer *et al.*, 2010). High velocity efforts per minute (>4.2 m.s⁻¹) for midfielders (3.2 efforts.min⁻¹) in comparison to all other positions were higher (2.2 to 2.6 efforts.min⁻¹) with the exception being small forwards/backs (2.9 efforts.min⁻¹) (Brewer *et al.*, 2010). The rucks (0.5 sprint.min⁻¹) had less sprint efforts per minute (>5.5 m.s⁻¹) compared to all other positions, with the exception of full/forwards/backs (0.7 sprints.min⁻¹). Small

forwards/backs (0.9 sprints.min⁻¹) had the highest rate of sprint efforts, followed by the midfielders (0.8 sprints.min⁻¹), and centre half forwards/backs (0.8 sprints.min⁻¹), however no difference was found between these. The distance or time of these efforts was not provided.

2.2.5 Differences based on level of competition

Comparisons between playing level in Australian football is limited to one study using GPS (Brewer *et al.*, 2010). Players from the same elite Australian football club were compared during elite and sub-elite or reserve grade matches (Brewer *et al.*, 2010). The centre half forwards/backs, small forwards/backs and rucks showed higher metres per minute for elite compared to sub-elite (Table 7). High velocity running efforts per minute were higher for all positions apart from midfielders at the elite level (Brewer *et al.*, 2010) (Table 7). Sprint efforts per minute were only different for small forwards/backs with the elite players performing a larger number of efforts over 5.5 m.s⁻¹ (Table 7). Research of elite junior players is limited, however one study using manual observation (Veale *et al.*, 2007), showed that total distances were substantially less than that of elite and sub-elite playing levels described here (Brewer *et al.*, 2010). Elite junior midfielders, rucks and small backs covered 11,877 m, 9,202 m, and 11,545 m, respectively. Total distance was the only comparable parameter between these studies. This research of elite junior players was also limited to fewer playing positions with no forwards of key position players used in the analysis (Veale *et al.*, 2007). Although interesting, this comparison between playing levels was conducted across two studies, which utilised different methodology, most notably the different time-motion analysis systems (GPS and manual notation). As there is currently a dearth of research comparing playing levels, practitioners may need to revert to meta-

analysis to acquire this type of information, albeit with a critical view of variation in methodology.

Table 7. Difference between playing level for Australian football. Data is reproduced from (Veale *et al.*, 2007; Brewer *et al.*, 2010).

Study	TMA Method	Playing level	Variable	Full Forwards / Backs	Centre-half Forwards/Backs	Midfielders	Small Forwards / Backs	Rucks
Brewer (2010)	GPS	Elite	Total distance (m)	11,147	12,130	12,637	12,963	10,811
			Metres per minute (m.min ⁻¹)	119	120	135	127	123
			High velocity efforts / min ⁻¹ (>15 km.h)	226	261	295	292	187
			Sprint efforts / min ⁻¹	0.7	0.8	0.8	0.9	0.5
Brewer (2010)	GPS	Sub-Elite	Total distance (m)	11,823	12,317	13,765	12,446	10,529
			Metres per minute (m.min ⁻¹)	107	107	132	120	113
			High velocity efforts / min ⁻¹ (>15 km.h)	203	272	305	254	179
			Sprint efforts / min ⁻¹	0.5	0.8	0.8	0.8	0.5
Veale (2007)	Manual	Junior Elite	Total distance (m)	-	11,545	11,527 to 11,877	N/A	9,203

2.2.6 Locomotor analysis of Australian football training

To date, two studies measuring locomotor movement in Australian football training exist (Dawson *et al.*, 2004a; Farrow *et al.*, 2008). The first assessed elite players using video methods, and compared training output to matches (Dawson *et al.*, 2004a). The time spent (% of total time) standing across all positions was greater in training than matches (~20 to 30%). This may be a product of the coaching instruction and breaks provided between drills at training. The opposite was true for walking; matches had a greater percentage of walking across all positions (9.5% to 32.5%). Similarly, in matches, the jogging (25% to 34%) and fast running (12% to 43%) component was higher except for full forwards and backs, and small forwards and backs; this may be represented by the position on the field and relative involvement in play. In the case of sprinting all positions except for the centre half forwards and backs had greater percentages in matches compared to training (43% to 100%). The number of efforts in the fast running zone were substantially larger in matches (128 to 186) compared to training (30 to 61). Sprinting trends were similar (matches: 17 to 31; training: 1 to 7). This may be a reflection of the duration differences between training and matches, unlike the percentage of total time statistic previously mentioned, the number of efforts is not adjusted according to time spent in activity. This is a potential limitation of the data collection methods employed. The length of fast running and sprinting, which was measured in time (s) was similar in training compared to matches. More fast running and sprint bouts were performed in the shorter duration band of 0-3 s, than the 9.1 s and greater band. Interestingly, there were no sprints sustained for longer than 9.1 s in both matches and training. Change of direction whilst sprinting was similar in training compared to matches, almost 80% were made between 0-90°. It was also noted that 15-23 changes of direction occurred in matches emphasising

that approximately 50% of sprint efforts will involve a change of direction. Rest periods between high intensity movements (fast running and sprinting) were longer in training (76 s) compared to matches (51 s), which again may reflect the allocated breaks and coaching instruction required at training.

A training investigation using GPS evaluated the difference in locomotor activity between closed and open skills drills in Australian football. Three different drills were used in the analysis, with each drill having an open and closed condition. Two of the three open skill (570 m to 721 m) drills elicited higher total distance compared to closed drills (496 m to 645 m) (Farrow *et al.*, 2008). Efforts performed between 2 and 4 m.s⁻¹ were higher for all three open drills (16 to 25 efforts) compared to closed drills (13 to 19 efforts). Only trivial to small differences were displayed for number of high intensity efforts, and high accelerations (Farrow *et al.*, 2008).

2.2.7 Limiting factors associated with locomotor analysis

Despite time-motion analysis providing valuable information on locomotor activity, numerous limitations exist within each of the analysis methods. Generally, time-motion analysis systems only provide a small sample, most often from one team. Varied outcomes based on the individual's performance, the team's strategy and possibly opposition strategy must be considered when interpreting findings (Dobson & Keogh, 2007). Large sample sizes can minimise these effects, however extensive analysis time and limited access to athletes can prevent this from occurring.

Manual time-motion analysis methods have a number of limitations. They are laborious with only one player able to be analysed per observer (Macleod *et al.*, 2009; Petersen *et al.*, 2009). Consistency within and between observers is also a challenge with this method (Macleod *et al.*, 2009). Video systems share similar restraints, however multiple players can be observed with correct camera configuration. Both

manual and video methods also fail to provide real-time information, which if available can assist in managing loads and assessing work rates of individual players during competitive matches and training. Despite computer-based systems automatically calculating variables as they are entered into a system, they also rely heavily on the observer, and again do not provide real-time data. In addition to these limitations, the categorisation of movement intensity is difficult to consistently quantify. Movement bands such as walking, jogging, striding and running are frequently used to determine the intensity of locomotion, however individual differences between players and observers will ultimately exist. Automated systems such as camera recognition, and GPS were developed to overcome many of the previous limitations. Automated camera recognition systems are expensive and require installation within each stadium. Currently these systems are designed for rectangular playing fields such as those used in soccer. Validity has not been determined on an oval shaped field. Expense is also an issue with GPS technology. These devices are also highly variable and rely on satellite coverage, which means that currently they are unable to record information during indoor sports. Similar outcomes have been found across the Australian football literature. However large variations in methodology and technology (Eg. manufacturer, sampling rate) from one study to the next, make comparisons between studies challenging. The widespread use of time-motion analysis across many professional and some semi-professional team contributes greatly to the variance in outcomes throughout the literature.

Despite the many methodological advances in time-motion analysis, numerous elements of team sports performance that contribute to the demands of the game are still either underestimated or overlooked. Acceleration is one element that may elicit similar metabolic cost as high velocity running (Osgnach *et al.*, 2010), but is currently

difficult to measure with the technology available. Utility activities incorporating many forceful movements in confined spaces such as cutting, evading and jumping have also been suggested as highly demanding activities. Current methods of analysis fail to measure these activities. The effect of multiple collisions is another component of Australian football that is currently unable to be measured apart from a basic frequency statistic. Research in rugby (Takarada, 2003), which will be discussed later in this review, suggests that these collisions contribute significantly to the demands of contact-based team sports.

2.3 Physiological response to team sports

The following section will describe the physiological methods used to assess the athlete's response to team sports performance.

2.3.1 Heart rate analysis

Heart rate, which is represented by the number of heart-beats per minute, has been utilised for many years to determine the cardiovascular response of athletes during exercise (Achten & Jeukendrup, 2003). Measuring heart rate began by simply listening to the heart or palpating the blood vessels close to the body's surface. The electrocardiograph (ECG) was developed in the early 20th century, these devices made it easier to monitor and recognise changes in heart rate (Achten & Jeukendrup, 2003). These devices however, were large in size and in some cases immovable, creating difficulties in monitoring exercise in the field. In the 1980's, the first wireless heart rate monitor was developed, consisting of a transmitter strap worn around the chest, and a watch receiver (Laukkanen & Virtanen, 1998). These advances stimulated the widespread usage of heart rate monitoring by athletes and coaches as an objective training tool (Coutts *et al.*, 2003; Johnston *et al.*, 2004; Rampinini *et al.*, 2005; Green *et al.*, 2006; Coutts *et al.*, 2007).

Heart rate is commonly used as a measure of exercise intensity (Macfarlane *et al.*, 1989; Coutts *et al.*, 2007). Thus heart rate values can be used to measure exercise loads to more effectively manage athletes. Alternatively, intensities can be used as parameters for training prescription. Physiological profiles of individual athletes can be constructed to assist with prescription or monitor changes in the athletes over time. The wireless design is relatively non-intrusive and allows heart rate recording over prolonged time-periods assisting in monitoring the physiological status of an individual whilst training or competing in matches.

2.3.1.1 Reliability

Assessing the reliability of heart rate monitors is a complex process that has had limited focus in the literature. A repeated trial is required to assess the measuring potential of a heart rate monitor. In human experimentation, this process is difficult as the physiological response to an identical bout of work may vary from trial to trial, or day to day (Beque *et al.*, 1993; Brisswalter & Legros, 1994). Although only small variations of up to 4 $\text{beat}\cdot\text{min}^{-1}$ have been observed it is difficult to replicate exercise trials and obtain a gold standard for comparison.

An attempt was made to test the reliability of heart rate during soccer training sessions (Rampinini *et al.*, 2005). Skills-based tactical drills and running-based conditioning drills were performed over two training sessions within the same week. Reliability between the corresponding drills for each session was determined using the Intra-class correlation coefficient (*ICC*). Training with the ball, involving technical, and tactical drills (*ICC*= <0.78) correlated poorly between sessions, whereas circuit running without the ball (*ICC*= <0.90) was much stronger (Rampinini *et al.*, 2005). Some of the variation in heart rate during the tactical drills may have been influenced by the level of instruction and/or encouragement provided by the coaches during the session. This may have altered the work and rest intervals, and to a small degree the motivation of the participants. Dietary factors such as fluid intake during exercise can influence heart rate by up to 8% (Gonzalez-Alonso *et al.*, 1997). These factors were not accounted for during this investigation. In addition there appeared to be no mention of the environmental conditions during each training session. Both hot and cold conditions can increase the heart rate response during exercise (Bell *et al.*, 1992; Gonzalez-Alonso *et al.*, 1999).

The variation associated with human activity, and the numerous external factors associated with sports scenarios, creates a challenge in determining the reliability of heart rate measures. Rather than assessing outcomes based on the measurement error associated with the devices as previously described for the various time-motion analysis systems (Section 2.1), it may be more appropriate to determine the day to day variability of heart rate monitoring. Real changes or differences can be calculated by accounting for the influence of environmental and biological factors.

2.3.1.2 Accuracy

The accuracy of heart rate monitors has been studied extensively (Leger & Thivierge, 1988; Macfarlane *et al.*, 1989; Seaward *et al.*, 1990; Terbizan *et al.*, 2002). Accuracy contributes greatly to the usefulness of the device, ensuring that the information acquired is representative of the body's response. Research dating back to the late 1980's used ECG to determine the accuracy of 13 heart rate monitor makes and models (Leger & Thivierge, 1988). Four transmitters all of which were chest-mounted (Exersentry, AMF Quantum XL, Pacer 2000 H, and Monark 1) displayed the strongest relationship with ECG ($r = 0.93$ to 0.98 ; $SEE = 3.7$ to 6.8%). In comparison the photo-electric sensors placed on the earlobe or fingers were not as accurate. These results are reflected in the design of current technology, with most major manufacturers using the chest mounted designs.

During various activities ECG was used as the gold standard in which to compare heart rate monitor outputs. Over a range of activities (treadmill running, rowing, cycle ergometry and weight training) heart rate was within $6 \text{ beats}\cdot\text{min}^{-1}$ of the ECG readings for 95% of the recording period (Godsen *et al.*, 1991). In similar research heart rate monitored during cross country skiing, walking, running and aerobics were compared to ECG (Seaward *et al.*, 1990). Strong relationships ($r = 0.99$) were

displayed suggesting that heart rate monitors have a high level of accuracy in comparison to ECG (Seaward *et al.*, 1990).

The intensity of physical activity is another contributing factor in the accuracy of heart rate monitor recording. The heart rate monitor accuracy of seven different models (6 chest mounted, 1 clipped to earlobe) was assessed at various intensities of treadmill activity (rest; low: 1.34 m.s⁻¹; moderate: 1.78 m.s⁻¹; high: 2.68 m.s⁻¹) (Terbizan *et al.*, 2002). The relationship with ECG measures deteriorated as the intensity increased from rest (rest: $r = 0.78$ to 0.95 , $SEE = <5.23$; low: $r = 0.55$ to 0.95 , $SEE = <7.81$; moderate: $r = 0.50$ to 0.94 , $SEE = <9.53$; high: $r = 0.23$ to 0.81 , $SEE = <13.34$) (Terbizan *et al.*, 2002). The high intensity zone in the present study was only 2.68 m.s⁻¹. If the analysis was completed at intensities that are reached in team sports activity (>5.55 m.s⁻¹), the accuracy may decrease further. These monitors calculate HR through recognition of the R-wave. When the cardiovascular system is under stress, ventricular arrhythmia's can occur. This may cause irregular or weak contractions, making it difficult for the monitor to provide an accurate representation of HR (Godsen *et al.*, 1991). Based on these findings it would seem that HR monitors can be confidently used in a range of sporting activities at low to moderate intensities. However, as exercise intensity increases, the accuracy of these monitors' decreases and an underestimation of exercise intensity may occur.

Now that the accuracy of the actual measuring device (HR monitor) has been assessed it is important to understand the value of HR as a measurement variable. The relationship between HR and other known measures of exercise intensity has been comprehensively researched to help us understand the information that HR can provide.

2.3.1.3 Validity

Validity research frequently uses correlation statistics to assess the relationship between HR monitoring and other common measures of physiological demands. On several occasions energy expenditure (EE) has been used as a benchmark for comparison with HR (Ebine *et al.*, 2002). Various predictive equations are used to calculate EE from HR, and are then compared to known EE values from methods such as the doubly labeled water method and calorimetry (Ceesay *et al.*, 1989; Schulz *et al.*, 1989; Rafamantanantsoa *et al.*, 2002). During standard living activities over 2 weeks the doubly labeled water method of measuring EE was compared with four different HR methods of predicting EE (Schulz *et al.*, 1989). Relationships were large to very large ($r = 0.53$ to 0.73), however the participants were of a non-sporting population, and the physical activity tasks lacked specificity to team sports intensities.

Oxygen consumption ($\dot{V}O_2$) is an indirect calorimetry method that measures the uptake, transportation and utilization of oxygen. This method is frequently used to determine the EE of physical activity. A linear relationship exists between $\dot{V}O_2$ and HR over a range of sub-maximal intensities (Figure 2.9) (Hoffman, 2002) however, this may change when maximal intensities are reached. In addition, this relationship is yet to be determined when intermittent protocols are executed. A number of investigations have used the HR/ $\dot{V}O_2$ relationship to predict EE during various activities.

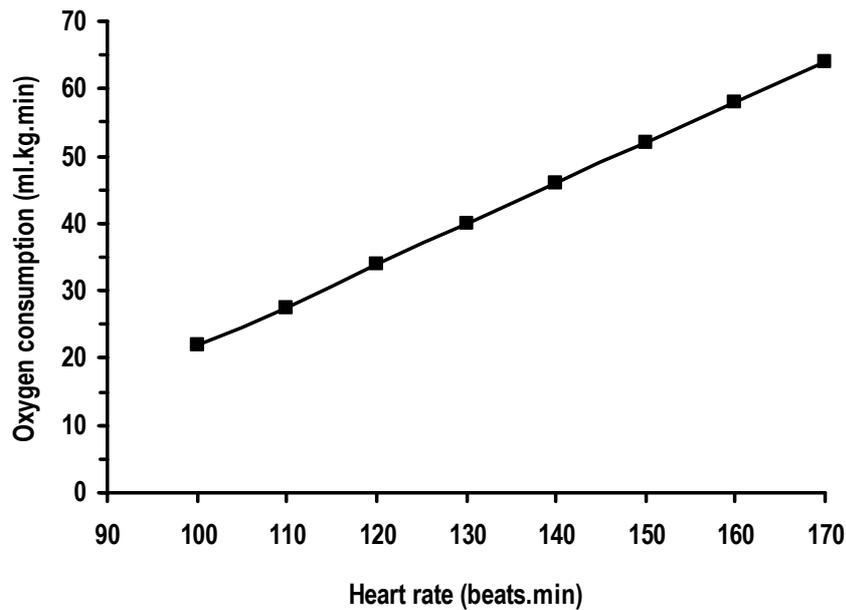


Figure 2.9. Relationship between heart rate and oxygen consumption ($\dot{V}O_2$). Reproduced from (Hoffman, 2002).

Treadmill, stationary cycling, and stationary rowing exercise bouts performed at three different intensities were used to compare 2 methods of predicting EE from HR, with indirect calorimetry in males and females (Crouter *et al.*, 2004). The EE using predicted $\dot{V}O_{2max}$ and HR_{max} , and EE using actual $\dot{V}O_{2max}$ and HR_{max} was compared to a computerised metabolic system's (TrueMax 2400. ParvoMedics, Salt Lake City, USA) calculation of EE. The HR estimate of EE using the actual $\dot{V}O_{2max}$ and HR_{max} proved to be a much better estimate than the EE from predicted $\dot{V}O_{2max}$ and HR_{max} . Estimates using actual values in male participants showed similar $\dot{V}O_{2max}$ results ($4.0 \pm 10.0\%$), whereas females displayed large discrepancies ($12.0 \pm 13.0\%$) (Crouter *et al.*, 2004). In most cases the EE prediction methods overestimated in comparison to indirect calorimetry. These findings suggest that HR estimates of EE are limited with no clear pattern existing for types or intensity of exercise.

A more recent investigation into well trained runners found HR to be ineffective in estimating $\dot{V}O_2$ during track running training sessions (Crisafulli *et al.*, 2006).

Individual HR/ $\dot{V}O_2$ regression equations were determined for each athlete using an incremental laboratory treadmill test to exhaustion. Following this, the athletes wore a portable gas analyser (Cosmed K4, Albano, Italy) during their regular training session, to determine the actual $\dot{V}O_2$. The estimated $\dot{V}O_2$ was determined from the HR information. Findings showed that HR overestimated $\dot{V}O_2$ values by $0.141 \text{ l}\cdot\text{min}^{-1}$. Again this work lacked specificity to team sports and although highly trained individuals, the participants were runners, not team sport athletes.

Heart rate validity in intermittent team sports was assessed during soccer training with positive outcomes (Esposito *et al.*, 2004). Participants wore a portable gas analysis system (K4b², Cosmed, Italy) and HR monitor during a simulated soccer field test, and laboratory treadmill test. The field test incorporated running at varied intensities and skill actions with the ball to ensure that the design was similar to actual soccer activity. The HR/ $\dot{V}O_2$ relationship was determined for each individual during the laboratory treadmill test. The HR obtained during the simulated circuit was then used to predict $\dot{V}O_2$ and then compared to the actual $\dot{V}O_2$ measured by the gas analysis system. A strong correlation ($r = 0.99$) existed between the actual $\dot{V}O_2$ recorded and predicted values obtained through HR integration (Figure 2.10).

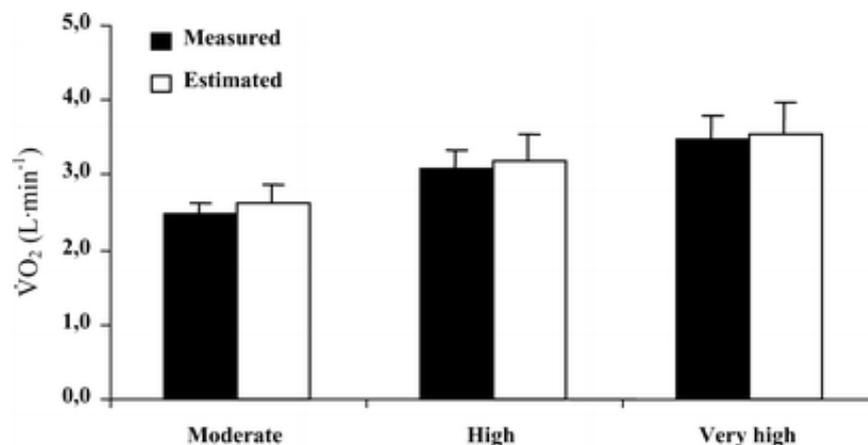


Figure 2.10. Comparison between $\dot{V}O_2$ estimated from HR and $\dot{V}O_2$ measured during the soccer circuit at different exercise intensities. Reproduced from (Esposito *et al.*, 2004).

The strength of this relationship indicating that the soccer specific activity can be measured effectively with the use of HR (Esposito *et al.*, 2004).

Similar findings were displayed using small sided games, and dribbling activity in soccer (Hoff *et al.*, 2002). These activities were again compared to a laboratory based treadmill protocol used to determine the HR/ $\dot{V}O_2$ relationship. During small-sided games, and a specially designed dribbling track, both HR and $\dot{V}O_2$ (portable metabolic testing system - Metamax II, Germany) were recorded. $\dot{V}O_2$ and HR correlated highly in both activities ($r = 0.88$), suggesting that HR is again an effective measure of physical demands in soccer specific drills.

The soccer activities used in these investigations were simulated drills and games designed to elicit maximal exertion, through coaching and rule manipulation. In addition, some of the protocols were designed to simulate constant intensities, which is not reflective of true match-play. Intermittent intensities may have produced different outcomes. The average HR of soccer players during matches was between 80 to 90% of HR_{max} whereas the validity studies discussed previously indicated between 93 to 97% of HR_{max} . This signifies more constant, high intensity activity in the

simulated drills and games compared to the intermittent patterns of actual match play. The athlete's psychological status may also be a contributing factor as the stimulus in a training environment is much different to actual matches (Eston *et al.*, 1998). Analysis within training may not account for the individual's ability to manage the mental stresses associated with performance. In addition, the sample sizes of these two soccer investigations (7, and 6, respectively) were small and may not represent all playing positions.

Similar research in handball (9 participants) using 4-a-side simulated games and an intermittent shuttle running protocol (15s effort alternated with 15s passive recovery) displayed contradicting results to the findings in soccer (Buchheit *et al.*, 2009). Estimated $\dot{V}O_2$ from HR for the simulated game was $8.7 \text{ ml.kg}^{-1}.\text{min}^{-1}$ ($r^2 = 0.52$) lower than actual $\dot{V}O_2$. Interestingly, handball in comparison to soccer is a contact sport; this may have contributed to the underestimation of $\dot{V}O_2$ during the simulated games. The $\dot{V}O_2$ measures picked up changes in energy cost related to physical contact whereas the HR did not. The intermittent shuttle run overestimated $\dot{V}O_2$ by $11.6 \text{ ml.kg}^{-1}.\text{min}^{-1}$ ($r^2 = 0.19$) (Buchheit *et al.*, 2009). The 8 minute shuttle may have elicited steady $\dot{V}O_2$ values whilst HR gradually rose resulting in inflated $\dot{V}O_2$ values (Crisafulli *et al.*, 2006). It is also perceivable that as the shuttle progressed so did the production of lactic acid and accumulation of Hydrogen, which in turn increases the volume of carbon dioxide, which may have contributed to the overestimation (Crisafulli *et al.*, 2006). The protocol used was also much less continuous than that of the soccer research, in turn supporting the misrepresentation of HR during intermittent activity.

The validity of HR as a measure of exercise intensity for team sports is limited. Similarly to the accuracy assessments, HR is a valid tool for measuring exercise intensity at continuous, low to moderate intensities. However as intensity nears maximal exertion, and when the stimulus is intermittent, the ability of HR to measure exercise intensity decreases. Aside from the study of handball, validity assessments of HR in contact sports are lacking.

In contact-based team sports such as rugby and Australian football, players may feel uncomfortable wearing HR monitors, and in some cases, the governing bodies do not allow them to be worn in competitive matches. These key factors in conjunction with the various external influences such as climate and nutritional status illustrate the need for improved methods of measuring exercise loads in the team sports environment.

2.3.2 Heart rate response in Australian football

Unlike many other team sports such as rugby and soccer, heart rate research in Australian football is deficient. Two investigations were conducted a number of years ago, focussing on the cardiovascular response to matches (Pyke & Smith, 1975; Hahn *et al.*, 1979). The first of these studies compared two different playing positions over one quarter of an Australian football match (Pyke & Smith, 1975). The small back player recorded a mean HR of 160 beats.min⁻¹, which combined low intensity (140 beats.min⁻¹), and very high intensity (180 beats.min⁻¹) periods. In comparison, the midfield player recorded a mean HR of 178 beats.min⁻¹. Although the high intensity periods of the midfielder (180 beats.min⁻¹) were similar to the small back, the low periods did not drop below 150 beats.min⁻¹. These findings suggest that midfield players maintain a more constant higher intensity in comparison to the small back, which is more intermittent (Pyke & Smith, 1975). Participant numbers were limited in this study with only one player from each position sampled. In another investigation

this time assessing two midfield players over a full match, mean HR's were between 159 and 164 beats.min⁻¹ (Hahn *et al.*, 1979). Similar to previous findings, high intensity periods were approx 180 beats.min⁻¹, however low periods were 140 beats.min⁻¹. Safety regulations mean that HR receiver watches are prohibited whereas chest straps may be uncomfortable for players to wear when frequent contact to players occurs. This may have contributed to the dearth of research using HR in Australian football despite the accessibility of HR in the training environment, few studies have assessed this response. The only training analysis that exists in Australian football used two sub-elite players during 3 separate training sessions (Hahn *et al.*, 1979). Maximal values reached 185 to 190 beats.min⁻¹, however these were infrequent and short in duration. Data collection was limited to 2 minute intervals, most likely due to the restraints of the technology, and only players from one position (nomadic) were assessed. Although only few investigations of Australian football exist, HR has been extensively used in sports such as soccer and rugby. The following section will describe the HR response to other team sports.

2.3.3 Additional heart rate methods used in other team sports

2.3.3.1 Training analysis

Measuring HR during team sports training can be used to monitor workrate, manage the loads of individual athletes, and determine exercise intensities for various training drills (Coutts *et al.*, 2009b). Soccer research used HR to profile various training activities (modified game, tactical drills & technical drills) (Eniseler, 2005). Modified games (135±28 beats.min⁻¹) had higher HR values than tactical (126±21 beats.min⁻¹) and technical drills (118±21 beats.min⁻¹). This may be a product of competitive pressure and more continuous activity in the modified games (Eniseler, 2005).

Additional soccer research compared the exercise intensities of small-sided games (SSG), and generic running training (Impellizzeri *et al.*, 2006). The average percentage of maximum HR was $90.7 \pm 1.2\%$ during SSG, and $91.3 \pm 2.2\%$ during generic running. These findings suggest that both modes of training stimulate similar cardiovascular responses when averaged over the duration of each activity. Results may have differed if the analysis utilised HR zones. Averages do not allow differentiation between steady-state and intermittent high to low intensity activity.

2.3.3.2 Match analysis

Mean HR values of 160 to 171 $\text{beats}\cdot\text{min}^{-1}$, and $\sim 166 \text{ beats}\cdot\text{min}^{-1}$ occurred in soccer (Van Gool *et al.*, 1988; Reilly, 1997; Edwards & Clark, 2006), and rugby matches (Deutsch *et al.*, 1998; Coutts *et al.*, 2003), respectively. In comparison to the previous findings in training, this suggests that the cardio-vascular response is much greater in matches.

First to second half decreases in HR occurred in sub-elite soccer (~ 171 to 167 $\text{beats}\cdot\text{min}^{-1}$) (Ali & Farrally, 1991), junior level soccer (~ 173 to 168 $\text{beats}\cdot\text{min}^{-1}$) (Stroyer *et al.*, 2004), and elite junior rugby league (167 to 165 $\text{beats}\cdot\text{min}^{-1}$) (Coutts *et al.*, 2003). These trends suggest that the decrease in intensity is related to fatigue during the second half of matches, which inhibits the ability to reach higher HR zones. However, alternative factors such as cardiovascular drift, and the score after half time may also be a contributing factor to this decline. Low motivation levels may initiate a reduction in physical effort as the team feels that a victory is unlikely, or too difficult to achieve.

Research assessing the variation in HR response from different playing levels in team sports has been assessed on one occasion in soccer (Ali & Farrally, 1991). Average HR values from semi-professional soccer players ($\sim 172 \text{ beats}\cdot\text{min}^{-1}$) were higher

compared to the university (~ 167 beats.min⁻¹) and recreational (~ 168 beats.min⁻¹) level players. It is difficult to state whether or not HR can determine differences in exercise intensity between playing level. Firstly, the cardiovascular response is individual and will vary greatly making it difficult to compare between groups. Secondly, it is possible that the physical status of individuals or groups of players will differ based on their training background.

Two investigations, one in soccer and one in rugby have used HR to differentiate exercise intensities between playing positions (Ali & Farrally, 1991; Deutsch *et al.*, 1998). Positional differences were assessed during soccer matches at three different playing levels (semi-professional, university, recreational) (Ali & Farrally, 1991). Players were separated into forwards, midfielders and defenders. The midfielders (176 ± 9 beats.min⁻¹) obtained higher HR compared to forwards (173 ± 12 beats.min⁻¹) and defenders (166 ± 15 beats.min⁻¹). These trends were supported during university level matches, however recreational analysis elicited the highest response from forwards, followed by midfielder and defenders (Ali & Farrally, 1991). In all cases defenders failed to achieve the same intensities as the midfield and forward players. Statistical support was not provided for these differences.

In rugby research 24 male junior rugby players were recruited to compare HR-based exercise intensities between forwards, and backs (Deutsch *et al.*, 1998). Forwards had higher average HR compared to backs during matches (Deutsch *et al.*, 1998). The percentage of game time spent in high HR zone (85 to 95% of max) was greater in the forwards (56.2 to 58.4%) than backs (33.9 to 40.5%). Similar outcomes existed for maximal HR zones (>95% of max), although differences were not significant (Deutsch *et al.*, 1998). Consequently, the backs (36.6 to 38.5%) spent greater percentages of time in the moderate HR zone (75 to 84% of max) compared to

forwards (22.6 to 19.8%). The results from this study indicate more frequent involvement in play from the forwards than the backs due to their positioning on the field relative to the where most of the play is. Physiological status may also contribute to these differences, as the mass and fitness profiles of the forwards to the backs differs significantly due to their role within the team (Deutsch *et al.*, 1998).

Cross-code comparisons have also been conducted between soccer and Gaelic football matches (Florida-James & Reilly, 1995). The HR response to Gaelic football is of great interest as this is often described as the most similar of football codes to Australian football. The results of this investigation demonstrate similarities in percentage of maximum HR for the 1st and 2nd halves (Soccer: 86%, 82%; Gaelic: 81%, 81%, respectively). The cardiovascular response of soccer players decreased slightly in the 2nd half of matches compared to the Gaelic players. This could be attributed to the lower mean HR during the 1st half of matches for Gaelic player allowing them to maintain intensity throughout the match. The duration of the game will also contribute, as soccer is 30 minutes longer. A higher exercise intensity may be easier to maintain over shorter periods of time for the Gaelic players (Florida-James & Reilly, 1995).

2.3.3.3 Limiting factors associated with heart rate analysis

Team sports such as rugby and Australian football reach near maximal intensities, are highly intermittent, and elicit frequent episodes of physical contact. Research suggests that the effectiveness of HR during high intensity intermittent activity is reduced. Intensity may be underestimated as exercises bouts may not be long enough to elevate HR levels. Frequent recovery periods between the high intensity bouts may also greatly affect the HR response in intermittent team sports. The HR response may be delayed during short bouts as the circulatory systems adaptation period may be

incomplete (Jeukendrup *et al.*, 1997; Terbizan *et al.*, 2002). Additionally, HR validity in team sports activity with the presence of physical contact is yet to be determined. Factors such as team tactics, the opposition team and variations in physical status of the athletes from match to match may also affect the outcome of HR analysis in competitive matches.

In addition, the studies presented in this review of HR in team sports failed to consider the effects of the environment on HR information. In hot conditions the body's core temperature eventually rises even with the presence of cooling mechanisms. HR can increase by up to 10 $\text{beat}\cdot\text{min}^{-1}$ due to an increase in oesophageal temperature, and activation of muscle thermo-reflexes (Gonzalez-Alonso *et al.*, 1999). Regions of high altitude also contribute to HR increases (~10 to 22%), in comparison to sea level (Vogel *et al.*, 1967; Klausen *et al.*, 1970). These factors become important when assessing sports that travel to various regions of the world. Soccer is one of these. As stated previously the rules and regulations of sporting bodies do not always allow these devices to be used in competition. Compliance from athlete is also an issue, as wearing HR monitors can sometime be uncomfortable especially in the presence of high-speed activity involving physical contact.

Additional factors such as hydration status can also affect HR responses. Dehydration can reduce stroke volume by up to 7% which can cause a rise in the HR (~5 to 7%) due to a lack of volume being pumped to the working muscles (Gonzalez-Alonso *et al.*, 1997). Research utilising HR should control fluid intake to ensure that the athletes are in a euhydrated state at the time of testing. This was not accounted for in the previously cited studies. It appears that the utility of HR in team sports relies on understanding the limitations, and being able to account for them in the analysis process. Used in isolation HR may be insufficient as an analysis tool, however in

combination with other methods, useful information may be found to assess the demands of team sports.

2.3.4 Blood lactate analysis

Lactate analysis in sports training and competition is frequently used to profile the aerobic and anaerobic energy system contribution, and individual response to exercise (Reilly, 1997; Deutsch *et al.*, 1998; Pyne *et al.*, 2000). The concentration of lactate ($[\text{Lac}^-]$) has for a long time been associated with reduced muscle function and shown the strong relationship that exists with intramuscular acidosis (Anderson & Rhodes, 1989). However more recent findings suggest that impaired muscle function is a bi-product of numerous other mechanisms and that the accumulation of lactic acid has a preserving effect on muscle function (Nielsen *et al.*, 2001). From a practical perspective $[\text{Lac}^-]$ has a moderate relationships with RPE (CR10 scale), which is proposed as an effective measure of exercise intensity in team sports (Coutts *et al.*, 2009b). Blood measures of $[\text{Lac}^-]$, which are most common in team sports may underestimate subsequent levels in the muscle (Krustrup *et al.*, 2006), however the impracticality of muscle sampling does not advocate regular application.

In an important step for the increased practicality of lactate measures in the field, portable analysers were developed to supplement laboratory-based analysers which are difficult to access in a practical environment (Accusport, Boeringer Mannheim, Castle Hill, Australia; & Lactate Pro, Akray, Japan). These devices enabled coaches and scientists to gain immediate feedback during training session and competition. Sports such as Australian football (Farrow *et al.*, 2008 ; Duffield *et al.*, 2009), rugby (Deutsch *et al.*, 1998; Takarada, 2003), soccer (Eniseler, 2005; Ispirlidis *et al.*, 2008;

Hill-Haas *et al.*, 2009), and Gaelic football (Florida-James & Reilly, 1995) have utilised this method.

2.3.4.1 Reliability and validity

Few studies have assessed the reliability and validity of portable analysers designed to measure $[\text{Lac}^-]$. One investigation used a progressive incremental swimming test to compare readings between portable analysers (Lactate Pro) (Pyne *et al.*, 2000). Results displayed strong relationships between devices of the same model ($r = 0.99$). This study also assessed the validity of portable analysers in comparison to a laboratory-based blood gas system (ABL 700, Radiometer Copenhagen, Denmark), which is classified as an accurate measure of $[\text{Lac}^-]$. The Lactate Pro displayed strong relationships with the ABL 700 ($r = 0.97$) with no bias across the range of 1.0 to 18.0 mmol.L^{-1} .

Similarly, the reliability and validity of a different portable analyser (Accusport) was assessed using blood samples taken from kayaker's during an incremental exercise test (Bishop, 2001). Reliability analysis displayed strong relationships at lower $[\text{Lac}^-]$ ($\sim 0.3 \text{ mmol.L}^{-1}$) when the same blood sample was repeatedly trialled using the same analyser ($r = 0.99$). When $[\text{Lac}^-]$ were higher ($\sim 8 \text{ mmol.L}^{-1}$), the intra-device reliability decreased ($r = 0.83$). Inter-day reliability, calculated using a solution of known $[\text{Lac}^-]$ concentration was high ($r = 0.99$) (Bishop, 2001). Validity of the Accusport was again assessed in comparison to a laboratory-based system (Micro Stat LM3), with using the same athlete group (Bishop, 2001). Relationships were strong ($r = 0.99$), however the Bland and Altman plot suggested that random variation between 1.9 mmol.L^{-1} above and 2.2 mmol.L^{-1} below the mean $[\text{Lac}^-]$ exists. The following section presents an overview of blood lactate analysis in team sports.

2.3.4.2 Blood lactate response to Australian football

Analysis of $[\text{Lac}^-]$ in Australian football is limited to few studies. Two elite senior Australian football practice matches used blood $[\text{Lac}^-]$ measures to describe the anaerobic energy requirements in hot conditions (Duffield *et al.*, 2009a). Blood samples were taken pre-match, during the breaks between quarters, and post-match. Pre-match $[\text{Lac}^-]$ of approximately $1.6 \text{ mmol}\cdot\text{L}^{-1}$ increased by the end of the 1st quarter to $8.6 \text{ mmol}\cdot\text{L}^{-1}$ and remained stable for the remainder of the match (Figure 2.11). Elevated $[\text{Lac}^-]$ indicates that intermittent team sports such as Australian football elicit a substantial glycolytic response from the body's energy systems (Duffield *et al.*, 2009a). Blood $[\text{Lac}^-]$ did not continue to rise possibly as a result of reduced high intensity activity and anaerobic energy production, as fatigue accumulated throughout the later stages of the match.

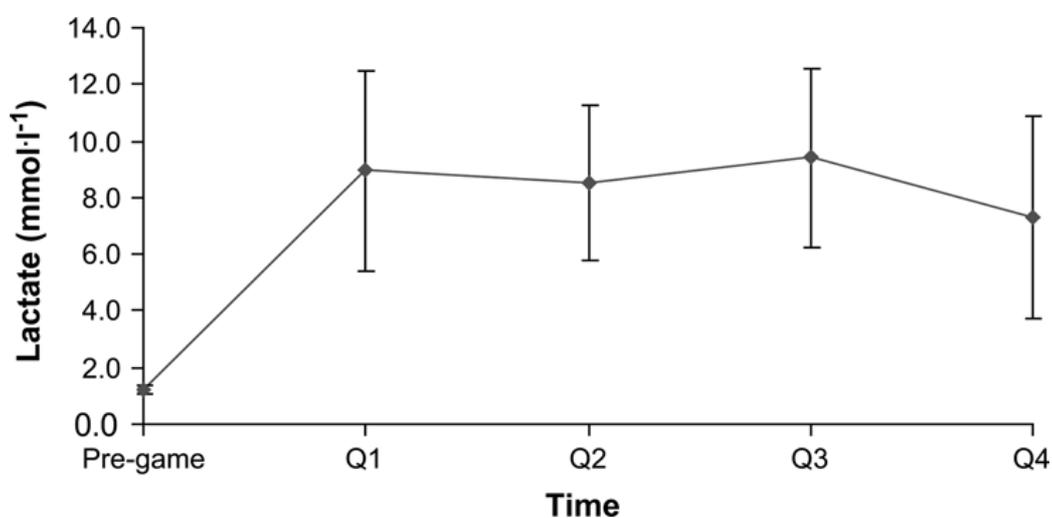


Figure 2.11. *Mean*±*SD* quarter by quarter blood lactate concentration over the duration of an intermittent-sprint competition in warm conditions ($n=14$). Reproduced from (Duffield *et al.*, 2009a).

A training study of 30 junior elite Australian football players (age: 16.7 ± 0.5 years), utilised blood $[\text{Lac}^-]$ to differentiate the physiological demands of closed and open skill Australian football drills (Farrow *et al.*, 2008). Blood samples taken at the

completion of each session displayed slightly higher $[\text{Lac}^-]$ after open skill training however only a small effect was shown ($ES = 0.27 \pm 0.55$). The levels (2.7 to 2.3 mmol.L^{-1}) from both conditions were substantially lower (~68-73%) than the level found in matches (~8.6 mmol.L^{-1}) (Duffield *et al.*, 2009a), however the match analysis was in hot conditions with elite senior levels athletes. Locomotor data (GPS) during both the training and match studies indicated that matches were played at higher intensities than the training analysis (Farrow *et al.*, 2008; Duffield *et al.*, 2009). Therefore a higher $[\text{Lac}^-]$ may be a bi-product of accumulation during anaerobic metabolism without adequate low intensity activity to aid clearance rates.

2.3.4.3 Blood lactate analysis in other team sports

Extensive work assessing blood $[\text{Lac}^-]$ exists in other team sport such as soccer and rugby. The following section will discuss the methods used and subsequent outcomes.

2.3.4.4 Blood lactate response to matches

Numerous studies of soccer activity have used Blood $[\text{Lac}^-]$ analysis, however in most cases simulated or practice match settings were used (Krustrup *et al.*, 2006; Ispirlidis *et al.*, 2008). Results from a series of three practice matches indicated that $[\text{Lac}^-]$ was $0.9 \pm 0.2 \text{ mmol.L}^{-1}$ at rest, reached a peak of $7.9 \pm 0.7 \text{ mmol.L}^{-1}$ during the match, and from then on slowly reduced as the match progressed to post game (~ 4.0 mmol.L^{-1}) (Krustrup *et al.*, 2006) (Figure 2.12). This aligns with similar work from a soccer practice match (rest: $1.04 \pm 0.10 \text{ mmol.L}^{-1}$; post game: $4.51 \pm 0.4 \text{ mmol.L}^{-1}$) (Ispirlidis *et al.*, 2008). Of note here is that $[\text{Lac}^-]$ was much higher in Australian football, and was maintained at higher levels across the match (Duffield *et al.*, 2009a). Factors such as field size, and interchange rules (Australian football - unlimited; Soccer - 3 substitutes only) may have contributed to this difference. Additional research also found that the 1st half $[\text{Lac}^-]$ was higher than 2nd half (Figure 2.12) (Krustrup *et al.*, 2006), which

aligns with previous soccer research (Ekblom, 1986; Bangsbo *et al.*, 1991; Bangsbo, 1994). This may be a direct consequence of a decrease in intensity from the 1st to 2nd half, which has been shown through heart rate (Ali & Farrally, 1991; Stroyer *et al.*, 2004) and time-motion analysis (Burgess *et al.*, 2006; Di Salvo *et al.*, 2009).

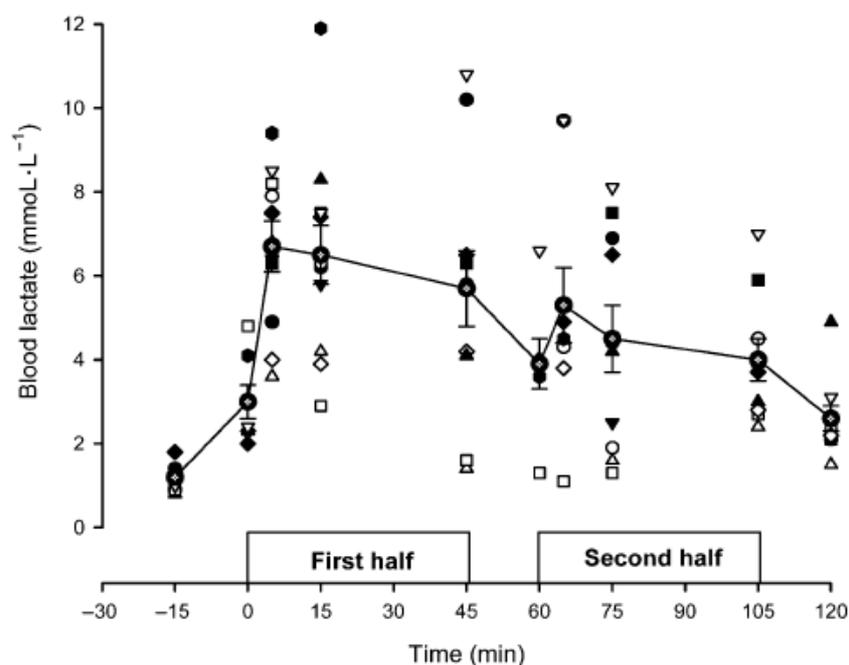


Figure 2.12. Blood lactate concentrations, before, during, and after a soccer game. Data are *Means*±*SEM* (*n* = 11) as well as individual values. Reproduced from (Krustrup *et al.*, 2006).

Research in rugby union and rugby league applied similar methodologies to assess [Lac⁻], this time during in-season fixtures (Deutsch *et al.*, 1998; Coutts *et al.*, 2003a; Takarada, 2003). Fifteen elite rugby union players displayed significant increases in [Lac⁻] from 48 hours pre-match (0.5 mmol.L⁻¹) to immediately post game (3.3 mmol.L⁻¹). Although a reduction followed, the concentration at 45-minutes (1.1 mmol.L⁻¹) and 90-minute (0.8 mmol.L⁻¹) post game were still significantly higher than pre-game values. At 24 hours post-match (0.4 mmol.L⁻¹), [Lac⁻] returned to resting values (Figure 2.13) (Takarada, 2003). Rugby, which requires frequent episodes of physical contact predominantly through tackling and being tackled, evoked a

substantially lower $[\text{Lac}^-]$ response compared to soccer and Australian football matches. With soccer being a predominantly non-contact sport and Australian football possibly representing a medium with some contact but not as much as rugby league and rugby union, these findings suggest that activities engaging physical contact do not appear to stimulate a greater $[\text{Lac}^-]$ response. This supports the notion that respiratory and metabolic stress sustained from high running-based activity during sport such as soccer and Australian football are responsible for the greater glycolytic contribution, rather than the mechanical stresses of physical contact.

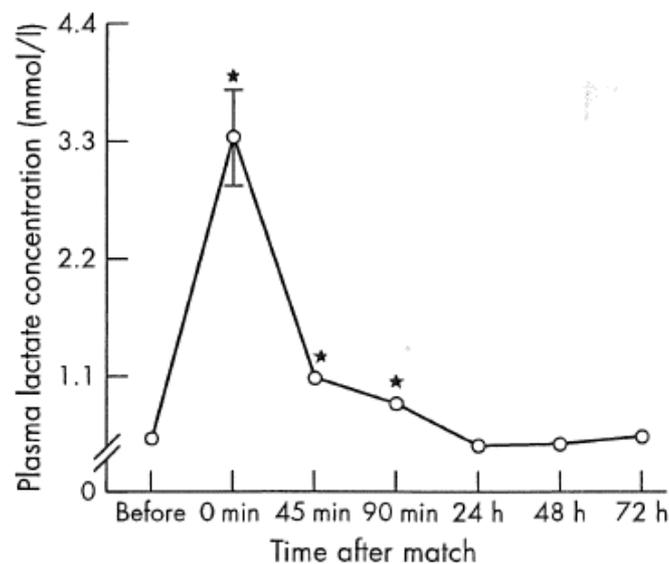


Figure 2.13. Changes in plasma concentration of lactate. Values are *Mean*±*SE* ($n = 14$).

*Significantly different from resting state within the same subjects ($p < 0.05$, Wilcoxon signed ranks test). Reproduced from (Takarada, 2003).

This theory is somewhat contradicted in additional rugby union analysis (Deutsch *et al.*, 1998). Peak $[\text{Lac}^-]$ for forwards (props, locks and back row forwards) were 8.1 to 8.9 mmol.L^{-1} which is equivalent to or higher than peak concentrations in soccer (7.9 mmol.L^{-1}), and Australian football (8.6 mmol.L^{-1}). Alternatively, this differed for the backs (inside and outside) who displayed peak concentrations of 6.1 to 7.2 mmol.L^{-1} . The physiological profile of back position players are similar to that of soccer and

Australian football, therefore this may be a more appropriate comparison to make between codes. Additionally, the players used in this rugby union analysis were junior elite and may not have fully developed their physiological capacities. Post match $[\text{Lac}^-]$ may have provided interesting comparisons between sports to assess the removal and re-utilisation rates, however the present study did not provide these values. This appears to be a major limitation of Lac^- analysis, as sample timing may represent different stages of the accumulation, removal, and re-utilisation phases of energy production.

Research in competitive rugby league matches using seventeen semi-professional players, found similar responses to rugby union analysis (Coutts *et al.*, 2003). Peak $[\text{Lac}^-]$ was approximately 8.5 mmol.L^{-1} with a significant decrease observed in the 2nd half (5.9 mmol.L^{-1}) of the match. This aligns with the previously discussed theory, where a drop in intensity in the 2nd half is reflected by lower $[\text{Lac}^-]$ (Ekblom, 1986; Bangsbo *et al.*, 1991; Krstrup *et al.*, 2006). Post game $[\text{Lac}^-]$ was 4.9 mmol.L^{-1} , which is similar to the findings from soccer, but much lower than Australian football. Again, it appears that a higher intensity was maintained across the entire match in Australian football. When comparing between codes it is difficult to determine whether differences or similarities are a product of the match demands, or a discrepancy between the physiological statuses of players. This makes conclusions difficult to determine with this type of analysis.

The physiological demands of Gaelic football were assessed by measuring $[\text{Lac}^-]$ at half- and full-time, during a match (Florida-James & Reilly, 1995). Half-time ($4.3 \pm 1.8 \text{ mmol.L}^{-1}$) $[\text{Lac}^-]$ was substantially lower than those recorded in Australian football and rugby league matches. Post-game ($3.4 \pm 1.6 \text{ mmol.L}^{-1}$) $[\text{Lac}^-]$ was similar to rugby union, slightly lower than soccer and rugby league, and substantially lower

than Australian football. These findings align with HR data that describes lower intensities for Gaelic football (~157 to 158 beats.min⁻¹) compared to Australian football (~160 to 178 beats.min⁻¹) (Pyke & Smith, 1975; Hahn *et al.*, 1979). Direct comparisons may be compromised as these players were of club standard verses the Australian football players who were playing in the elite competition.

2.3.4.5 Blood lactate response to training

Blood sampling during matches can be impractical whereas the training environment lends itself to more favourable testing conditions. Common analysis used [Lac⁻] to assess the anaerobic contribution of various training activities such as modified games (Rampinini *et al.*, 2007b; Hill-Haas *et al.*, 2009), or to determine the physiological response to various sports specific running protocols (Greig *et al.*, 2006; Buchheit *et al.*, 2009) aimed at replicating match demands.

Modifications were made to soccer small-sided games (altered player numbers, field size and rules) and were subsequently assessed using [Lac⁻] as a measure of anaerobic demands (Rampinini *et al.*, 2007b). As expected, games with fewer players and larger pitch sizes stimulated a higher [Lac⁻], as did the small-sided games with coach encouragement. These variables may be manipulated to alter training, either to progress the stimulus for enhancement or reduce for recovery and regeneration. A major limitation of this was that the small-sided games protocols were measured across a 10-month period. The physiological status and [Lac⁻] may be different as a result of changes in the player's fitness status across such a lengthy testing period, rather than the change in stimulus from the various small-sided games protocols.

In similar research, Lac⁻ analysis displayed no difference when player numbers were manipulated (Hill-Haas *et al.*, 2009). However, differences were found when technical rules were manipulated. For example, when players were required to be in

the two attacking thirds of the pitch for a goal to count $[\text{Lac}^-]$ increased, indicating a potentially greater stimulus resulting in higher anaerobic contribution (Hill-Haas *et al.*, 2009). The methodology states that samples were taken within 5-minutes of each small-sided game finishing. Removal rates of Lac^- from the muscle, and clearance rates from the blood will differ greatly across a 5-minute period post exercise (Jacobs, 1986; Bangsbo, 1994). More rigid sampling protocols should have been adopted.

An intermittent soccer specific treadmill protocol, developed using time-motion analysis data from matches, compared $[\text{Lac}^-]$ to a steady state treadmill run of the same distance, (Greig *et al.*, 2006). Results indicated that no difference in $[\text{Lac}^-]$ existed between steady state and intermittent running (Figure 2.14).

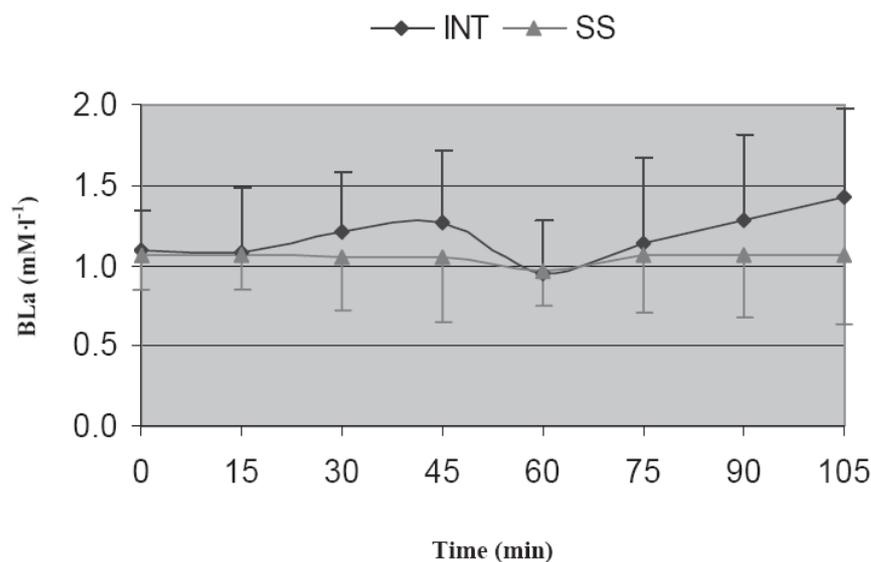


Figure 2.14. Mean \pm SD blood lactate (BLa) concentration ($\text{mM}\cdot\text{l}^{-1}$) during the soccer-specific intermittent (INT) and steady-state (SS) protocols. Reproduced from (Greig *et al.*, 2006).

Interestingly, in the same investigation, Electromyography was used to indicate the mechanical loading of specific muscles in the lower limbs (Greig *et al.*, 2006). Significantly greater mechanical loading was displayed for the soccer specific intermittent protocol. This may have been a bi-product of more acceleration and deceleration required to change velocity as part of this intermittent protocol. From

these findings, it appears that physiological analysis such as $[\text{Lac}^-]$ may underestimate the demands of intermittent exercise as performed in team sports. Further analysis may consider replacing the distance variable with others such as HR to match the intermittent and steady state protocols. The steady state protocol was performed at $1.8 \text{ m}\cdot\text{s}^{-1}$, which in most cases is a fast walking pace.

Another training study this time using handball players, compared an 8-minute modified game to an 8-minute intermittent running bout consisting of 15 second efforts interspersed with 15 second recovery periods (Buchheit *et al.*, 2009). The intermittent running protocol displayed higher post $[\text{Lac}^-]$ concentrations (2.6%) compared to the modified game, however significance was not shown. During modified games high intensity efforts may be interspersed with low intensity activity which may facilitate lactate removal. Coupled with the higher $\dot{V}\text{O}_2 \text{ max}$ during the modified game (3.2%) compared to the intermittent running protocol, this again suggests that $[\text{Lac}^-]$ analysis methods may not be the most appropriate measure to represent the physiological response to sports specific activity.

2.3.4.6 Limiting factors associated with Blood lactate analysis

The rationale for Lac^- analysis in sport has been debated amongst the scientific community for many years. Blood Lac^- analysis has long been assumed to be a marker of fatigue, however contradicting ideas exist. Some believe that lactate accumulation limits the muscle ability to contract and perform optimally due to increased hydrogen ions and acidity levels (Allen *et al.*, 1995). Others believe that alternative mechanisms are responsible for fatigue and that lactate accumulation has a performance enhancing effect. This concept known as the 'lactate shuttle hypothesis' proposes that working muscles release lactate which is then taken up by other cells to be utilised as a metabolic fuel (Brooks, 2000; Gladden, 2004).

Another key limitation is the day to day variation of an individual's response. Despite positive reliability and validity outcomes for the portable analysers, high individual variations has been reported ($CV= 16.5$ to 34.4%) (Hill-Haas *et al.*, 2008). With various factors affecting $[Lac^-]$, the intra- and inter-athlete variation also need to be determined if a change is to be classed as meaningful. Differences in physiological status between or within individuals may affect the outcome of analysis. For example, it has been proposed that a higher $\dot{V}O_{2max}$ will increase the point of Lac^- accumulation, therefore allowing an athlete to work to a greater capacity before production rate exceeds removal rate (Bangsbo, 1994). Dietary intake is another factor that must be considered, as appearance rates may be influenced by the amount of glycogen stored prior to, or during exercise (Jacobs, 1986). Finally, sample timing is highly influential to the outcome of Lac^- analysis following activity. The concentrations of Lac^- may only represent the period of work directly preceding the sample (Bangsbo, 1994). Even if sample times were standardised across studies, the volume and intensity of the activity completed prior to sampling will vary based on trends such as game style and tactics within each competitive match.

2.3.5 Blood markers of muscle damage

Damage to muscle structures occurs frequently during intense physical activity. Side effects such as swelling, soreness, and stiffness can impair regular muscle function, which lead to declines in performance, and generates a subsequent need for recovery (Clarkson *et al.*, 1992; Cleak & Eston, 1992; Byrne & Eston, 2002; Braun & Dutto, 2003). Physical activity with repeated eccentric contractions will increase damage to the muscular structure (Schwane *et al.*, 1983; Tee *et al.*, 2007). It has also been proposed that blunt forces sustained during physical contact to the body can also initiate muscular damage (Zuliani *et al.*, 1985; Takarada, 2003). Australian football

elicits high eccentric loading from large running distance, combined with multiple episodes (~34 to 127) of physical contact through tackling, bumping, blocking and contested situations on the ground and in the air. As discussed previously, current methods of analysis in Australian football have failed to quantify all demanding elements of the sport. Therefore assessing the damage to muscle structures may provide information that is currently being overlooked. Currently though, no literature examining muscle damage in Australian football is available. Despite neither rugby nor soccer containing the combination of high running volume and physical contact that Australian football does, these are the only team sports to have assessed muscle damage (Hoffman *et al.*, 2002; Takarada, 2003; Hoffman *et al.*, 2005; Ispirlidis *et al.*, 2008).

2.3.5.1 Reliability and validity

Reliability and validity studies assessing biological markers of muscle damage do not exist in isolation. However studies using these techniques often display reliability statistics for the analysis procedures used in each study. Biochemical analysis often involve assays, which are quantitative techniques used to measure the presence or amount of a target entity. Studies of American football, and soccer have reported the reliability of assays that were used to detect myoglobin, creatine kinase and lactate dehydrogenase, which are substances that leak out of muscle cell when damage has occurred to the structures. Variance of $CV= 3.5$ to 10% , and $CV= 2.4$ to 7.3% have been reported for intra- and inter-assay reliability, respectively (Hoffman *et al.*, 2002; Hoffman *et al.*, 2005; Ispirlidis *et al.*, 2008).

2.3.5.2 Structural damage from competitive matches

Currently few studies of team sports have measured blood markers of muscle damage, which suggests that this method of analysis is still relatively innovative. Venous

sampling techniques are the most common in this setting, therefore friendly or practice matches are commonly used, as they provided the most suitable environment compared to actual competitive matches. Two soccer investigations assessing blood markers of muscle damage currently exist (Ascensao, 2008; Ispirlidis *et al.*, 2008). The first of these investigations indicated that creatine kinase ([CK]) increased by almost 700%, and lactate dehydrogenase ([LDH]) 160%, with both enzymes peaking at 48 hours post match (Figure 2.15) (Ispirlidis *et al.*, 2008).

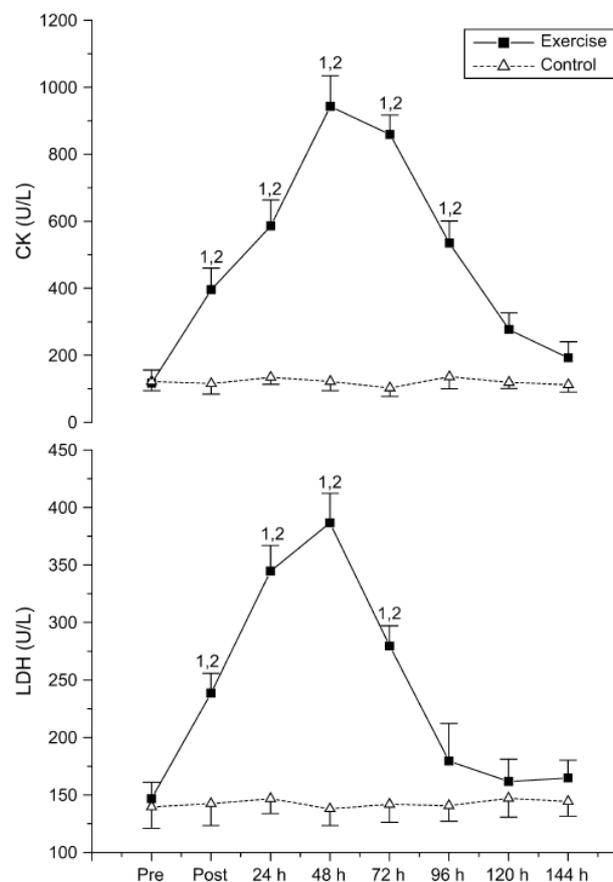


Figure 2.15. [CK] and [LDH] changes after a soccer game (Mean±SE). 1, Significant difference with baseline; 2, significant difference between groups. Reproduced from (Ispirlidis *et al.*, 2008).

Although soccer is a predominantly non-contact sport, these values were only slightly lower than findings from a competitive rugby union match (Takarada, 2003). Both [LDH] and [CK] remained elevated at 72 hours and 96 hours post, respectively. This is important to consider for team sports that compete on a week to week basis. The

regeneration status of muscle structures may influence training and recovery practices to ensure that the athletes are able to prepare for, and play the next match. Similarly, in other soccer research [CK] levels peaked at 48 hours post-match and remained elevated from pre-match levels at 72 hours post-match (Ascensao, 2008). Myoglobin ([Mb]) however differed with peak values obtained 30-minutes post game which then dissipated rapidly back to baseline levels by 24 hours post (Figure 2.16). The molecular mass of Mb (17,800 Da), which is substantially less than CK (40,000 Da) may have contributed to the immediate release from the muscle fibres at 30 minute post, and rapid dissipation from the blood (Hoffman *et al.*, 2002).

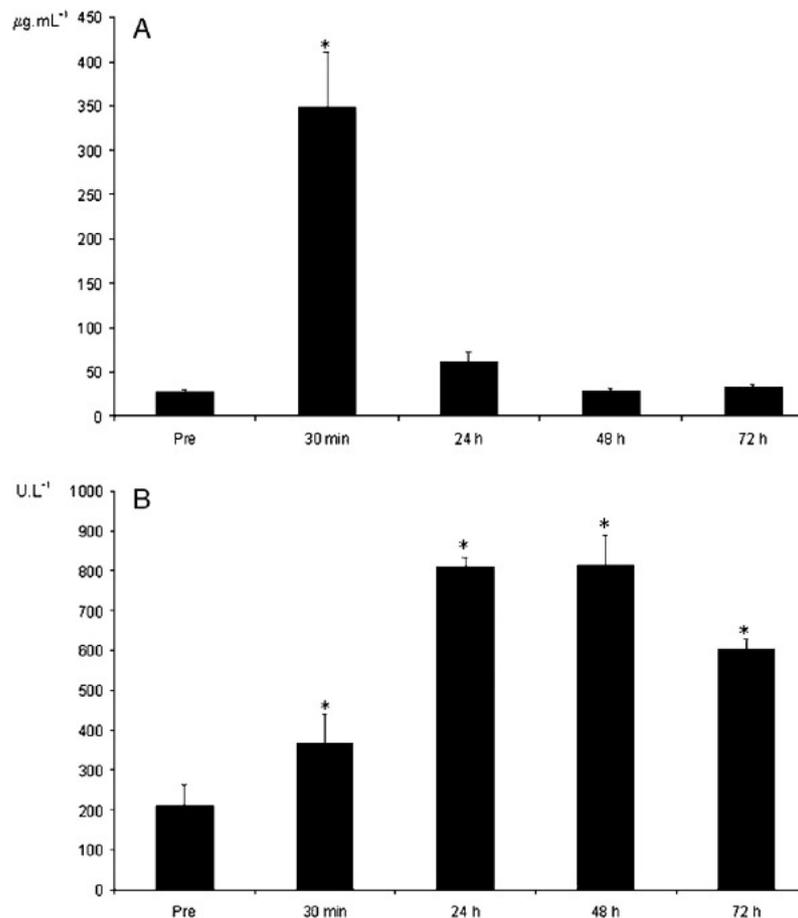


Figure 2.16. Plasma [Mb] (A) and [CK] (B) levels before and 30 min, 24, 48 and 72 h after a soccer match. Values are *Means*±*SEM*, * vs. Pre ($p < 0.05$). Reproduced from (Ascensao, 2008).

Other football codes incorporating higher levels of physical contact such as American football and rugby have also been subject to investigations of muscle damage (Hoffman *et al.*, 2002; Takarada, 2003). Time course changes in [Mb] across a college level gridiron match displayed similar trends to the previous soccer investigation, with Mb increasing by (~450%) immediately after the match (Hoffman *et al.*, 2002). This research did not assess responses beyond the post-match time point. Therefore it is unknown as to whether [Mb] rapidly decreased at 24 hours post-match in gridiron, as displayed previously in soccer. Interestingly, [CK] levels did not rise significantly (Figure 2.17). This again may be a bi-product of the molecular weight of the markers used (Hoffman *et al.*, 2002).

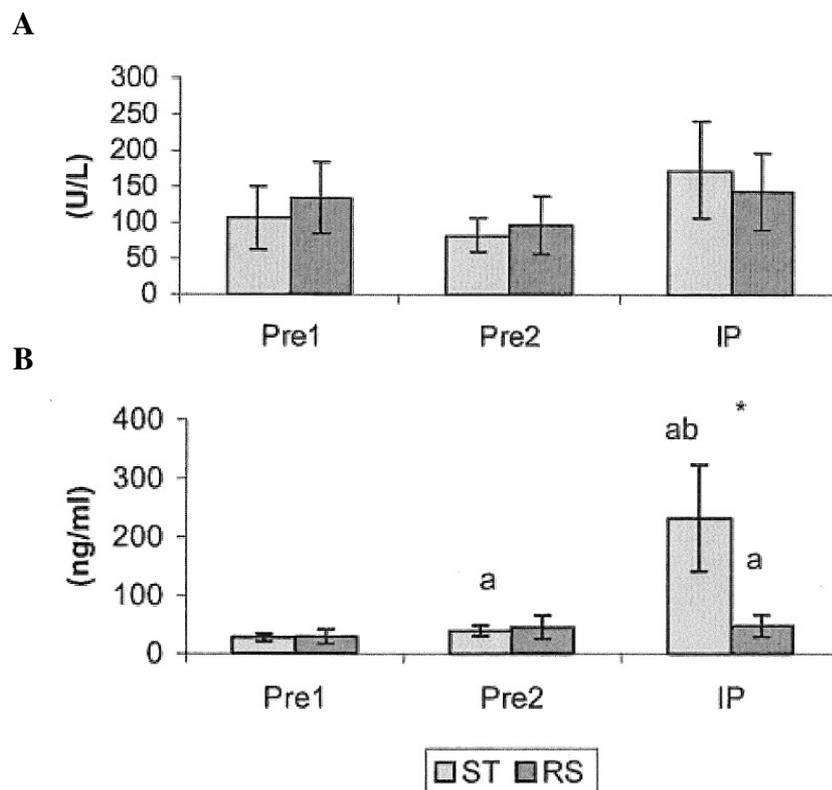


Figure 2.17. Serum creatine kinase (A) and myoglobin (B) concentrations. Blood samples obtained afternoon before game (PRE1), 2 to 2.5 h before game (PRE2), and within 15 min of game's conclusion (IP). All data are reported as $Mean \pm SD$; * Significant difference between ST and RS; a, significantly different from corresponding value at Pre1; ab, significantly differently from corresponding values at Pre 1 and Pre2. Reproduced from (Hoffman *et al.*, 2002).

The lower activity levels of American football, more specifically playing time and running distances, may not stimulate sufficient levels of micro-trauma compared sport such as soccer (American football: $\sim 170 \text{ U/L}^{-1}$; Soccer: $\sim 400 \text{ U/L}^{-1}$). This reduced disruption to the muscle structure may have hindered the larger [CK] molecules from crossing the membrane, unlike the smaller [Mb] molecules that were present in the blood. Aspartate aminotransferase also increased following the match, however the release of this enzyme is difficult to interpret as a number of other factors such as liver damage and myocardial infarction are associated with appearance rates in the blood (Brancaccio *et al.*, 2010).

Similar to American football, rugby incorporates high levels of physical contact, however, running distances are much greater. Subsequently it might be expected that muscular trauma would be greater from the added eccentric component in rugby union compared to American football. This concept was supported in a recent investigation, with [CK] ($\sim 157\%$) and [Mb] ($\sim 345\%$) levels substantially higher for rugby union compared to American football immediately post match (Takarada, 2003). In comparison to soccer, rugby union results indicated that [CK] levels were similar immediately post, however once a peak was reached at approximately 24 hours, rugby union was higher (Figure 2.18). These findings suggest that disruption to muscle structures following rugby union is sustained for longer periods of time compared to soccer. This information can be utilised to plan recovery and preparation for sports that compete on a week to week basis. The [Mb] results were similar with peak values immediately post higher in rugby and by 24 hours both had subsided to similar levels (Figure 2.18) (Takarada, 2003).

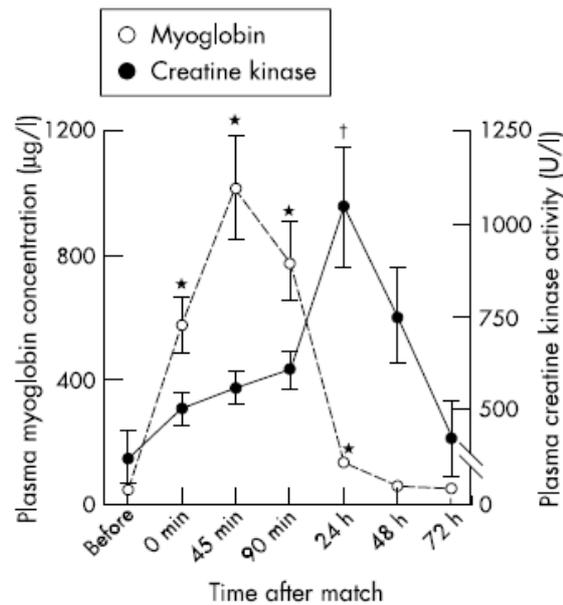


Figure 2.18. Changes in plasma [Mb] and [CK] after the rugby matches. Values are *mean*±*SE* (*n* = 14). *, † Significantly different from resting state within the same subjects (*p* < 0.05, Wilcoxon signed ranks test). Reproduced from (Takarada, 2003).

The competition level and subsequently the training status of the rugby union players (amateur) used in this investigation may have contributed to the higher concentrations, compared to soccer (elite) and American football (college). Well trained athletes have a greater resistance and ability to regenerate from incidence of micro-trauma (Vincent & Vincent, 1997). Another major component of this rugby investigation was the relationship between the number of tackles performed and received, and both [CK] ($r = 0.92$) and [Mb] ($r = 0.85$) (Takarada, 2003). This is an important finding as it supports the concept that direct forces applied during tackling and collision type actions directly affect the structure and subsequent function of the muscles.

2.3.5.3 Structural damage sustained across a competitive season

Longitudinal changes in muscle damage across an American football college season used both [Mb] and [CK] to determine if a resistance was developed against damage to the muscle structure (Hoffman *et al.*, 2005). Blood samples were taken at the

beginning of pre-season prior to a training camp, on the last day of the camp, and at three time points throughout the competitive season (Hoffman *et al.*, 2005). The concentration of Mb was unchanged, this may have been influenced by the sampling timing. Previous findings from other team sports matches show that Mb returns to baseline by 24 hours post (Takarada, 2003; Ascensao, 2008; Ispirlidis *et al.*, 2008). In the current study, [Mb] may have already been transported to and removed by the kidney prior to the sample being taken. Alternatively, [CK] levels increased significantly from the beginning of pre-season training camp to the end of the camp. This was followed by a reduction in [CK] concentration throughout the competitive season. These findings supported the hypothesis, suggesting that when athletes are in a de-trained state at the beginning of a preparation muscle structures are vulnerable, however as training progresses a resistance to trauma is developed (Hoffman *et al.*, 2005).

2.3.5.4 Limiting factors associated with markers of muscle damage

Blood sampling from elite athletes is often challenging as both regulations enforced by sports governing bodies, and athlete compliance are primary limitations. Additionally, there are a number of issues relating to the internal processes following muscular trauma. The various molecules used to express muscle damage, will each cross the sarcolemma, and subsequently be transported from the extracellular fluid to their site of removal at varying rates. As discussed previously, the size and molecular weight of a substance may facilitate a more rapid exit from the muscle cell into the blood stream, which will then be transported faster to the site of re-uptake (Hoffman *et al.*, 2002; Hoffman *et al.*, 2005). This makes for a very difficult comparison if studies have not used the same markers and time stamps. Training status is also a key consideration as previous work has shown that populations with little exposure to

strenuous exercise may experience higher levels of trauma compared to those who have a better training history (Vincent & Vincent, 1997).

2.3.6 Measuring the endocrine response in sports activity

Several researchers have observed the response of the endocrine system to team sports. (Filaire *et al.*, 2001; Hoffman *et al.*, 2002; Elloumi *et al.*, 2003; Gorostiaga *et al.*, 2004; Kraemer *et al.*, 2004; Hoffman *et al.*, 2005; Greig *et al.*, 2006; Coutts *et al.*, 2007b; Cormack *et al.*, 2008a; Cormack *et al.*, 2008b; Ispirlidis *et al.*, 2008; Kraemer *et al.*, 2009; Moreira *et al.*, 2009). Of most interest is testosterone and cortisol, which are proposed as indicators of anabolic and catabolic activity, respectively (Urhausen *et al.*, 1995; Cormack *et al.*, 2008a; Cormack *et al.*, 2008b). Increased protein synthesis with elevated levels of testosterone positively affects the development of muscular strength and hypertrophy. Being able to measure anabolic status using testosterone may assist in maximising skeletal muscle development during training and competition phases. Conversely, cortisol degrades tissue protein to form amino acids, which are then converted to glucose for energy production. This catabolic process can be a protective response to stresses such as illness and injury. The homeostatic balance between these two key hormonal markers can influence muscle function and stimulate either a positive or negative performance outcome (Kraemer *et al.*, 2004). However, in team sports cortisol is most often used to reflect the exercise stress associated with training and competition to manage athletes from week-to-week.

Within the literature, there are two methods of hormonal analysis, salivary and serum. The primary difference between the two methods is the non-invasive nature of the salivary testing. Secondly, salivary testing measures the un-bound, or free hormone concentration, in comparison to serum which only detects the protein-bound

hormones. These protein-bound hormones are inactive and do not accurately reflect the concentration of hormones that can be transported around the body. Although there are strong correlations between the two sampling methods, it is important to understand that the protein-bound hormones measured in serum make up approximately 95% of the total body content. This method will thus give higher values than saliva sampling.

2.3.6.1 Reliability and validity

Similarly to the previous section which discussed muscle damage in team sports, the reliability and validity of these markers does not exist in isolation. Studies using these techniques reported variance of 3.9 to 10.0% (CV) for intra- and inter-assay reliability within the methodology (Hoffman *et al.*, 2002; Cormack *et al.*, 2008a). The following section will discuss the findings of various hormonal investigations of team sports activity.

2.3.7 Endocrine response to Australian football

To date only two Australian football investigations assessing the endocrine response exist. The following sections will discuss these two studies.

2.3.7.1 Acute response from matches

The short-term hormonal response to Australian football matches was measured through salivary sampling of 22 elite level players (Cormack *et al.*, 2008a). Saliva samples were taken 48 hours and immediately pre-match, and immediately, 24, 72, 96 and 120 hours post-match (Figure 2.19). Elevated cortisol levels immediately post (34.2%; $ES = 2.34 \pm 1.06$) and 24 hours post (41.8%; $ES = 2.78 \pm 1.16$) in comparison to pre-match levels indicated that prolonged (≥ 120 minutes) team sports activity may increase the catabolic state of the body. This was supported by the decreased testosterone to cortisol ratio immediately post (-36.0%; $ES = -0.52 \pm 0.42$) and 24 hours

post (-43.7%; $ES = -0.67 \pm 0.52$) (Cormack *et al.*, 2008a). Testosterone measures displayed unclear outcomes. Any Changes at 72 hours post-match or beyond may be a response to training stress during the following week (Cormack *et al.*, 2008a). Additional findings demonstrated an anticipatory response pre-match as cortisol levels increase from 48 hours pre-match to immediately pre-match (16.5%; $ES = 1.43 \pm 0.42$).

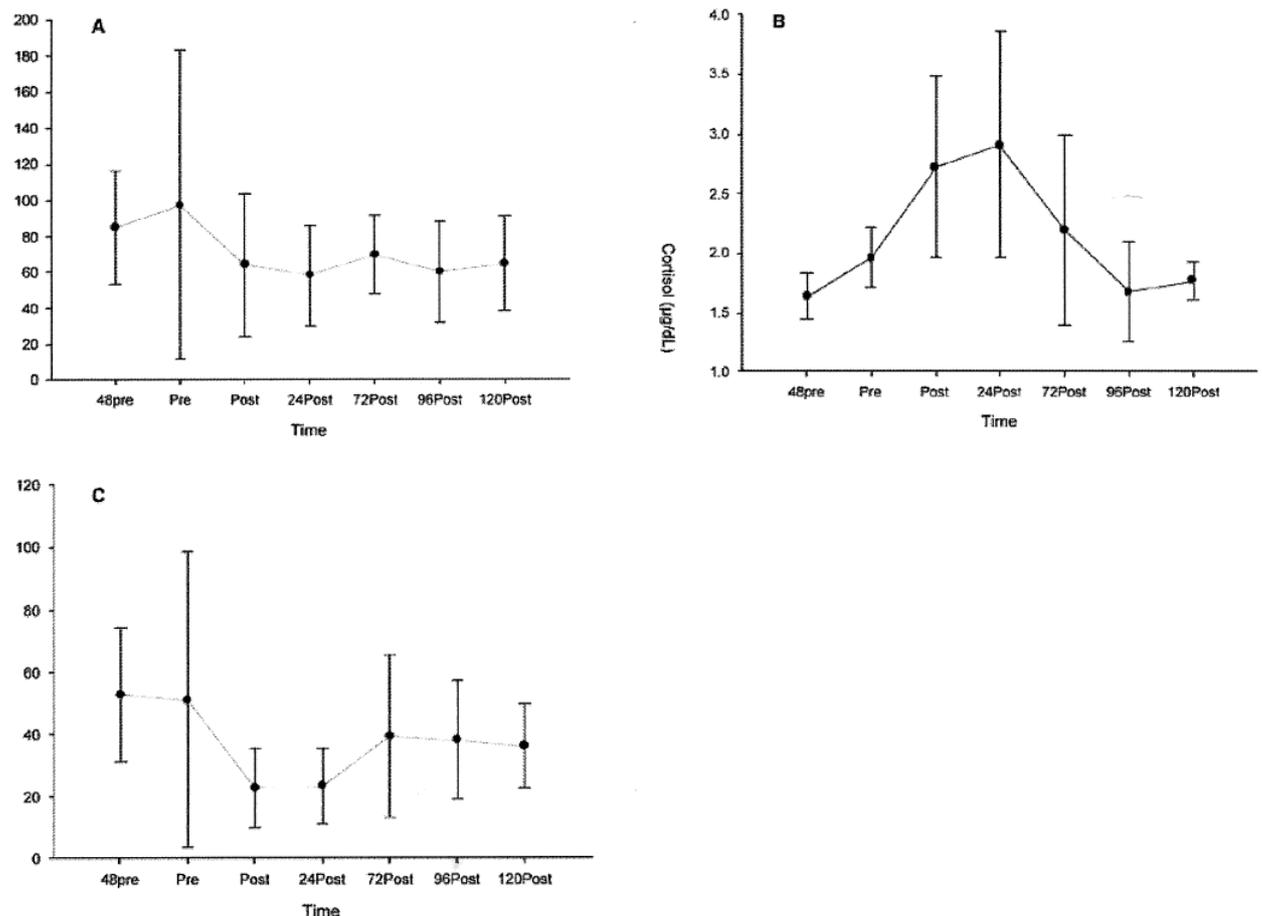


Figure 2.19. Endocrine responses 48pre game to 120post game. (A) Testosterone (pg/mL), (B) Cortisol, and (C) Testosterone:Cortisol (T:C). Values are represented as $Mean \pm SD$. Reproduced from (Cormack *et al.*, 2008a).

2.3.7.2 Longitudinal changes across a competitive season

Longitudinal changes across an Australian football season were also assessed by the same research group (Cormack *et al.*, 2008b). Saliva samples were taken mid-week on 20 occasions and compared to a baseline sample taken in the week leading up the first

match of the home and away season (Figure 2.20 - only testosterone and T:C was displayed). Cortisol decreased substantially across 19 of the 20 rounds, suggesting that either the baseline measure was elevated from a rigorous pre-season training period, or that athletes were able to tolerate in-season stress (Cormack *et al.*, 2008b). Similarly, this was supported by the increased T:C ratio in comparison to baseline for 70% of data points, indicating a maintenance of anabolic status. Again, testosterone failed to display any clear patterns, as was the case with the match data discussed previously.

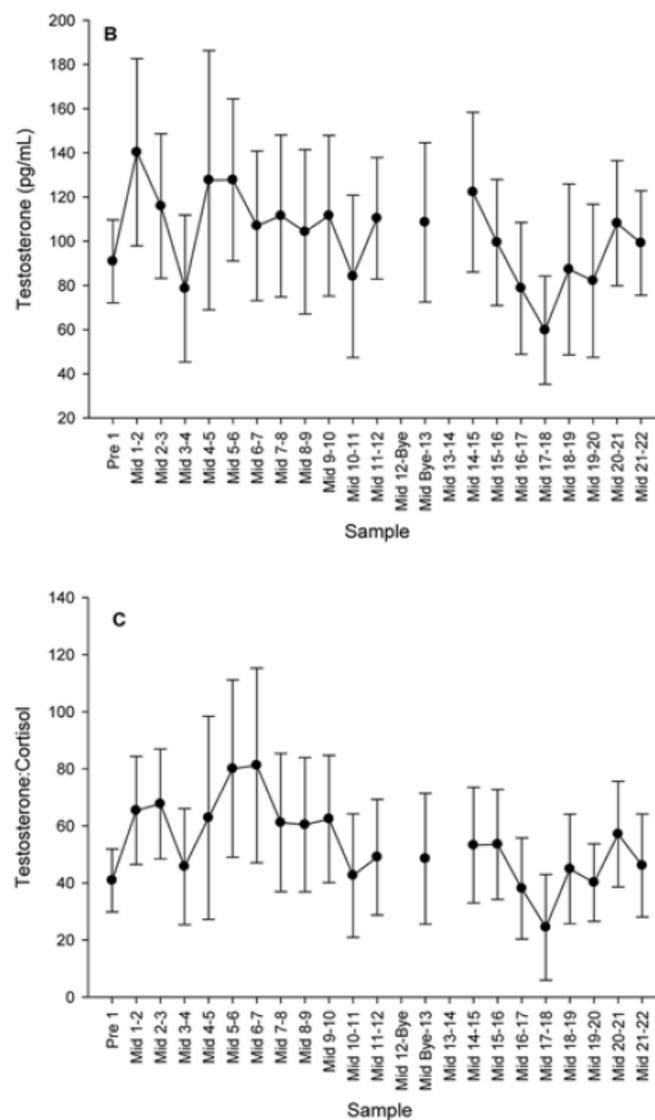


Figure 2.20. (B) Testosterone (pg.mL), and (C) Testosterone:Cortisol Pre to Mid 21 to 22. Values are displayed as *Mean*±*SD*. Reproduced from (Cormack *et al.*, 2008b).

Based on these findings it appears that testosterone is limited in providing useful information due to the variability of the outcomes from individual matches and across a season. Given that the T:C ratio shows similar patterns to cortisol it may be cost- and time-effective to measure one marker rather than two.

2.3.8 Response from other team sports

Similarly to Australian football, the acute hormonal response to matches, and the accumulative effect across a season have been assessed in soccer, rugby union, and American football. The following sections will discuss the findings of the current research in other team sports.

2.3.8.1 Acute response to matches

A summary of the endocrine response, more specifically, cortisol and testosterone are displayed in table 8.

Table 8. Pre to post game hormonal response across various team sports. * denotes a significant change from pre to post.

Sport	Study	Method	Change from pre to post game (%)		
			Cortisol	Testosterone	T:C Ratio
Australian football	Cormack et.al. (2008a)	Saliva	↑34.2% *	↓21.8%	↓36.0% *
Soccer	Moriera et.al. (2009)	Saliva	~↑40%	-	-
	Ispirlidis et al. (2008)	Serum	~↑42%	~↓15%	-
	Haneishi et al. (2007)	Saliva	~↑150% *	-	-
Rugby Union	Elloumi et al. (2003)	Saliva	~↑148% *	~↓16% *	↓62% *
Gridiron	Hoffman et.al. (2002)	Serum	~↓33%	~↓5%	-
	Kraemer et.al. (2009)	Serum	~↑7%	~↓7%	~↑1%

The current literature describing the endocrine response to soccer matches is ambiguous. An investigation of 22 elite soccer players measured salivary cortisol concentrations before and after a training match (2 x 35 minute halves). No changes in

cortisol concentration from pre to post for a training match (Moreira *et al.*, 2009).

It was suggested that the importance of a training match was reduced, which may have lessened the psychological stress compared to actual in-season matches. Parallel research of twenty-four elite male soccer players from the same squad participated in a simulated soccer match (2 x 45 min halves) (Ispirlidis *et al.*, 2008). Serum cortisol and testosterone was measured pre-match, immediately post-match and every 24 hours after that up to 6 days post-match. Cortisol displayed a significant rise immediately post game (~42 %) from baseline measures taken 2 hours before (Figure 2.21). Testosterone values remained unchanged from pre-game to 6 days post game (Ispirlidis *et al.*, 2008). The reduced game (20 minutes less) time in the first of these studies (Moreira *et al.*, 2009) may have contributed to the varied responses. Additionally, these two investigations used different sampling methods (saliva and serum).

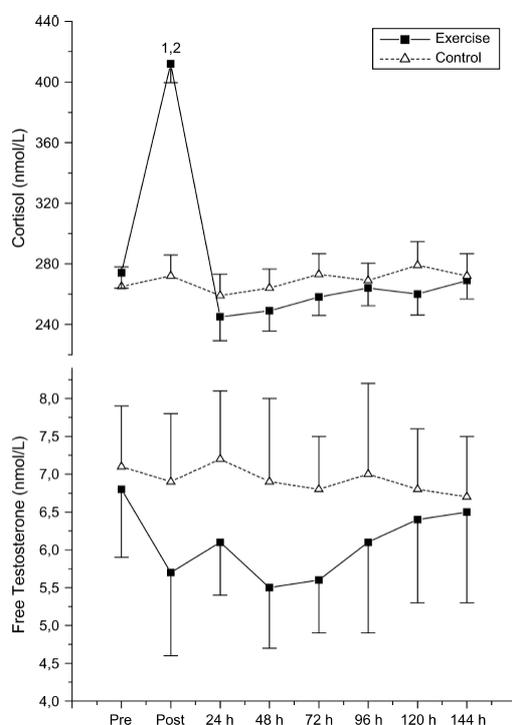


Figure 2.21. Hormonal responses to a soccer game (Mean±SE). ¹, Significant difference with baseline; ², significant difference between groups. Statistical significance was accepted at $p < 0.05$. Reproduced from (Ispirlidis *et al.*, 2008).

In a third report from soccer, twenty elite female college players were recruited and tested during an actual match (Haneishi *et al.*, 2007). Salivary cortisol was measured pre- and post-match. A rise of approximately 150% and 130% were observed in starters (~85% game time) and non-starters (~8% game time), respectively (Figure 2.22). A large relationship ($r = 0.70$) was also observed pre-game between cortisol concentration and cognitive anxiety (Haneishi *et al.*, 2007). This may have contributed to the similar responses from starters to non-starters. Worrying or concerning thoughts associated with competitive environments may contribute to elevated cortisol level in the lead up to matches regardless of the physical stresses on the athletes. This competitive anxiety response may also explain the large rise in cortisol levels in the current study from in-season matches, compared to the previous findings from training matches (Ispirlidis *et al.*, 2008; Moreira *et al.*, 2009).

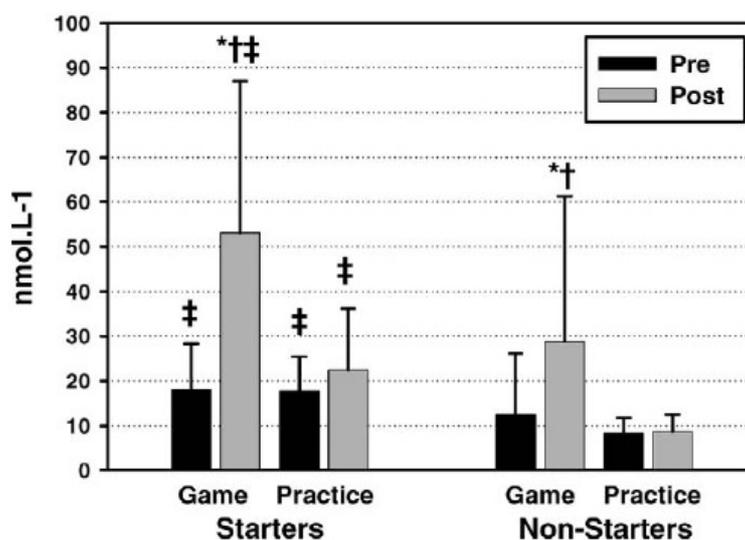


Figure 2.22. Salivary cortisol concentrations ($Mean \pm SD$; $\text{nmol} \cdot \text{L}^{-1}$) in response to a competitive game and a typical practice for both starters ($n = 10$) and non-starters ($n = 8$) on a female collegiate soccer team. * Different from pre-game, ‡ Different from non-starters ($p < 0.05$). Reproduced from (Haneishi *et al.*, 2007).

These responses from soccer were substantially greater compared to the previously reported from Australian football. Soccer increased by approximately 42 to 150%,

compared to Australian football, which was only 34 to 41%, from pre- to post-match. This is an interesting outcome as it appears that the impact-related stress from tackles and collisions in Australian football which is a contact-sport did not increase the stress response. Well trained Australian football participants competing at elite levels may have been able to cope with the physical stresses compared to collegiate level soccer players.

Rugby union bears similarities to Australian football with impact-related actions such as tackling and bumping frequently occurring. A substantial locomotor element also exists over 80 minutes of match play (Duthie *et al.*, 2003a). Changes in cortisol and testosterone from pre- to post-match, and in the subsequent days following, were assessed in comparison to baseline measures sampled from a rest day (Elloumi *et al.*, 2003). Pre-game values were not regarded as baseline due to the diurnal effect on cortisol (Thuma *et al.*, 1995; Dorn *et al.*, 2007). Increases of 148% were shown post match in comparison to resting cortisol values at the same time of day. Conversely, these values dropped to resting values 4 hours post game (Elloumi *et al.*, 2003). Testosterone dropped by 16% immediately post game and returned to resting values within 4 hours. The testosterone to cortisol ratio dropped by 62% immediately post and gradually returned to resting levels by 4 hours post game. These findings showed similarities to research in soccer where cortisol increases were as large as 150% (Haneishi *et al.*, 2007). Although significant, again it appears that testosterone displayed minimal changes in comparison to cortisol. This suggests that cortisol responds to acute stress to protect and preserve energy stores, whereas this intense activity appears not to have as greater effect on slowing the anabolic state of the body through a reduction in testosterone. These findings from rugby displayed similar

trends to Australian football matches however again the magnitude of cortisol increase was much greater.

Although dynamic by nature, American football has a substantially lower volume of activity compared to the majority of other football codes, and may present very different profiles. One study of American football measured the hormonal response across a collegiate level match (Division 3) (Hoffman *et al.*, 2002). Participants consisted of starters (ST) who participated in the match, and red-shirts (RS) who did not participate. Cortisol increased from the day before, to 2 hours pre-game (~60%). This could possibly be related to the anticipatory response seen before competitive games or the diurnal patterns of testing hormonal markers. Following the game, cortisol returned to the same level as recorded from the day before (Figure 2.23) (Hoffman *et al.*, 2002).

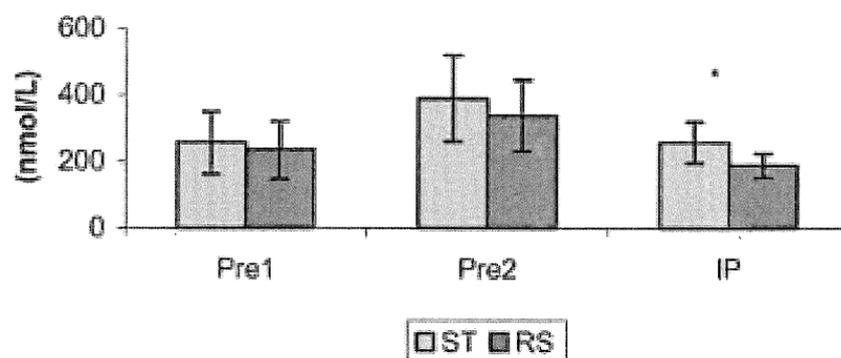


Figure 2.23. Serum cortisol concentrations at Pre1, Pre2, and IP. Blood samples obtained afternoon before game (PRE1), 2 to 2.5 h before game (PRE2), and within 15 min of games conclusion (IP). All data are reported as *Mean±SD*; * Significant difference between ST and RS. Reproduced from (Hoffman *et al.*, 2002).

These findings suggest that the low volume of activity may not be enough to elicit a stress response beyond baseline levels. Interestingly, the non-playing participants displayed a lower concentration of cortisol immediately following the game compared to the starters (~20%). Some might suggest that this represents a higher stress for

those that participated, however the two pre-games values were similar. No changes were observed for testosterone.

Similar findings were displayed during a division 1 college gridiron match (Kraemer *et al.*, 2009). Serum cortisol and testosterone was measured pre-match, approximately 1 and 2 days post-match. Cortisol did not change across the match, however when measured 2 days after the game a drop was observed (Figure 2.24) (Kraemer *et al.*, 2009).

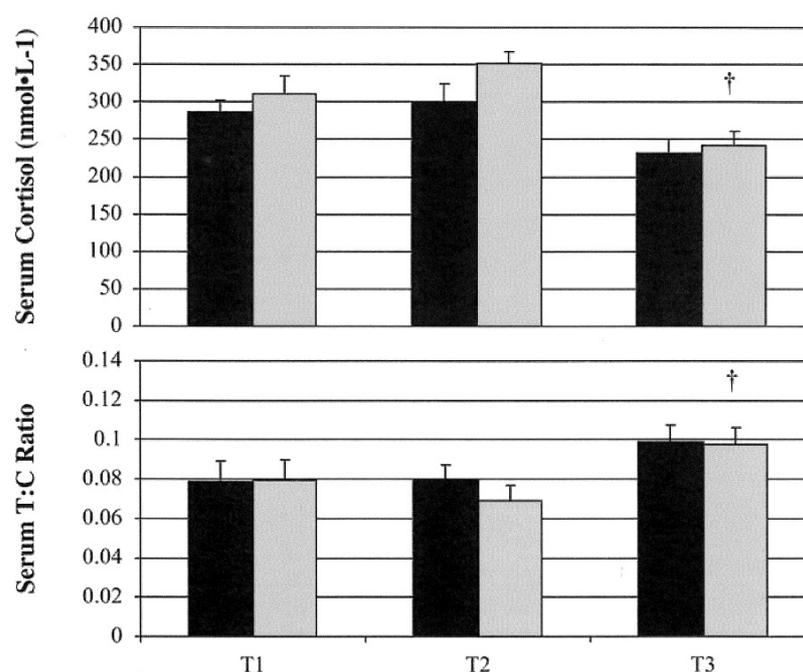


Figure 2.24. Cortisol responses to football competition in players (PL) and bench-players (DNP). The testosterone and cortisol concentrations were determined before the game (T1), 18 to 20 hours after the game (T2), and 42 to 44 hours after the game (T3). † T3 is significantly different from T2 and T1. A trend ($p = 0.06$) existed for PL where cortisol at T3 < T2 and T1. Reproduced from (Kraemer *et al.*, 2009).

Similar to the previous American football research, pre-match levels may have encountered an anticipatory rise pre-game, in turn making it difficult to observe a change from the match stress. These findings suggest that in the days following the game, this anticipatory response will diminish, returning cortisol levels to below what was observed pre-game. Again, testosterone measures were unclear.

Both of these American football investigations displayed minimal changes in cortisol across a competitive match (Hoffman *et al.*, 2002; Kraemer *et al.*, 2009). Changes observed in markers of muscle damages measured simultaneously with cortisol, indicated otherwise. As discussed previously, both investigations displayed a rise in [Mb] (~72 to 360%) (Hoffman *et al.*, 2002; Kraemer *et al.*, 2009), and one study found a rise in [CK] (~41%) (Kraemer *et al.*, 2009), and LDH (~12%) (Kraemer *et al.*, 2009) from pre to post game. This again supports the concept that the amount of physical activity was not high enough to elicit a stress response, however physical contact (blunt force trauma) may elevate damage to muscles from contusions rather than the volume (chronic stress) of work performed during matches.

2.3.8.2 Longitudinal changes across a competitive season

Hormonal changes across a college soccer (division 1) season were observed one week prior to the season, week 3, 5, 7 and 9 during the season, and 1 week post season (Kraemer *et al.*, 2004). Initial cortisol levels 1 week prior were high possibly from an excessive training stimulus over the pre-season period. These levels remained elevated without any major increases across the 11-week season. Testosterone concentration 1-week prior was low and did not display a significant increase until 1-week post. From these findings, it could be implied that a predominantly catabolic state was evident across an 11-week soccer season with anabolic processes increasing once the season had ceased. Additional soccer research with professional players determined the hormonal changes across the pre- and competitive season (Filaire *et al.*, 2001). Results suggested that a 7-week high intensity training block in the pre-season may elicit a catabolic response with testosterone decreasing and cortisol increasing (Filaire *et al.*, 2001). Changes across the competitive phase of the season were unclear. Although not statistically significant, it also appeared that once a high

intensity training block was complete, a shift towards the anabolic state might occur. This supports the previous investigation, which indicated that pre-season training programs may place the body in a catabolic state prior to competing in actual matches, potentially decreasing performance. Similarities from these soccer investigations can be made to Australian football outcomes, which also indicated a decrease in cortisol concentration throughout the competitive season, however testosterone was unclear (Cormack *et al.*, 2008b).

Gridiron research across a pre- and competitive season displayed vastly differing results to both Australian football and soccer. Cortisol concentrations at the beginning of a pre-season camp (T1) were significantly higher than those recorded upon return from the camp (T2) (~20%). This decrease was subsequently followed with an increase in cortisol as the season progressed (T3 = week 3; T4 = week 7; T5 = week 10) (~40% by week 10) (Figure 2.25) (Hoffman *et al.*, 2005).

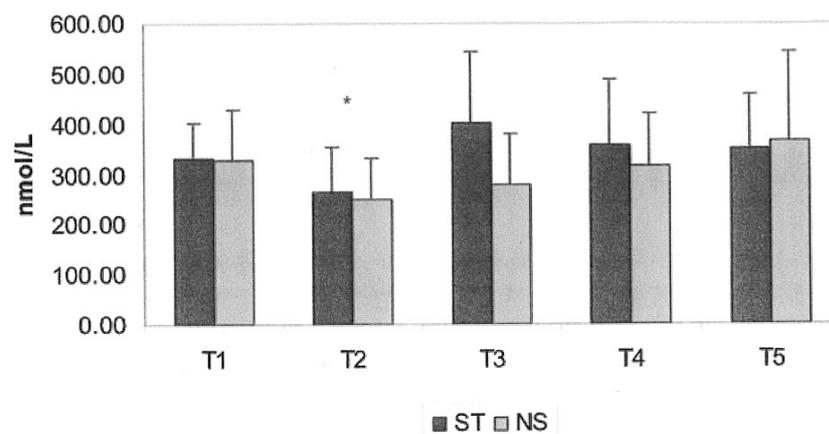


Figure 2.25. Cortisol. All data are reported as *Mean*±*SD*. **p* < 0.05 T2 vs T1, T3–T5. Reproduced by (Hoffman *et al.*, 2005).

These findings from American football oppose the decrease shown in soccer and Australian football (Filaire *et al.*, 2001; Kraemer *et al.*, 2004; Cormack *et al.*, 2008b). The high concentrations observed pre-camp were proposed as a psycho-physiological response to feelings of anxiety prior to an intense and highly demanding camp

(Hoffman *et al.*, 2005). Similarly, these psycho-physiological factors may have also contributed to the increase in cortisol during the competitive season. Unlike the changes associated with matches in the previous section, these findings differ considerably. In the present, it appears that the competitive stresses of American football accumulate whereas Australian football and soccer did not. This may be a reflection of the large aerobic conditioning phase that is often employed by Australian football and soccer programs, which in turn reflect an enhanced tolerance to competitive stresses. American football players, which present a more anaerobic physiological foundation, train for short duration high intensity bouts mixed with long rest periods (25 to 35 s). As the season progresses their ability to recover from the accumulative stress of week-to-week performance may be reduced compared to other football codes.

Rugby analysis has not assessed seasonal changes in hormonal markers. One study compared a group of players that were deliberately overreached to a group that maintained a normal training regime (Coutts *et al.*, 2007b). Cortisol and testosterone were unable to detect difference between the groups. Testosterone results however, did suggest a state of reduced anabolic activity at 4 weeks (-9.7%) and again to a greater extent at 6 weeks (-19.1%), compared to baseline values taken before the training block. Similarly, the T:C ratio was also reduced at 6 weeks (-27%) and during the taper (-16.2%) for the overreached group. In comparison the normally trained group displayed decrements in the T:C ratio at 6 weeks (-6.1%), however increases were seen during the taper (18%). Although unable to recognise difference between groups of various training stimulus, it was proposed that the T:C ratio may help to indicate which athletes are recovering and adapting to the training program. In contrast to other football codes, cortisol failed to demonstrate changes across a 6-

week training block. Cortisol measures were taken after 24 hours of rest which may have dulled the acute response that has been shown previously in team sports. In turn, the 6-week block may not have been substantial enough to stimulate an accumulative effect.

2.3.8.3 Limitations of hormonal analysis

One limitation that exists with hormonal markers is the intra and inter assay reliability which has ranged between $CV= 3.9\%$ and 10.9% (Filaire *et al.*, 2001; Elloumi *et al.*, 2003; Kraemer *et al.*, 2004; Hoffman *et al.*, 2005; Cormack *et al.*, 2008a; Kraemer *et al.*, 2009; Moreira *et al.*, 2009). Changes or differences may be difficult to interpret with large variations in the analysis process potentially concealing real effects. Increased inflammation from team sports activity may also influence cortisol levels. The anti-inflammatory properties of cortisol may display an increase from acute injuries with minimal long-term accumulative affect. Sample collection procedures, hydration and nutritional status, diurnal variation, psychological, and environmental conditions may also influence results. Findings suggest that hormonal markers of catabolic and anabolic status may be useful as one component of a system for monitoring physical demands. In isolation, the highly variable information may not accurately represent the stress of contact team sports.

2.4 Perceptual measures in team sports

2.4.1 Rating of perceived exertion in team sports

The rating of perceived exertion (RPE) method has been used as a measure of exercise intensity for over 40 years (Doherty *et al.*, 2001; Day *et al.*, 2004). Although subjective, RPE was developed as a simple, individualised measure that incorporated the physiological, physical and psychological stresses associated with exercise (Doherty *et al.*, 2001; Day *et al.*, 2004; Borresen & Lambert, 2008). The original RPE

scale (6-20) has evolved into the category ratio scale (CR10) (Figure 2.26) which was more suitable for inter-individual comparisons, and exercise in the higher intensity ranges (Borg, 1998). These RPE scales are used to distinguish the intensity of a single bout of exercise. In the 1990's the session RPE method was developed. This concept incorporated the intensity value and the duration of exercise to quantify exercise loads over an entire exercise session (Foster *et al.*, 1996; Foster, 1998; Foster *et al.*, 2001). Previous methods of quantifying session loads were primarily based around the volume of training using distance and time variables to monitor training loads. The session RPE method incorporates the volume component with the addition of a perceived exertion measure (1-10) to determine the intensity. For each given period of work the individual athlete is required to express their rating of perceived exertion approximately 30 minutes following exercise using with a numbered scale with visual anchors. The RPE is then multiplied by the time to represent a measure of physical activity in arbitrary units (au). The CR10 session RPE is the most commonly used method across a range of team sports, most notably in soccer, rugby, and Australian football (Castagna *et al.*, 2007; Coutts *et al.*, 2007b; Hill-Haas *et al.*, 2008; Farrow *et al.*, 2008). In some cases it has been referred to it as a global measure of load in sport (Impellizzeri *et al.*, 2004).

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

Figure 2.26. Category ratio scale of perceived exertion (RPE). Reproduced from (Borg, 1998).

2.4.1.1 Reliability

The reliability of RPE for measuring exercise intensity has been assessed in a range of exercise environments such as running, cycling and resistance training (Eston & Williams, 1988; Doherty *et al.*, 2001; Gearhart *et al.*, 2002). Some of the earliest research assessing RPE (6-20) reliability in a variety of activities (walking, jogging, cycling, stepping) showed strong test-retest correlations ($r = 0.71$ to 0.90) during randomised bouts at steady state, wave form, and gradually increasing intensities (Skinner *et al.*, 1973; Stamford, 1976). Reliability of the 6-20 scale was determined using repeat trials of treadmill running at 4 gradients (Lamb *et al.*, 1999). Relationships were strong at low intensities ($r = 0.81$), but weakened as the intensity increased ($r = 0.60$). Similarly, RPE (6-20) reliability was again assessed in treadmill running, this time during only high intensities (Doherty *et al.*, 2001). Across three supra-maximal (125% of $\dot{V}O_{2max}$) bouts the within-subject CV ranged between 4.4 and 6.0%. Relationships between subjects expressed as ICC were between 0.79 and 0.78. These findings suggest that RPE during graded and high intensity exercise are relatively reliable however investigations of intermittent exercise may differ.

Reliability of the session RPE (CR10) method is limited to a small number of studies focussed on aerobic exercise, resistance training and team sports (Day *et al.*, 2004; Egan *et al.*, 2006; Herman *et al.*, 2006; Gabbett & Domrow, 2007). The intra-athlete reliability of session RPE was assessed during aerobic exercise bouts of running or cycling, depending on the participants regular exercise regime (Herman *et al.*, 2006). Six 30 minute exercise bouts at three pre-selected intensities were (easy: ~40 to 50% $\dot{V}O_2$ peak; moderate: ~60 to 70% $\dot{V}O_2$ peak; hard: ~80 to 90% $\dot{V}O_2$ peak) repeated twice in random order. No less than 2 days was allowed between exercise bouts. Error statistics ($SEE= 1.2\%$) were small and relationships between the repeat trials for session RPE were strong ($r^2 = 0.78$) (Figure 2.27). These findings suggest that the session RPE method is reliable for continuous exercise at various steady-state intensities.

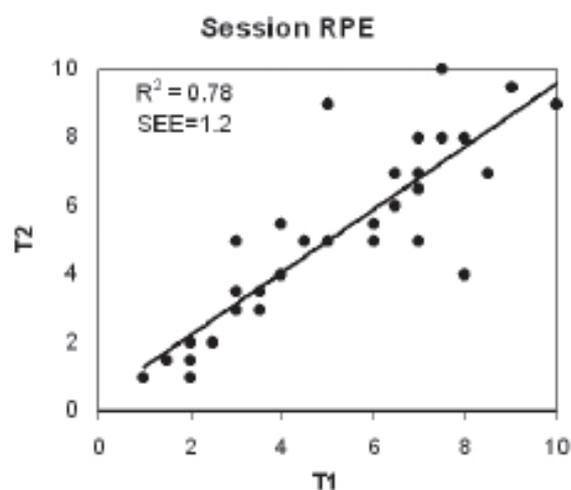


Figure 2.27. Scatter plots of individual responses of Session RPE, during Trial 1 and Trial 2, with all three intensities combined. Reproduced from (Herman *et al.*, 2006).

Very few studies have investigated the reliability of the session RPE method in intermittent sports. One study does exist in team sports where test-retest reliability was assessed (Gabbett & Domrow, 2007). Reliability was not the sole focus, instead it was used as part of the method to ensure that session RPE was a repeatable measure

of training loads. Eleven rugby players completed two identical training sessions, one week apart. Intra-athlete relationships were strong ($ICC = 0.99$, $CV 4.0\%$) indicating that the session RPE method was a suitable method for assessing training loads in contact-based team sports such as rugby (Gabbett & Domrow, 2007). Between subject reliability has not been determined in these two investigations. The concept behind RPE is that programs are individualised, therefore between-athlete reliability is relatively insignificant.

2.4.1.2 Validity

Session RPE was developed as a simple, practical and inexpensive method to quantify the training impulse. The validity of the session will be determined by the relationship shown with other frequently used methods in sport, more importantly, team sports. Several studies have assessed the validity in both individual sports such as cycling (Green *et al.*, 2006), and team sports, most notably in soccer (Impellizzeri *et al.*, 2004; Coutts *et al.*, 2007a).

The validity of RPE during prolonged, repeated exercises (running or cycling) bouts was assessed using 6 bouts of 30 minute aerobic exercise at 3 different intensities. Bouts were randomly ordered and assigned to subjects to assess the relationship between RPE (CR10 scale), HR, and $\dot{V}O_2$ (Herman *et al.*, 2006). Correlations were strong with $\dot{V}O_{2peak}$ ($r = 0.78$), $\% HR_{max}$ ($r = 0.82$), and $\% HR_{reserve}$ ($r = 0.80$). Intermittent protocols rather than steady state may have caused varying outcomes.

Conversely, an interval-based protocol (5 x 2 min, with 3 min recovery between) was used to determine the validity of RPE in relation to HR, and $[Lac^-]$ during high-intensity cycling (Green *et al.*, 2006). Moderate correlations with HR ($r = 0.63$) were found, however $[Lac^-]$ ($r = 0.43$) had a weak relationship with RPE. It was suggested that the time course of $[Lac^-]$ kinetics contributed to the poor relationship, as the

recovery interval between bouts was not sufficient to allow $[\text{Lac}^-]$ to lower as much as HR or perceived exertion (Figure 2.28) (Green *et al.*, 2006). It was also suggested that HR and RPE were more effective methods of recognising acute metabolic changes (Green *et al.*, 2006). Again steady state protocols were used, with maximal HR values reaching 174 ± 8 beats.min⁻¹ in comparison to previous team sport reports which show maximal HR of >185 beats.min⁻¹ (Ekblom, 1986; Bangsbo *et al.*, 1991; Krstrup *et al.*, 2006).

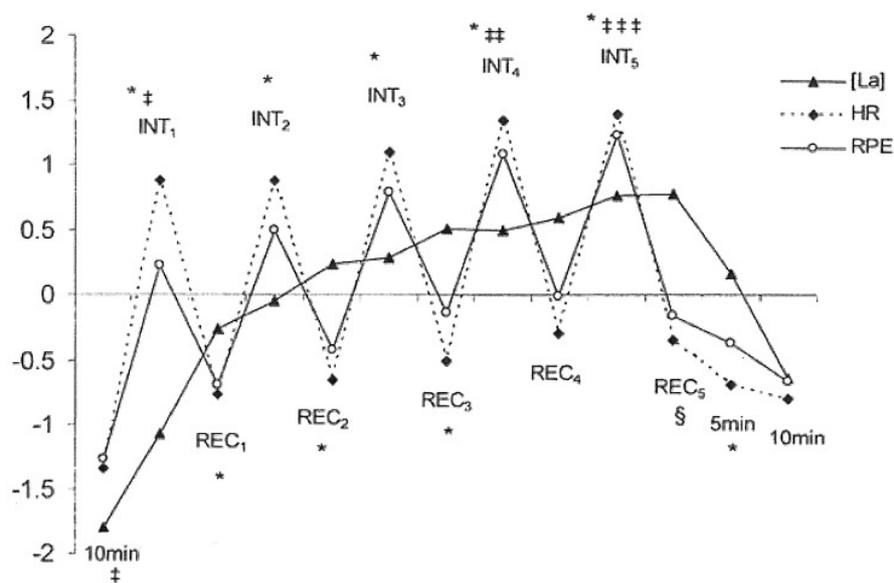


Figure 2.28. $[\text{Lac}^-]$, HR, RPE results from 5 x 2 min high intensity cycling bouts. INT = high-intensity cycling bout, REC = recovery period between bouts. Reproduced from (Green *et al.*, 2006).

The increased use of session RPE in team sports has led to multiple validity assessments to understand the value of this perceptual measure. Basketball research compared the session RPE method to the Edwards TRIMPS HR zone method (Edwards, 1993) during training and matches (Foster *et al.*, 2001). Although RPE scores were higher than the HR zone method, regression analysis confirmed that the pattern of difference was consistent. From these findings it was suggested that the simplicity of session RPE provided greater practical value than the TRIMPS method.

This investigation did not provide any statistical support for the strong relationships reported between the session RPE and TRIMPS methods of quantifying training.

Soccer research assessed RPE in relation to several HR-based training load calculation methods (Impellizzeri *et al.*, 2004). Seven weeks of soccer training was assessed with individual training loads calculated for each session over 19 players. Three variations of the TRIMPS (training impulse) were used to assess the validity of the session RPE method (Banister, 1991; Edwards, 1993; Lucia *et al.*, 2003). Moderate to strong correlations ($r = 0.50$ to 0.85) with session RPE were reported (Impellizzeri *et al.*, 2004). It was suggested that the discrepancies between the session-RPE and HR-based training load measures may have derived from the potential inability of HR to detect acute changes associated with intermittent activity. In addition, the high anaerobic requirements of soccer activity may be underestimated by HR measures, whereas perceived efforts may increase. This will in turn display higher loads using the session-RPE method.

Parallel work in soccer, instead focussing on small-sided games in training over 67 training sessions established the relationship between the session RPE method, $[\text{Lac}^-]$, and HR (Coutts *et al.*, 2007). The small-sided games protocol consisted of 3 x 4 min periods with 3 min recovery between. Moderate relationships were shown with $[\text{Lac}^-]$ ($r = 0.63$), and HR ($r = 0.60$) (Coutts *et al.*, 2007). When a stepwise multiple regression analysis was performed it was revealed that HR alone predicted 43.1% of the variance in RPE whereas both HR and $[\text{Lac}^-]$ accounted for 57.8%. These relationships suggest that HR and $[\text{Lac}^-]$ responses can partly be accounted for by session RPE, however when combined they are most closely related to RPE values. Relationships between these variable during actual matches would be interesting.

Matches will vary in intensity much more than small-sided games which tend to elicit consistent high intensities. This is reflected by the lower average percentage of max HR shown in matches, compared to small-sided games (Ali & Farrally, 1991; Eniseler, 2005; Coutts *et al.*, 2007a).

2.4.2 Ratings of perceived exertion and the session RPE method in team sports

As described previously in section 2.4.1, RPE in isolation is used to represent the intensity of an exercise bout. Research applications include differentiating between exercises modalities (Eg. Steady-state vs intermittent exercise), or between different types of training (Eg. Small-sided games vs interval running). The session RPE method, which incorporates the exercise duration, is for the purpose of measuring exercises loads. This may be from session to session, or from week to week. Often training-based studies will use session RPE to match the training loads of two experimental groups (Impellizzeri *et al.*, 2006; Coutts *et al.*, 2007b). This is to ensure that it is the training intervention that is causing the change rather than a discrepancy in the training impulse of training between groups.

Soccer research has used the RPE method to profile various types of activities. Perceptual differences in various small-sided games protocols were assessed in youth soccer players (Hill-Haas *et al.*, 2008; Hill-Haas *et al.*, 2009). The aim was to develop an understanding of the intensity of each small-sided game to facilitate training prescription. The perceptual response of players was expressed using the 6-20 RPE scale. Each small-sided game was manipulated by altering the number of players and game rules. The perceptual response of players who were on under-loaded (15.8 ± 1.5) teams with one less player than the opposition, was significantly higher in comparison to the overloaded teams (14.7 ± 1.5). No difference was shown when players were evenly matched. This outcome is to be expected however the physiological and time-

motion characteristics (Hill-Haas *et al.*, 2008) that were assessed simultaneously showed no differences based on player numbers. Rule changes on the other hand caused no differences in RPE, whereas physiological and time-motion characteristics did. This finding suggests that RPE may not be sensitive enough to detect changes in external loading through rule manipulation, but was suitable for use when player numbers are modified. Longitudinal work presents many challenges, the most prominent being the day to day variability of the players. In this small-sided games study (Hill-Haas *et al.*, 2008), a 16 week period was used to assess perceptual responses to small-sided games in soccer. During this time players may vary physically and psychologically therefore affecting their response to a training stimulus.

A comparison of a soccer specific intermittent treadmill protocol to a steady state treadmill protocol used the 6-20 RPE scale to determine perceptual responses in semi professional soccer players (Greig *et al.*, 2006). Over a 90-minute period with matched distance, RPE were higher for the intermittent running compared to the steady state running (Greig *et al.*, 2006). The RPE results were similar to HR and $[\text{Lac}^-]$ with the intermittent running being higher compared to steady-state, however the intensity of the activity used in this investigation may not have been high enough. Physiological responses to both protocols were lower than those reported in actual soccer matches, for example HR peaked at approximately 130 to 135 $\text{beats}\cdot\text{min}^{-1}$, in comparison to matches which have shown HR responses of $>170 \text{ beats}\cdot\text{min}^{-1}$ (Ali & Farrally, 1991). The findings from this investigation may have varied if actual match intensities were replicated.

Session RPE was used to compare the training loads across two competitive rugby league seasons (Gabbett & Domrow, 2007). Each season was separated into three

training phases; 1.) pre-season, 2.) early-competition, and 3.) late-competition.

The accumulated training loads across each phase of a rugby league season were significantly different. Pre-season loads (1981 au), were significantly greater than early-competition (1345 au), and late-competition (1488 au).

2.4.3 Limitations of the RPE, and session RPE methods

Although easily implemented, quick and inexpensive (Foster *et al.*, 2001; Coutts *et al.*, 2003b), session RPE is a subjective measure (Foster *et al.*, 2001) that may be interpreted differently between individuals. The process is reliant on the participants' honesty, and understanding of the methodology which may be exposed to bias or misrepresentation. In combination with other perceptual, and physiological measures of intensity and load, RPE may provide useful information, however in isolation this method is erroneous, as numerous other physical and physiological factors that are unseen by the individual will contribute to the loads imposed on individual athletes. Coupled with a lack of research in collision sports such as Australian football, and rugby, the RPE method still requires investigation in team sports.

2.5 Accelerometry technology

Accelerometers are devices that detect and record the frequency and magnitude of acceleration (Hendelman *et al.*, 2000). The earliest devices date back to the 1960's (Cavagna *et al.*, 1961). Uni-axial accelerometers, measuring in 1 plane of movement (Caltrac, CSA/MTI, ActiGraph GT1M, and Biotrainer Pro), and tri-axial models measuring in three dimensions (Tracomor, Tritrac R3D, RT3, 3dNX, Locometrix) are commonly used to measure free-living physical activity in a variety of population (Steele *et al.*, 2000; Quigg *et al.*, 2010). Accelerometers measure kinetic energy (motion) which is converted into electrical energy and translated by the device as acceleration measurement data. These devices are usually accompanied with internal

storage and transmission ability so that data can be recorded over long periods, and easily viewed during or after bouts of activity.

Initially, activity counts were used to quantify physical activity levels. This parameter measured the number of accelerations that occurred in a set time epoch (Rowlands, 2007). More recently, parameters integrating the activity count with the magnitude of each acceleration have been developed to provide a measure of physical activity that accounted for the frequency and intensity of movement. This analysis method is often referred to as the vector magnitude which is a parameter made up of the sum of all accelerations in three dimensions. Estimates of energy expenditure have also been explored (Bouten *et al.*, 1994; Chen & Sun, 1997; Jakicic *et al.*, 1999; Rafamantanantsoa *et al.*, 2002), however the methods used to calculate energy expenditure using accelerometers are broad.

Preliminary research focused on using accelerometer to quantify physical activity levels in general populations such as the ageing (Sumukadas *et al.*, 2008; Hansen *et al.*, 2011), youth (Eston *et al.*, 1998; Dencker & Andersen, 2006), and diseased (Steele *et al.*, 2000; Gebruers *et al.*, 2010). This work motivated researchers from sporting populations to explore potential accelerometer applications (Coe & Pivarnik, 2001; Sato *et al.*, 2009; Tsivgoulis *et al.*, 2009; Gabbett *et al.*, 2010; Montgomery *et al.*, 2010). The following section will provide an overview of the current accelerometer research. Reliability and validity will be discussed, followed by a summary of current sports applications.

2.5.1.1 Reliability

As with the majority of new analysis methods, reliability and validity has been a key component of accelerometer research. Accelerometer research utilises highly repeatable mechanical devices such as shakers or agitators (Nichols *et al.*, 1999;

Powell *et al.*, 2003; Powell & Rowlands, 2004; Esliger & Tremblay, 2006; Krasnoff *et al.*, 2008; Van Hees *et al.*, 2009), as well as performing testing with human instrumentation (Jakicic *et al.*, 1999; Nichols *et al.*, 1999; Powell & Rowlands, 2004; Welk *et al.*, 2004), to assess reliability.

A mechanical testing protocol was used to assess the inter-unit reliability of four Tritrac R3D (Reining International, Madison, WI) accelerometers (Nichols *et al.*, 1999). All of the devices were attached simultaneously to a shaker table, with both the vector magnitude and activity level in kilocalories showing high reliability ($CV= 1.57\%$ & 3.57% , respectively). The Tritrac R3D consists of three separate uni-axial accelerometers, where as the newer model, the RT3 (StayHealthy, Inc. Monrovia, CA) has one tri-axial sensor (Welk *et al.*, 2004). The reliability of the RT3 model again using a mechanical shaker over 6 different protocols ranging from 0.5 to 1.25 g, was lower than the previous model (Esliger & Tremblay, 2006). Both intra- and inter-unit reliability for the activity count in all three planes was poor ($CV= 46.4\%$ & 42.9% , respectively). The repeatability of the shaker, rather than the units was highlighted as a possible origin of this large variation, with no reliability data presented for the device. In the same investigation, the Actical model (Mini Mitter Co., Inc., Bend OR) was assessed for reliability (Esliger & Tremblay, 2006). Intra-unit assessments showed variation of 0.4% (CV), whereas inter- was poor with variation of 15.5% (CV). When a larger sample of devices were used the variation was reduced ($CV= 5.4\%$). It was suggested that the narrow frequency range of the Actical (0.5 to 3.0 Hz) devices compared to the RT3 (2.0 to 10.0 Hz) may have influenced these findings.

The RT3 was the focus of a separate reliability investigation using a mechanical shaker, this time using a different model and protocol (Powell *et al.*, 2003). Over 18

minutes at 3 separate frequencies (2.1, 5.1 and 10.2 Hz) the intra- and inter-unit reliability outcomes were again poor ($CV= 0.2$ to 56.2% & 4.2 to 26.7% , respectively). Once again poor inter-unit reliability may be explained by the shaker used in this investigation, which only allows one unit to be attached per trial therefore making it difficult to compare between devices. A third report, this time using a shaker with the ability to repeat trials ($CV= <0.52\%$) echoed the two previous investigations ($CV= 0.29$ to 34.7%) (Krasnoff *et al.*, 2008), suggesting that it may not be the testing apparatus causing the variation but in fact the poor repeatability of the RT3 model.

More recently, the DynaPort accelerometer (ADXL202; Analog Devices, Norwood, MA) has been assessed for reliability, using a mechanical shaker over a range of 0 to $1.27 g$ (Van Hees *et al.*, 2009). Relationship statistics were high for both intra- and inter-unit reliability, and unlike the previous models, the variation was low ($CV=$ Intra: 1.13% ; Inter: 1.37%).

Reliability testing using human participants during physical activity has assessed inter- and intra-unit reliability of accelerometers (Jakicic *et al.*, 1999; Nichols *et al.*, 1999; Powell & Rowlands, 2004). The vector magnitude calculated from the Tritrac devices was assessed for inter-unit reliability with one unit positioned on each hip, as well as intra-reliability during walking and jogging trials (Nichols *et al.*, 1999). The Tritrac was highly reliable between units ($CV= 1.79\%$; & $ICC= 0.73$ to 0.87) and for the same unit over multiple trials on separate days ($ICC= 0.87$ to 0.92). However when inter-unit reliability of estimated energy expenditure from the Tritrac was assessed, the error increased ($CV= 3.57\%$) (Nichols *et al.*, 1999). A similar design was used, again to assess the reliability of the Tritrac during 5 different modes of exercise (walking, running, cycling, stepping and slideboard) (Jakicic *et al.*, 1999).

Estimated energy expenditure, calculated from the accelerometers showed high reliability for walking (ICC = Intra: 0.86 to 0.96; Inter: 0.76 to 0.87), running (ICC = Intra: 0.68 to 0.92; Inter: 0.80 to 0.92) and slideboard (ICC = Intra: 0.71 to 0.89; Inter: 0.75 to 0.87), whereas the cycling and stepping was more variable. Results also suggested that as the velocity of running increased so did the reliability, which may be related to a more consistent stride pattern when running velocity is higher. Unlike previous studies these investigations did not report $CV\%$, making it difficult to determine the magnitude of variation within and between units. The findings from intra-unit testing with human physical activity trials can be difficult to interpret as it can be challenging to perform identical repeated trials.

The vector magnitude from the RT3 accelerometer was assessed, this time for inter-unit reliability during walking and running between 1.11 and 2.78 $m.s^{-1}$, and during a repeated sit to stand task (Powell & Rowlands, 2004). Variation was relatively low during walking and running trials (CV = <3.8%), whereas the sit to stand task displayed poor reliability (CV = 8.7 to 14.4%). With the accelerometers positioned on the left and right hips, this inter-unit variation from the sit to stand task may be related to functional imbalances during the physical activity rather than the measuring capabilities of the devices.

In addition to the variation of the accelerometers' measuring capacity, the issue of instrumentation is critical to establish if a change or a difference is meaningful. One recent study assessed the intra- and inter-tester variation (Van Hees *et al.*, 2009), whereby the participant was instructed and instrumented by the same tester multiple times, and by different observers. Variations within and between testers were 0.97 and 0.88 (ICC), respectively. This suggests that data from accelerometers will be more reliable if the same tester is used.

2.5.1.2 Validity

The validation of accelerometers in free-living activity is challenging as a gold standard of measurement in which to compare is currently unavailable. Because of this limitation, the research validating accelerometers has used physiological parameters such as metabolic equivalents, energy expenditure, heart rate, and oxygen consumption (Hendelman *et al.*, 2000; Levine *et al.*, 2001; Rowlands *et al.*, 2004). Although uncommon, accelerometer variables have also been compared to locomotor velocity (Fudge *et al.*, 2007).

As the majority of research has been directed to non-sporting populations, walking is a common activity mode used to validate accelerometers. The Tracomor (Maastricht, The Netherlands) was validated by comparing the energy expenditure derived from the device to an indirect calorimetry system (Levine *et al.*, 2001). There was a linear increase in Tracomor accelerometer counts with increased velocity during walking on level ground ($r = 0.99$) and on a treadmill ($r = 0.99$) (Figure 2.29). This relationship was supported in another study where the RT3 accelerometer vector magnitude increased with walking and running velocity (4 to 26 km.h⁻¹) ($r = \sim 0.80$) (Rowlands *et al.*, 2007). Walking on an incline did not display linear relationship, as accelerometer values remained constant as energy expenditure values increased (Levine *et al.*, 2001). An investigation assessing the Tritrac accelerometer also displayed an underestimation of energy expenditure during incline walking (Nichols *et al.*, 1999). This suggests that the application of these devices to locomotion on undulating terrain is somewhat questionable.

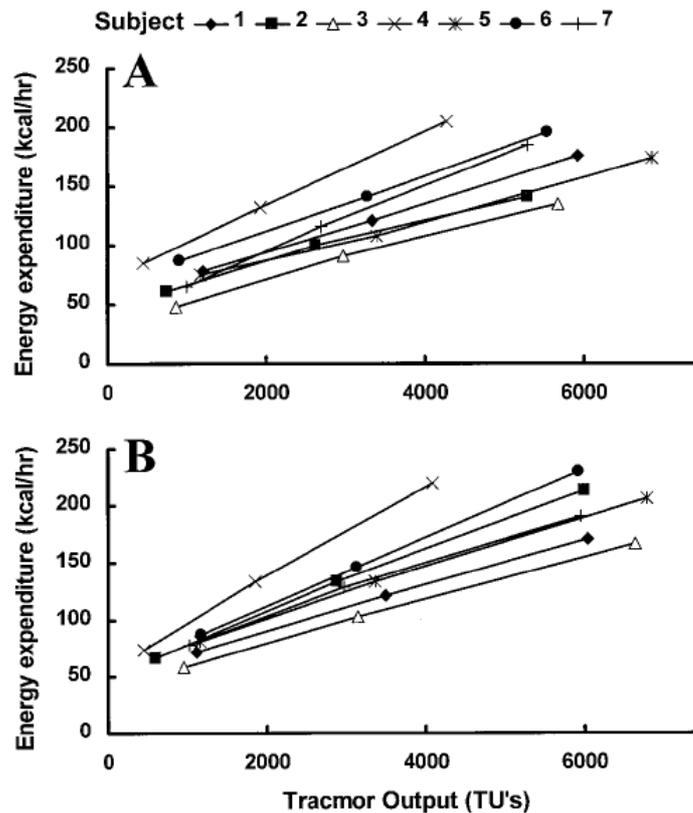


Figure 2.29. Changes in energy expenditure and Tracmor output above resting for seven healthy subjects walking on (A) a treadmill and (B) level ground at 32, 62, and 86 $\text{m}\cdot\text{min}^{-1}$. For each subject (1 through 7), three data points represent the effect on each variable at 32, 62, and 86 $\text{m}\cdot\text{min}^{-1}$. Reproduced from (Levine *et al.*, 2001).

Similarly, a second investigation of the Tritrac accelerometer also determined validity during walking (Hendelman *et al.*, 2000). Relationships between the accelerometer count and values derived from a portable metabolic measurement system were very large ($r = 0.89$). The Tritrac accelerometer was again the focus of another validation study, along with the updated RT3 model for walking and running (1.1 to 2.78 $\text{m}\cdot\text{s}^{-1}$) activity of boys and men (Rowlands *et al.*, 2004). Accelerometer counts in all three axes were compared with $\dot{V}\text{O}_2$ relative to body mass, raised to the power of 0.75 ($\dot{V}\text{O}_2$), which has been used in previous research to assess the difference between children and adults (Rogers *et al.*, 1995). Both accelerometer models displayed very large relationships with $\dot{V}\text{O}_2$ during walking and running (RT3: $r = 0.79$ to 0.88;

Tritrac: $r = 0.87$) (Rowlands *et al.*, 2004). Despite strong correlations, from both models, the RT3 model recorded consistently higher counts. This must be taken into consideration when comparing different accelerometers models. This study also compared the predicted oxygen consumption from the vector magnitude and vertical axis alone, for each device (Rowlands *et al.*, 2004). The Tritrac vector magnitude was no better than the vertical axis alone in predicting $\dot{V}O_2$, whereas the RT3 vector magnitude was significantly better. This suggests that the more recent model (RT3) of accelerometer is not influenced as much by the vertical axis; rather it incorporates all three, which displays a positive relationship with the $\dot{V}O_2$ measurements.

A separate investigation supported this notion, when comparing both tri-axial (3dNX, BioTel Lts., Bristol, UK) and uni-axial accelerometers (CSA, ActiGraph and Actiheart) to locomotor velocity, heart rate and $\dot{V}O_2$ (Fudge *et al.*, 2007). Strong relationships between both uni- ($r = 0.95$ to 0.96) and tri-axial ($r = 0.96$) devices were evident for walking, however only the tri-axial model continued to display linearity when velocities reached $\sim 5.56 \text{ m}\cdot\text{s}^{-1}$ (Figure 2.30). At walking velocities accelerometer relationships with $\dot{V}O_2$ (Uni-axial: $r = 0.70$ to 0.90 ; Tri-axial: $r = 0.91$) were much stronger than those displayed with heart rate (Uni-axial: $r = 0.49$ to 0.56 ; Tri-axial: $r = 0.58$). When running activity (>3.33 to $3.89 \text{ m}\cdot\text{s}^{-1}$) was assessed, the relationship between uni-axial devices and $\dot{V}O_2$ dropped, whereas the tri-axial devices ($r = 0.87$) remained strong. Multiple linear regressions were used to predict $\dot{V}O_2$ from the accelerometer and HR data. This again showed that the tri-axial accelerometer in combination with HR was better at predicting $\dot{V}O_2$ ($r = 0.85$) (Fudge *et al.*, 2007). The rationale behind this variation between tri- and uni-axial devices is believed to be a result of the biomechanics of running compared to walking. At higher velocities the

contribution of the 2 horizontal planes is much greater, this allows for continual measurement over higher velocities where the uni-axial devices can't measure in these planes, preventing measurements from being taken. The higher sampling rate of the tri-axial device was also a contributing factor in measuring activity at higher velocities (Fudge *et al.*, 2007).

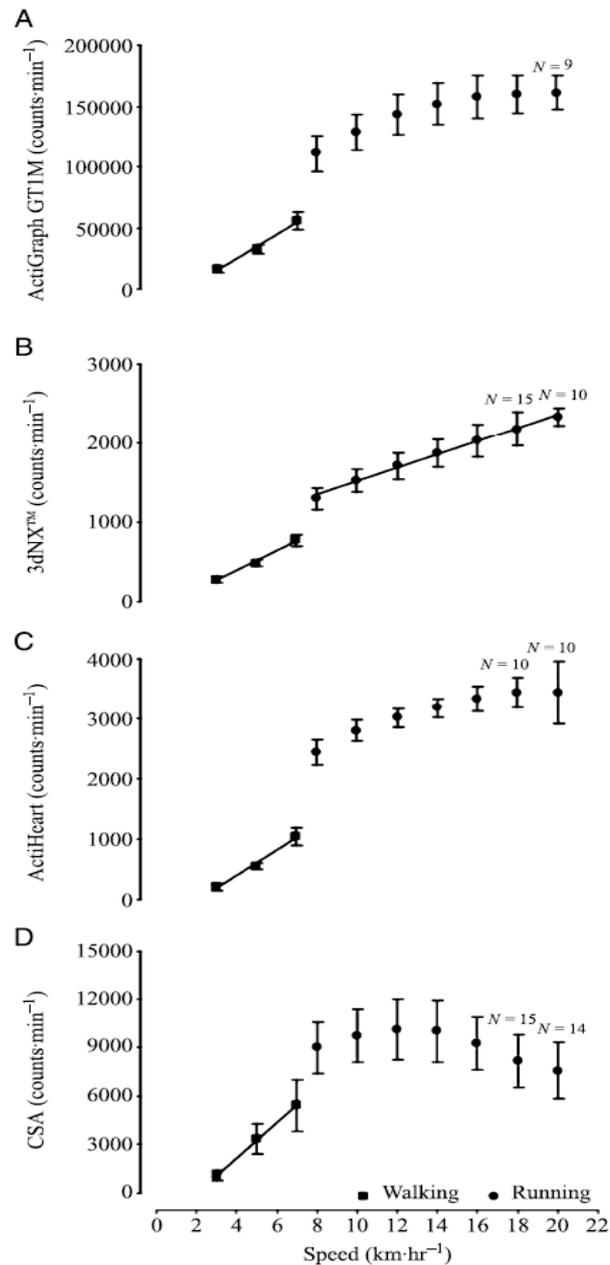


Figure 2.30. ActiGraph GT1M (graph A; $n = 11$, unless otherwise stated), 3dNX (graph B; $n = 16$ unless otherwise stated), ActiHeart (graph C; $n = 12$, unless otherwise stated), and CSA (graph D; $n = 16$, unless otherwise stated) outputs plotted against treadmill speed. Values are $Mean \pm SD$ Reproduced from (Fudge *et al.*, 2007).

Although not directly related to the competitive sporting environment, numerous investigations have validated accelerometers during common daily activities (Hendelman *et al.*, 2000; Welk *et al.*, 2000; Rowlands *et al.*, 2004). Daily tasks can often incorporate upper body activity, whereas the previous section was focussed on lower limb dominant activities such as walking and running.

The Tritrac accelerometer was validated during daily physical activity tasks such as household cleaning and outdoor maintenance chores, and recreational activities such as golf (Hendelman *et al.*, 2000). In comparison to a portable metabolic measurement system the Tritrac underestimated the energy costs of these activities (Figure 2.31). This suggests that underestimation of daily activities incorporating upper-body movement is occurring, possibly due to the positioning of the device, which is typically around the hip and pelvic region. Three additional investigations support this concept (Welk *et al.*, 2000; Howe *et al.*, 2009; Kozey *et al.*, 2010). Firstly, the RT3 underestimated upper-body activities (24 to 65%), and overestimated lower body activities (20 to 55%) in comparison to a portable metabolic analyser during similar household and outdoor chores (Howe *et al.*, 2009). The second supporting investigation again indicated that the Tritrac accelerometer underestimated (~52%) MET values during similar activities (Welk *et al.*, 2000).

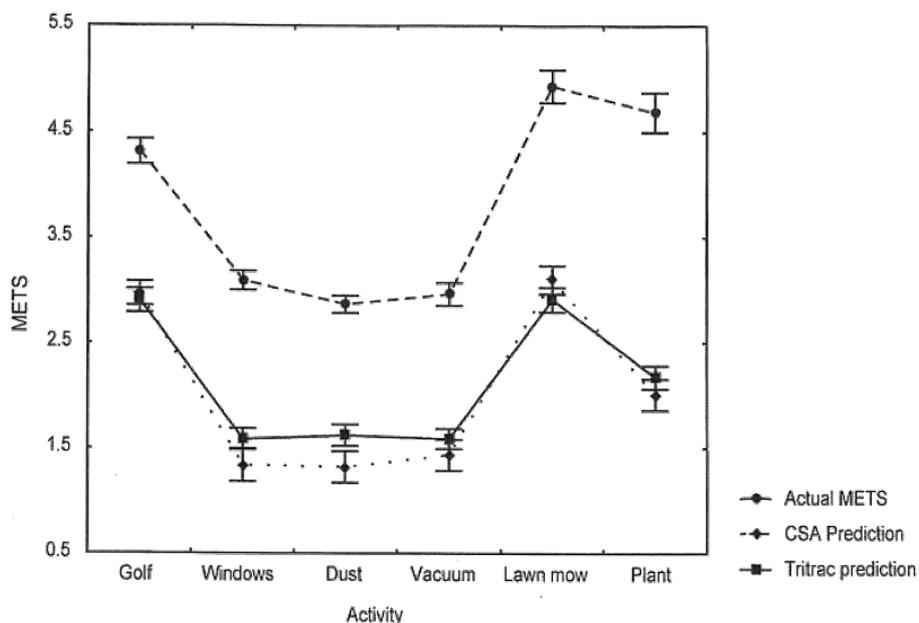


Figure 2.31. Actual and predicted METs ($Mean \pm SE$) for recreational and household activities. Reproduced from (Hendelman *et al.*, 2000).

Lastly, the number of accelerations in three dimensions counted through an accelerometer were compared to MET values calculated with a portable metabolic system during common daily tasks (Kozey *et al.*, 2010). An example of the gross underestimation was shown when higher accelerometer counts were displayed for walking (2970) compared to carrying a box (2156), however MET values indicated that carrying a box (4.5) was greater than walking (3.3). Results may have been exaggerated compared to the previous studies, as the device used in this investigation was uni-axial (ActiGraph GT1M, Pensacola, FL). These findings raise the issue of sensor location and possibly provide rationale for the instrumentation of accelerometers to other regions of the body specific to the activity type, or possibly attaching multiple devices.

With recent interest from sporting populations, research is now beginning to assess the validity of accelerometers to measure specific parameters, often as a tool for analysing performance. Although not specific to elite sports, one research project

determined the validity of CSA uni-axial accelerometer (Shalimar, FL) for measuring physical activity during junior high school basketball training (Coe & Pivarnik, 2001). Over 55 minutes of training the correlation between CSA and heart rate was large ($r = 0.54$ to 0.81). The CSA was also validated against the Children's Activity Rating Scale (CARS), which conducted through manual observation of activity intensity (Puhl *et al.*, 1990). As the CARS intensity levels increased so did accelerometer counts, suggesting that the CSA was capable of detecting the intensity of activity (Coe & Pivarnik, 2001). A potential increase in validity may occur with tri-axial devices.

Accelerometers have potential application in contact-sports where collisions and impacts occur frequently during tackling, bumping and contested scenarios. Recent work assessed the validity of a tri-axial device (MinimaxX, Catapult Innovations, Melbourne, Victoria) in detecting collisions in rugby league training (Gabbett *et al.*, 2010). Collisions were detected through custom designed accelerometer algorithms and compared to coded video-recordings of the training session. The magnitude of each collision was categorised as mild, moderate or heavy. Mild collisions were the most difficult to detect ($r = 0.89$) in comparison to moderate ($r = 0.97$) and heavy ($r = 0.99$). However across all three magnitudes relationships between the criterion measure (video), and the accelerometer detection method were very high (Figure 2.32). Distinguishing a mild collision from an event of non-significance may have been difficult as the definition for this category was very broad ("contact made with player but able to continue forward progress/momentum out of tackle") (Gabbett *et al.*, 2010). Despite this, it appears that the MinimaxX was a valid tool for detecting the frequency and magnitude of collisions in rugby league training. The application of these algorithms in other contact sports is still to be determined.

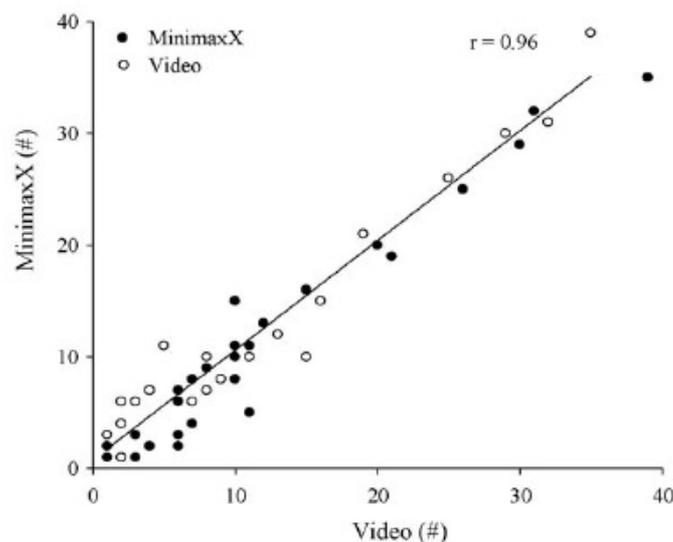


Figure 2.32. Comparison of MinimaxX and video methods for recording collisions. Data are recorded as counts for ‘video’ and ‘MinimaxX’ tackle detection methods. Each data point on the figure represents the individual player collisions coded from video and recorded via MinimaxX. Reproduced by (Gabbett *et al.*, 2010).

An alternative approach was employed in two separate studies using accelerometers as a measuring tool for strength (Rontu *et al.*, 2010) and power (Sato *et al.*, 2009) training. A Passport (PS-2119, PASCO, Roseville, California) triaxial accelerometer was attached to a barbell during a ‘high pull’ power exercise, and compared to high speed video to quantify the acceleration of the bar movement (Sato *et al.*, 2009). Relationships between acceleration measures from the accelerometer and video were strong ($r = 0.94$ to 0.99), across 7 subjects performing 2 ‘high pull’ repetitions each (Figure 2.33).

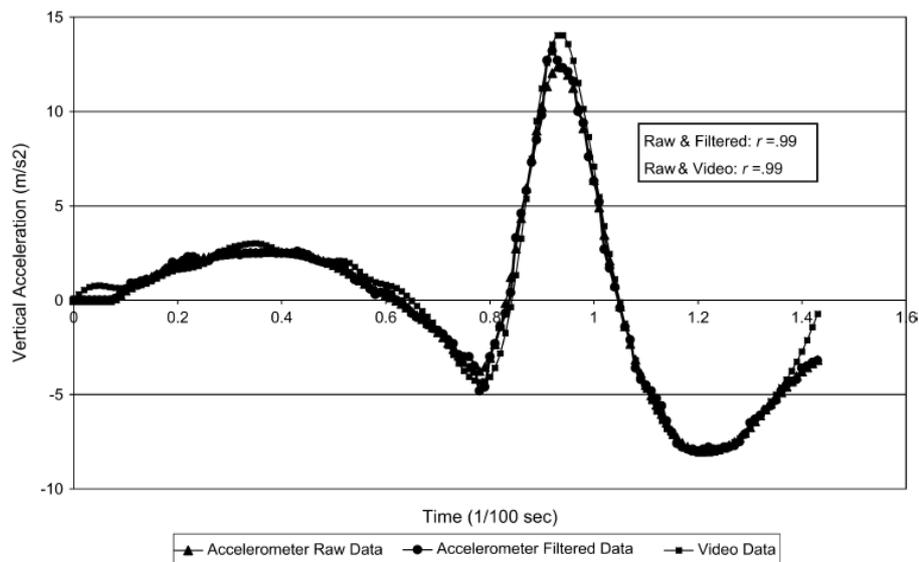


Figure 2.33. A graphic example of acceleration match-up data between raw data and kinematic analysis obtained from high-speed video. Reproduced by (Sato *et al.*, 2009).

Another resistance training study attempted to predict 1RM ‘bench press’ performance from a sub-maximal lift (Rontu *et al.*, 2010). The mass lifted by the participant and the acceleration measured using an accelerometer (LIS3L02AQ 3-axis linear accelerometer, ST Microelectronics, Inc., Geneva, Switzerland) were used to predict 1RM and then subsequently correlated to actual 1RM. Again the findings were positive with strong relationships existing between the participants actual 1RM and the estimated 1RM from a sub-maximal lift ($r = 0.89$ to 0.97). The magnitude of difference between the actual and measured 1RM ranged between 4.1% and 8.4%. As the sub-maximal lifting percentage increased so did the ability to predict 1RM performance. These results highlight the sensitivity of the devices, and potential to measure subtle differences in movement.

These findings suggest that the sensitivity of the accelerometer is sufficient to recognise a difference or change. However factors such as device positioning need to be considered based on the activity that is to be quantified. The following section will outline how accelerometers have been utilised in research as a measurement tool.

2.5.2 *Accelerometry in sport*

Gait analysis is a prominent area of research using accelerometers. The energetic costs of walking and daily physical activity has been analysed extensively. Although sparsely assessed, running was the focus of an investigation relating to the effects of fatigue on running stride patterns (Le Bris *et al.*, 2006). A tri-axial accelerometer was attached to participants at the hip whilst running at individual maximal aerobic speed to exhaustion. Variables obtained from the accelerometers were recorded at the onset, midway, and endpoint of the test. As the runners fatigued, the medio-lateral movement increased (21 to 47%). Decreased motor control under fatigue may also translate to an increase in energy expenditure (Le Bris *et al.*, 2006). Stride regularity decreased (~11%) as the trial progressed, which suggests that consistency in stride pattern is difficult to maintain under fatigue. Additional gait analysis research using accelerometers also found a very small link between gait regularity and training volumes in soccer players (Tsivgoulis *et al.*, 2009). Those players that elicited larger volumes tended to show greater variability in gait. Electromyography during long-distance running suggests that ground forces will increase as fatigue accumulates (Mizrahi. J *et al.*, 2000). However data from the vertical axis was not reported in the current investigation.

Contact sports such as American football and lacrosse discovered an alternative use for accelerometers (Caswell & Deivert, 2002; Duma *et al.*, 2005). Each of these studies assessed the forces applied to the head during impact episodes. The first of these studies in American football measured head impacts during training and matches by intimating a helmet with 6 accelerometers (Duma *et al.*, 2005). Figure 2.34 displays the distribution of impacts, with the majority for 38 players over 10 games and 35 training sessions. A total of 3,312 head impacts occurred at an average

of 32 ± 25 g. It was recommended that this in-helmet measuring system may add additional objective information to current clinical evaluation techniques used to define episodes of concussion in American football.

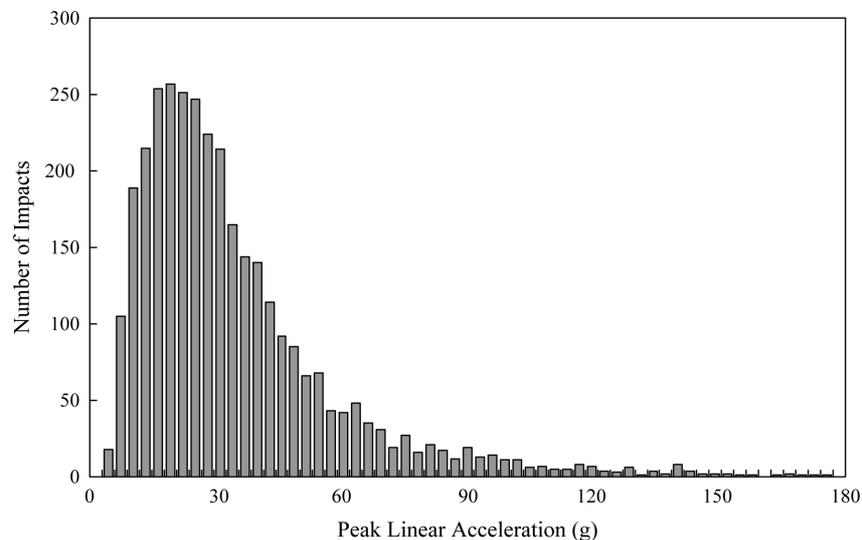


Figure 2.34. Distribution of peak linear accelerations of the head centre of gravity for all instrumented players from a single season. Reproduced from (Duma *et al.*, 2005).

The second of these studies, this time in lacrosse, assessed the effectiveness of 4 different helmets, two traditional and two contemporary designs (Caswell & Deivert, 2002). Tri-axial accelerometers (354MO3) were instrumented inside a model of the human head so that the magnitude of force applied through the helmet could be measured. The force attenuation capabilities of the helmets varied between designs, suggesting that accelerometers were a useful tool for assessing helmet design. The findings from this research provided grounds for further investigation into helmet designs in contact sports such as lacrosse and American football. These studies highlight the sensitivity of accelerometers as a measuring device, especially in sports involving frequent episodes of physical contact.

Two studies in rugby assessed impact forces, however this time the focus was on the impact that occurred to the body (Cunniffe *et al.*, 2009; Gabbett *et al.*, 2010). The first of these assessed the frequency, and magnitude of impacts in rugby union using a tri-

axial accelerometer (SPI Elite; GPSports Systems, Canberra, ACT, Australia) (Cunniffe *et al.*, 2009). Impacts were categorised as light (5 to 6 g); light-moderate (6 to 6.5 g); moderate-heavy (6.5 to 7 g); heavy (7 to 8 g); very heavy (8 to 10 g); and severe (10+ g). The forwards (1275) encountered a substantially high number of impacts across all grades compared to the backs (798). With regards to impacts at or exceeding the heavy grade (>7 g), the forwards experienced 60% more compared to the backs. These findings correspond with the role and involvement of each playing position, with forwards generally being involved in close proximity to the opposition compared to backs, which have more space to move (Cunniffe *et al.*, 2009). The second investigation assessed collisions during rugby league training and matches, and the link with injury rates (Gabbett *et al.*, 2010). Collisions, quantified using tri-axial accelerometer (MinimaxX), were categorised as mild, moderate and heavy however no descriptive values was provided for each category of collision. The difference between four playing positions (hit-up forwards, running forwards, halves and outside backs) was assessed. The number of collisions in training was highest in the two forward positions (20 to 23), compared to the halves and outside backs (16 to 18). A similar pattern existed in matches (forwards: 0.59 to 1.02 collision.min⁻¹; halves & backs: 0.45 to 0.48 collision.min⁻¹) however across all positions the number of heavy collisions was much greater in matches (16 to 37) compared to training (2) (Gabbett *et al.*, 2010). Minimal association was discovered between the frequency and magnitude of collisions and injury rates. Interestingly, a potential link was discussed between collisions, periodising training and recovery, however currently little is known about the consequences of collisions sustained in contact team sports. Aside from one investigation which displayed positive relationships between the number of tackles and concentration of muscle damage markers in the blood ([Mb]: $r = 0.85$;

[CK]: $r = 0.92$) (Takarada, 2003), no link has been established between accelerometer derived parameters and common measures of physical status in sport. Additional methods of utilising accelerometer data were displayed in two recent studies (Cunniffe *et al.*, 2009; Montgomery *et al.*, 2010). Whole body movement was calculated by accumulating the accelerations in three dimensions using a vector magnitude algorithm (See equation 1 in chapter 3). This parameter is proposed as a measure of physical load or whole body dynamics (Montgomery *et al.*, 2010). The first study of rugby union, using SPI Elite (GPSports Systems, Canberra, Australia) showed that the forwards ($1426 \text{ load}\cdot\text{min}^{-1}$) accumulated greater body loads in comparison to backs ($376 \text{ load}\cdot\text{min}^{-1}$). Accelerometers (MinimaxX, Catapult Innovations, Scoresby, Victoria) were also utilised in basketball training and matches. Again total load (Player loadTM) was calculated using combined acceleration data from a tri-axial accelerometer (MinimaxX) (Montgomery *et al.*, 2010). Accumulated load from matches (279 ± 58) was substantially higher than defensive (58 ± 26), offensive (55 ± 15) and 5 vs 5 scrimmage (171 ± 84). It was proposed that this difference was associated with greater court coverage during matches and subsequently higher running volumes. Interestingly, these investigations failed to discuss the impacts and body load data any further than the descriptive results. These investigations are the first to utilise accelerometers in contact team sports. The relatively novel application of accelerometers in this environment suggests that further exploration is required to fully understand the information that can be gathered from these devices. In addition, the absence of reliability data relative to the devices and their respective algorithms used in these rugby investigations, additional research is required. From a practical perspective, accelerometers may provide alternative

information in understanding the rigours of sports activity. Potential links to physical status following exercise may assist in managing athletes, to enhance performance.

2.5.3 Potential for accelerometer use in team sports

Numerous team sports incorporate prolonged bouts of movement, rapid activity, and frequent episodes of physical contact over the course of a match. As discussed throughout this literature review, exercise loads have been quantified through various measures. In some cases these methods can be time consuming, impractical, and sometimes prohibited in the team sports environment. The development of a universal measuring system that incorporates all forms of external load in contact team sports may facilitate preparation, recovery and overall athlete management. Accelerometers show strong correlations with physiological measures of activity such as calorimetry, energy expenditure, and heart rate, but to date have not been utilised to measure the external loads of contact-based team sports. There is potential for research to link accelerometer data to movements performed in confined spaces, and impact related activities that current methods of analysis underestimate or fail to measure. This may enable a system to be developed for monitoring the all forms of external load placed on the body during contact-based team sports activity. Therefore this thesis will comprise of a series of studies establishing the reliability, concurrent validity, and practical application of the MinimaxX accelerometer (Catapult Innovations, Scoresby, Australia) in contact-based team sports, more specifically, Australian football. The following section will describe the aims of this research in greater detail.

2.6 Aims and hypotheses

Research assessing the potential for accelerometers to measure external load in team sports is currently limited.

The specific aims of this thesis are:

2.6.1 Study 1

The first aim of this thesis was to assess the reliability of MinimaxX accelerometers, more specifically, the Player load parameter which is proposed as a measure of exercise loads.

The specific hypotheses tested were that:

1. MinimaxX would be a reliable measuring tool within devices, between devices, in a controlled setting, and in a sports specific setting.
2. MinimaxX would be capable of detecting small practically important differences in external load.

2.6.2 Study 2

The second study aimed to assess the concurrent validity of Player load by determining if any relationships were present between Player load, and other common measures utilised in team sports. Secondly, this study compared Player load from two small-sided Australian football games conditions, one allowing physical contact and the other not allowing it. The aim was to test if Player load was sensitive enough to recognise activity that involved physical contact. Locomotor loads, internal responses, perceptual responses, and physical performance were also compared between two small-sided games conditions.

The specific hypotheses tested were that:

1. Positive relationships would exist between accelerometer-derived external loads and locomotor outcomes from time-motion analysis.

2. Positive relationships would exist between accelerometer derived external loads, and internal and perceptual responses.
3. Negative relationship would be shown between accelerometer-derived external loads and physical performance measures. As loads increased, performance would decrease.
4. Small-sided games with physical contact permitted would elicit greater external loads from accelerometer-based measures.
5. The presence of physical contact would increase internal Responses. More specifically, cortisol and Mb concentrations.
6. The presence of physical contact would increase perceptual measures of fatigue, soreness and exertion.
7. Physical performance would decrease following small-sided games with physical contact.

2.6.3 Study 3

The third study aimed to measure and describe external loads from Australian football matches and training using accelerometers.

The specific hypotheses tested were that:

1. Accelerometers-derived load measures were capable of detecting differences between:
 - a. Playing positions
 - b. Playing levels (elite vs sub-elite)
 - c. Matches and training
2. The Player load^{SLOW} parameter would provide different information to the original Player load parameter.

CHAPTER 3. STUDY 1

3.1 The reliability of MinimaxX accelerometers for measuring physical activity in Australian football

3.1.1 Introduction

Measuring the physical demands experienced by the athlete in the training and competitive environment can provide valuable information to coaches and support staff to facilitate subsequent performance enhancement (Dawson *et al.*, 2004a; Brewer *et al.*, 2010). Common methods used to measure physical demands include heart rate telemetry (Deutsch *et al.*, 1998; Coutts *et al.*, 2009b), and time-motion analysis through video (Dawson *et al.*, 2004b, a) and more recently, global positioning systems (Aughey & Falloon, 2009; Coutts *et al.*, 2009a; Wisbey *et al.*, 2009; Brewer *et al.*, 2010). These methods have been used in many team sports including Australian football (Coutts *et al.*, 2009a; Aughey, 2010), rugby codes (Deutsch *et al.*, 1998; Duthie *et al.*, 2005) and hockey (Johnston *et al.*, 2004). In particular, in Australian football, many elite and many sub-elite teams rely on time-motion analysis information for organising rotations (where players substitute on and off the field), measuring locomotor activity, and overall management of load from week to week.

Current systems used to quantify the physical demands of team sport competition are limited. The validity of heart rate information is questionable when activity levels are intermittent and at high intensities (Godsen *et al.*, 1991; Terbizan *et al.*, 2002). Video time-motion analysis is labour intensive, typically observes only one player at a time, is prone to human error, and cannot function in real-time (Edgercomb & Norton, 2006). Global positioning system (GPS) time-motion analysis can eliminate many of these issues, however poor reliability and validity ($CV = \leq 34\%$) in measuring distance

especially at high velocities over short distances have been exposed in previous work (Jennings *et al.*, 2010a). This method is also unavailable during indoor competition. Current practice also fails to account for the skill (passing, jumping, kicking, marking) and contact based (tackling, blocking) activities that occur up to 173 times per game, or every 45 seconds in Australian football (Dawson *et al.*, 2004b). These activities are currently analysed using only frequency statistics rather than assessing the acute and accumulated magnitude of the activity. Failure to adequately account for these activities may greatly underestimate the physical demands of Australian football.

Tri-axial accelerometers are highly responsive motion sensors used to measure the frequency and magnitude of movement in 3 dimensions (anterior-posterior, medio-lateral, and longitudinal) (Krasnoff *et al.*, 2008). These devices have been used to quantify physical activity in a variety of populations such as the ageing, sedentary, diseased, and youth (Kozey *et al.*, 2010; Quigg *et al.*, 2010). Accelerometers may offer a measurement system that circumvents some of the limitations that exist with heart rate and time-motion analysis, including a higher sample rate compared to GPS, the ability to monitor multiple players indoor as well as outdoor, reduced labour, and the inclusion of skill and contact based aspects of team sports that can contribute to player demands. These devices have the potential to represent gross fatiguing movements, not just locomotor activity.

Published research using accelerometers has focussed largely on the relationship between accelerometers and other measures such as heart rate, energy expenditure and oxygen uptake during various types of physical activity (Coe & Pivarnik, 2001; Kozey *et al.*, 2010). Small quantities of team sport research have explored the activity levels of basketball in junior high school students (Coe & Pivarnik, 2001), and elite

junior players (Montgomery *et al.*, 2010). Gait patterns in runners (Le Bris *et al.*, 2006), and head impacts in various contact sports have also been assessed (Caswell & Deivert, 2002; Duma *et al.*, 2005). However, an assessment of the reliability of accelerometer data in the team sports environment is notably absent from the literature. Existing assessments of the reliability of accelerometers have been limited to mechanical tests and basic physical activity tasks, the results of which have been somewhat mixed (between device: $CV= 1.79$ to 14.4% ; within device: $CV= 1.13$ to 34.7%) (Nichols *et al.*, 1999; Krasnoff *et al.*, 2008; Van Hees *et al.*, 2009). Currently, literature-based evidence of accelerometer reliability in the sporting environment does not exist. Given the recent introduction of accelerometers such as the MinimaxX (Catapult Innovations, Scoresby, Australia) this research is critical to understanding the information that is extracted from these devices.

On this basis, a full evaluation of the reliability of accelerometers in a laboratory, and field setting was required to determine if changes in accelerometer output are evident, and if the observed changes are meaningful. Devices will typically be instrumented on multiple players, therefore both the within- and between-device reliability needs to be established. Therefore, the aim of this investigation was to assess the reliability of MinimaxX accelerometers within- and between-devices in the laboratory, and between-devices in the field. In addition, this investigation assessed the ‘signal’ to ‘noise’ ratio of the MinimaxX accelerometers, which determined the sensitivity of the devices to detect real differences in performance between individuals and groups of athletes.

3.1.2 Methodology

3.1.2.1 MinimaxX 2.0 Accelerometer:

The MinimaxX 2.0 (Catapult Innovations, Scoresby, Victoria) contains a triaxial piezoelectric linear accelerometer (Kionix: KXP94) that detects and measures movement using a micro-electro-mechanical system at 100 Hz. The full-scale output range is ± 6 g. Each device has its own microprocessor, 1 GB flash memory and high-speed USB interface, to record, store and upload data. The device is powered by an internal battery with 5 hours of life, weighs 67 grams and is 88x50x19 mm in dimension.

3.1.2.1.1 Temperature regulation:

Manufacturers specify temperature regulation ranges from -40 to 85° Celsius for the MinimaxX accelerometers. To verify these figures, stability testing was performed on two MinimaxX accelerometers in an environmental chamber (Tabai build-in chamber, model No. TBL-4RS-5) to assess any drift from the baseline gravity measure. Over a three-hour period the temperature was gradually increased from 15° to 35° C then decreased to 15° C. Changes of 0.1 Player load units were found which is considered negligible as Player load values of 1500+ are regularly seen in team sports matches and training (Boyd and Aughey unpublished observations).

Player load is a modified vector magnitude developed by Catapult using the MinimaxX accelerometer data. It is expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y and Z axis) and divided by 100 (equation 1). Data was expressed in arbitrary units (au). This variable was used in both sections of analysis. Device calibration was carried out prior to all reliability testing.

Equation 1: Player load equation (Catapult Innovations, Scoresby, Victoria)

$$PLAYERLOAD = \sqrt{\frac{(a_{y1} - a_{y-1})^2 + (a_{x1} - a_{x-1})^2 + (a_{z1} - a_{z-1})^2}{100}}$$

Where:

a_y = Forwards accelerometer

a_x = Sideways accelerometer

a_z = Vertical accelerometer

Reliability was established in two ways. The first utilised mechanical equipment in a laboratory to assess technical reliability. The second utilised Australian football players, this time to determine the technical reliability in a field setting.

3.1.2.2 Laboratory assessment

3.1.2.2.1 Study design

Static Reliability:

Ten MinimaxX accelerometers were positioned statically with the Z axis aligned to the vertical using a custom-designed cradle on a levelled surface. Given the units were static, the accelerometers should only have detecting acceleration due to gravity (constant value). Each device was subjected to six 30-second trials with a 2 minute interim between. Following each trial the devices were detached from the cradle and subsequently reattached for the next trial. After three static trials, the devices were attached to 10 athletes who performed a 180-minute team sport skills training session (volleyball) involving large volumes of high intensity short duration activities such as jumping and changing direction (Sheppard *et al.*, 2009). Each device was mounted in a customised vest, which was fitted tightly to the body of each athlete. Following the

skills training session, units were re-secured to the cradle and another three 30 s static trials were conducted. This was to determine if high intensity activity affected the stability of the device, and if re-calibration was required regularly. Each static trial was downloaded using the manufacturer's software (Logan Plus 4.2), to obtain the Player load value.

Dynamic Reliability:

To perform a standardised and repeatable movement test for the MinimaxX accelerometers, an Instron 8501 hydraulic shaker was used. The Instron 8501 is a servo-hydraulic universal testing machine with an arm that oscillates in a single plane of movement (vertical). The machine had a stroke of 50 cm, and adjustable frequency to simulate various acceleration ranges. A certified calibrated accelerometer (Brüel & Kjaer, 4370) was attached to the Instron to determine the reliability of the oscillations for each test. The CV was 0.26% over ten 10-second trials, confirming that the hydraulic testing machine is capable of producing highly repeatable dynamic movements. Previous research has utilised mechanical equipment with high repeatability to assess the reliability both within and between devices (Krasnoff *et al.*, 2008; Van Hees *et al.*, 2009).

Eight MinimaxX accelerometers were rigidly attached to the Instron 8501 shaker using hot melt adhesive. A metal plate was attached to the hydraulic arm so that all of the MinimaxX devices could be attached simultaneously. The devices aligned identically, lying flat on the metal plate attached to the hydraulic arm (Y axis - anterior-posterior). For protocol 1 the frequency was set at 3 Hz and the amplitude adjusted to represent a wave form of 0.5 g; protocol 2 was set at 8 Hz and had the amplitude adjusted to represent a 3 g wave form. The selected range of acceleration was based on typical values obtained during Australian football activity (Unpublished

observations). Each unit was subjected to 10 trials of 10 s, for each protocol. Between each trial the shaker was stopped and restarted. Each trial was downloaded using the manufacturer's software (Logan Plus 4.2), to obtain the Player load value.

3.1.2.3 Field assessment

3.1.2.3.1 Participants

Ten male semi-professional Australian football players currently playing in the Victorian Football League were recruited to participate in the study (Age: 23.2 ± 2.3 yrs; Height: 181.6 ± 5.4 cm; Body mass: 83.0 ± 4.8 kg; *Mean \pm SD*). Subjects were informed of the procedures verbally, and in a plain language statement and signed consent forms prior to participation. At the time of testing, participants were training a minimum of three times per week, and participating in one match per week. The research was approved by the University Human Research Ethics Committee.

3.1.2.3.2 Study design

Accelerometer data was collected during nine Victorian football league matches over the 2009 pre- and premierships-seasons. The venue changed from week to week depending on the club's fixture. Five different venues were used in the analysis. For each of the nine games, participants were instrumented with two MinimaxX accelerometers. A minimum of one and maximum of four participants were used in each game. All of the players used in the analysis were from a similar position on the ground. Each participant wore the units for two consecutive matches. The two units were taped together so that their accelerometer axes were aligned. The device placed distally to the body recorded slightly higher Player load values ($CV = 1.6\%$; $r = 0.999$). This was accounted for by swapping the device position for the second match so that each device pairing produced data in both the proximal and distal position. Both units were inserted into a custom vest located on the posterior side of the upper

torso fitted tightly to the body as is typically used in games. The participants were familiar with the procedure as the devices are a regular part of training and match analysis.

Player load obtained from matches was cropped (Logan Plus 4.2) to remove rest breaks (e.g. half time) so that only data during time on the field was included in the analysis. The start and end time points for each period of time spent on the field participating were aligned to the 0.001 seconds to ensure that the data obtained from both units had equal epochs. Player load values from each device for each corresponding playing periods were compared to assess the difference in accelerometer output between devices.

3.1.2.4 Statistical Analysis:

The Player load values were log transformed to reduce bias due to non-uniformity of error and analysed using a customised spreadsheet (Hopkins 2009 – Analysis of Reliability [Microsoft Excel spreadsheet]). Within device reliability was calculated as the mean difference between laboratory trials for each device. Between device reliability was calculated as the mean difference between the devices across all laboratory trials. Reliability during the laboratory assessment was expressed as an absolute using Typical Error (*TE*) with upper and lower 95% confidence intervals (*CI*). The magnitude of difference was expressed as a coefficient of variation (*CV%*). Similarly for the field assessment, The $TE \pm 95\%CI$ was again used to display absolute differences and the *CV%* to determine the magnitude of differences displayed between units. Pearson's product moment correlation coefficient (*r*) was also calculated to express the relationship between devices during the field assessment across each period of time spent participating on the ground. The smallest worthwhile difference (*SWD*) was calculated as $0.2 \times$ between-subject *SD* from the match data collected

during the field assessment section of the study (section 3.1.2.3.2). The *SWD* represents the smallest ‘real’ difference of practical importance (Batterham & Hopkins, 2006). This investigation used the term ‘noise’ to represent the technical reliability, and the term ‘signal’ to represent the *SWD*. When the ‘noise (*CV%*) was \leq ‘signal’ (*SWD*), the accelerometer was considered capable of detecting differences.

3.1.3 Results

All reliability results are displayed in table 9.

Table 9. Summary of reliability results expressed as the *Mean*±*SD* of raw data from all trials; technical error (*TE*); Confidence interval (*CI*); and coefficient of variation (*CV%*).

	<i>Mean</i>	<i>SD</i>	<i>TE</i>	<i>Lower</i> 95% <i>CI</i>	<i>Upper</i> 95% <i>CI</i>	<i>CV%</i>
Static (within device)	0.062	0.07	0.055	0.046	0.069	1.01
Static (between device)	0.062	0.05	0.065	0.055	0.081	1.10
Dynamic 0.5 g (within device)	0.748	0.019	0.007	0.006	0.008	0.91
Dynamic 0.5 g (between device)	0.748	0.007	0.008	0.007	0.009	1.04
Dynamic 3.0 g (within device)	7.698	0.090	0.081	0.070	0.098	1.05
Dynamic 3.0 g (between device)	7.698	0.080	0.079	0.068	0.095	1.02
Sports Specific (between devices)	227.692	101.246	5.064	4.497	5.841	1.94

3.1.3.1 Laboratory assessment

Static assessments for within- and between-device reliability were *CV*= 1.0% and *CV*= 1.0%, respectively.

The dynamic assessment of between device reliability was *CV*= 1.04% for the 0.5 g trial and *CV*= 1.02 for the 3.0 g trial (Figure 3.1). Similarly, within devices dynamic assessments were *CV*= 0.91% for the 0.5 g trial and *CV*= 1.05% for the 3.0 g trial (Figure 3.1).

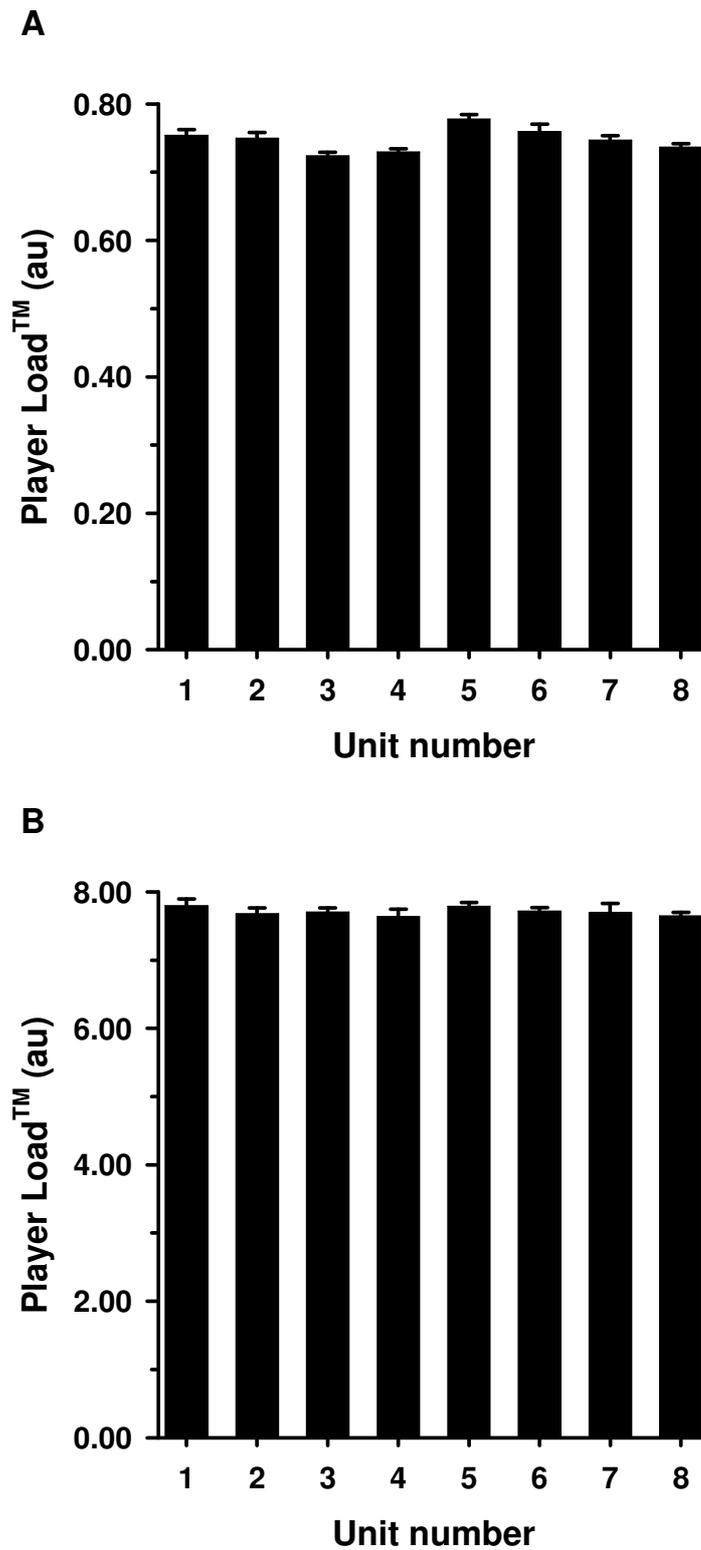


Figure 3.1 Raw player load values (square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors, divided by 100). A.) Between device – shaken at 0.5 g for ten trials of 10-seconds; B.) Between device – shaken at 3.0 g for ten trials of 10-seconds.

3.1.3.2 Field assessment

The between-device reliability of accelerometers during Australian football matches was 1.9% (CV) (Table 9). The results from individual player data indicated that all differences between units were $\leq 2.80\%$. Relationships between data from devices on the same individual ranged from $r = 0.996$ to 0.999 (Figure 3.2).

Both the laboratory (CV= 0.91 to 1.05%) and field testing (CV= 1.9%) measurement error or noise was less than the signal (SWD= 5.88%).

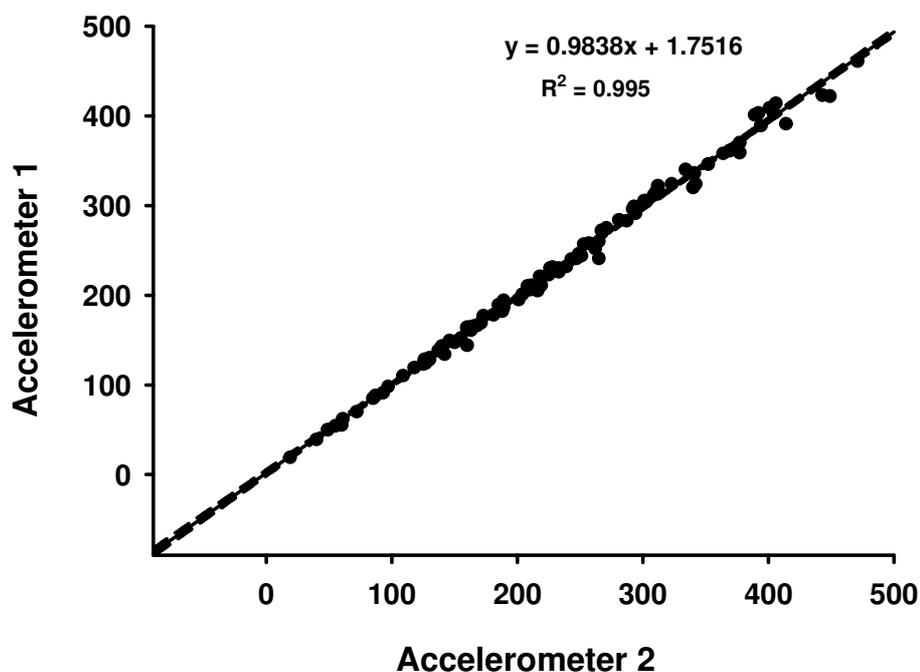


Figure 3.2 The relationship between two accelerometers placed on the same player during Australian football matches. The solid line is a line of best fit, hatched lines represent 95%CI; the slope of the line is also given in text ($n = 104$).

3.1.4 Discussion

MinimaxX accelerometers demonstrated an acceptable level of technical reliability both within- and between-devices for measuring physical activity in team sports. The noise (technical reliability CV%) for both the laboratory and field testing was below

2%. These values were well below the signal (*SWD*) which was 5.88%, suggesting that MinimaxX accelerometers are suitable for detecting differences in Australian football physical activity (Cormack *et al.*, 2008c; Jennings *et al.*, 2010b).

3.1.4.1 Laboratory assessment

Both within- and between-device reliability was superior for the MinimaxX compared to other accelerometers reported in the literature during dynamic testing. The within device reliability ($CV= 0.9$ to 1.05%) of the MinimaxX accelerometer was equal or superior to both the RT3 (Krasnoff *et al.*, 2008), and DynaPort devices (Van Hees *et al.*, 2009) trialled on mechanical testing machines. The between-device reliability ($CV= 1.02$ to 1.04%) of the MinimaxX was also superior to the Tritrac-R3D, RT3 and Dynaport using similar testing methods (Nichols *et al.*, 1999; Krasnoff *et al.*, 2008; Van Hees *et al.*, 2009). The MinimaxX therefore has acceptable levels of reliability compared to equivalent devices already in regular use.

It is important to note that in the current investigation the MinimaxX accelerometers were exposed to much higher rates of acceleration compared to previous literature during mechanical testing. If these previously employed ranges (0.35 to 0.64 g) were used, only approximately 21% of the data collected during team Australian football matches would be accounted for in the reliability trials. The greater range (0.5 to 3.0 g) used here would account for 96% of the values obtained during Australian football match activity. Thus, it can be confident that the testing is representative of the likely range of accelerations regularly imposed on these devices in competition.

The acceptable level of reliability indicated from the static testing ($CV= 1.01$ to 1.10%) we conducted is an important finding. The devices used in this study remained stable over a long period without drifting from the baseline measurement. Static periods are frequent in team-sport activity, such as when the ball is not in proximity to

players, or during natural breaks in play (Dawson *et al.*, 2004b). During periods of negligible-motion the devices should not contribute to the total Player load value obtained for a given activity bout. Assuming that the athlete is motionless during these periods, then the player load values obtained should be close to zero, and any recorded values during this static period may lead to overestimation of the Player load. The drift in Player load reported here is trivial compared to the values typically obtained for training and matches of 1500 or more Player load units.

3.1.4.2 Field assessment

Previous assessment of the vector magnitude of various accelerometer models has commonly used mechanical or carefully controlled physical activity trials rather than in actual sports activity. Thus, if applied in a sports setting, the actual reliability of these accelerometers may be lower than in carefully controlled settings. Notwithstanding the chaotic nature of collision team sports, the field testing carried out in this investigation resulted in superior between-device reliability ($CV= 1.94\%$) than previously reported for other accelerometers tested on mechanical devices (Krasnoff *et al.*, 2008). The MinimaxX also displayed far greater reliability than reported for low intensity physical activity ($CV= 6.0$ to 25.0%) (Powell & Rowlands, 2004). Indeed, strong relationships also existed between-devices ($r = 0.996$ to 0.999) during high intensity Australian football activity, indicating that Player load results are consistent regardless of the unit used. The between-device reliability is important given multiple devices are typically used to measure Player load across numerous players and from one match to another. The relationships displayed in the current investigation were much stronger than those reported for physical activity trials such as treadmill walking and running ($r = 0.73$ to 0.87) (Nichols *et al.*, 1999). It might have been expected that controlled physical activity trials such as walking and

running would be more reliable compared to the variable activity displayed in team sports match performance. In the current investigation this was not the case. This may be a reflection of the superiority of the MinimaxX sensors.

The signal (*SWD*) for Player load during matches was 5.88%. These results revealed that the noise ($CV = <2\%$) was much less than the signal, which supports the ability of the MinimaxX to detect differences in physical activity during Australian football (Pyne, 2003; Cormack *et al.*, 2008c). Best practice would require the determination of this value for discrete data sets and populations, as this study is only representative of a small cohort of Australian football players.

Further investigation of MinimaxX accelerometers requires laboratory based reliability analysis at higher accelerations (Eg. 3 to 6 *g*) to match the full range of activity patterns likely in Australian football matches. In the current investigation, the mechanical shaker was unable to meet these specifications, however only 4% of typical values obtained during Australian football matches are between 3.0 and 6.0 *g*. The dynamic laboratory testing was also conducted in one plane of movement. As all three accelerometers operate in the same way, it was assumed that the outcomes from reliability testing in one plane could be extrapolated to all three planes of movement. An assessment within devices in random dynamic field settings would also be of interest however, this appears to be challenging. Physical activity trials would not service these needs, as repeated trials are difficult to conduct. Laboratory testing using mechanical devices, may be the only plausible way to test the devices, however random protocols may need to be generated. Finally, research assessing the relationship between accelerometers and other common measures of physical activity is still required in team sports.

3.1.4.3 Practical Applications

The MinimaxX accelerometers can be confidently applied to assess changes or differences over multiple periods of activity, or between players. Although low, the variation displayed should be taken into account when making inferences about the meaningfulness of differences. Further, for these activities, players can be equipped with any device rather than needing to use the same one at all times.

3.1.5 Conclusions

MinimaxX accelerometers vary by <2% during laboratory and field testing indicating acceptable reliability. The noise (*CV%*) was less than the signal (*SWD* 5.88%), suggesting that they are capable of detecting differences in physical activity levels. In addition, these values were below the 5% suggested in the literature as an acceptable level of reliability for sports analysis technology (Petersen *et al.*, 2009; Jennings *et al.*, 2010a). Technological variation must be considered in determining the appropriateness of a device for use in testing and analysis. MinimaxX accelerometers are suitable for use in Australian football and in team sports where the signal (*SWD*) is greater than 2%.

CHAPTER 4. STUDY 2

4.1 Measuring external loads and internal responses of small-sided Australian football games

4.1.1 Introduction

Team sport training and competition elicit high exercise loads on athletes. Monitoring load is critical to optimising the exercise stimulus and therefore performance of athletes. External load (i.e. running distance, frequency of sprints, number of tackles) has a significant influence on the internal stress placed on athletes (Impellizzeri *et al.*, 2005). Australian football is an invasion team sport that integrates high volumes of locomotor activity (~10,000 to 14,000 m), coupled with frequent execution of game-specific or non-locomotor activity, many of which involve body contact between players or with the playing surface (Dawson *et al.*, 2004c). In combination these external loads stimulate high levels of stress on the body's internal structures and systems.

A variety of methods have been used to quantify the load on team sport athletes during training and competition, yet each has important limitations. Whilst heart rate monitoring is commonly used in team sports (Montgomery *et al.*, 2010), the validity of this method decreases during the intermittent activity (Terbizan *et al.*, 2002). Time motion analysis methods including global positioning systems (GPS) are utilised frequently to determine the stresses of Australian football (Aughey, 2010), however only locomotor activity is accounted for. In some instances, factors such as weather conditions (Duffield *et al.*, 2009b), and the tactics and style of opposition teams (Rampinini *et al.*, 2009) may change locomotor activity, and potentially change the alternative forms of non-locomotor activity, such as those involving physical contact.

Currently, these activities are overlooked as a quantitative measure does not exist, therefore an underestimation of the true external load on players may occur.

Valid systems of external load should take into account the physical contact experienced by players in collision sports such as Australian football. Evidence from rugby and boxing suggests that external load from physical contact is linked to various internal responses (Zuliani *et al.*, 1985; Takarada, 2003). A strong relationship exists between the number of tackles in rugby and markers of muscle damage (creatinine kinase: $r = 0.92$; myoglobin: $r = 0.85$), suggesting that blunt forces from physical contact disturb the internal muscle structure (Takarada, 2003). Creatinine kinase concentration was higher following rugby matches compared to after a 90-minute simulated team sports running protocol without physical contact (Thompson *et al.*, 1999). Higher muscle damage evidenced by higher creatinine kinase and myoglobin concentrations following full-contact boxing, in comparison to shadow boxing also supports this theory (Zuliani *et al.*, 1985). The development of a simple, non-invasive and objective measure that incorporates both locomotor and physical contact activity, would help to accurately represent the external loads of contact sports such as Australian football.

Triaxial accelerometers are highly responsive motion sensors that measure the frequency and magnitude of movement in three dimensions. Small and un-obtrusive accelerometer designs are tolerable to wear during sports activity. Initial accelerometer research focused on basic physical activity assessments (Hendelman *et al.*, 2000). The vector magnitude, which is the instantaneous rate of change in acceleration in three planes (z = cranio-caudal; y = medio-lateral; x = antero-posterior) (Boyd *et al.*, 2011), is commonly used to characterise physical activity levels. Recent research in team sports proposed that the vector magnitude may

provide a quantitative measure of external loads incorporating whole body movements, not just lower limb activity as with time-motion analysis (Montgomery *et al.*, 2010). Two studies of rugby union (Cunniffe *et al.*, 2009) and basketball (Montgomery *et al.*, 2010) attempted to quantify the external loads of matches and training using the vector magnitude (Player load). These studies have reported that Player load displayed differences in external loads between playing positions and different types of activities, however no link has been established with other external load measures and internal responses.

Small-sided games are a modified version of game play that can be manipulated through player numbers, field dimensions and game rules, to control the intensity and volume of physical activity (Rampinini *et al.*, 2007b). The reliable and specific (Gabbett, 2005) qualities of small-sided games provide a suitable stimulus to assess the quantitative capacity of accelerometers for measuring locomotor and physical contact activity during Australian football.

First, this investigation aimed to establish the concurrent validity of the vector magnitude derived from a triaxial accelerometer (Player load) by assessing the relationship with other common measures of load analysis in team sports. Correlation analysis was conducted between the Player load parameters, and external measures from time-motion analysis, internal response through biochemical analysis, perceptual responses, and performance measures. The secondary aim was to utilise various forms of Player load to identify and measure Australian football activity that involves physical contact. Two small-sided games conditions were compared, one allowing physical contact activity such as tackling, bumping and contested situations, and the other not allowing these activities. It was hypothesised that the contact small-sided game would stimulate higher external loads compared to non-contact. Additional

measures of external load from time-motion analysis, internal responses through biochemical analysis, perceptual responses, and performance measures were also compared, to characterise any differences between the non-contact and contact small-sided games.

4.1.2 Methodology

4.1.2.1 Participants

Twenty-four elite Australian footballers (Age 24.2 ± 3.5 years; height 189 ± 5.6 cm; body mass 88.6 ± 7.6 kg; *Mean* \pm *SD*) gave informed consent to participate in this study. All were full-time athletes registered with the Australian Football League. Participants were informed of the procedures verbally, and in a plain language statement, and signed consent forms prior to involvement. The research was approved by the Victoria University Human Research Ethics Committee and supporting organisation.

4.1.2.2 Study design

A quasi-experimental crossover design was employed. In week one a small-sided game was conducted with physical contact activities, such as tackling and bumping not permitted (non-contact, NC). Players were instructed not to dive on the ground to retrieve the ball to minimise contact from contested situations when the ball was in dispute. In week two, tackling, bumping and contested situations were allowed, in line with the rules of Australian football matches (Contact, C). The game duration was 4 x 3 minute quarters with 2 minutes recovery between each quarter. A 4 vs 4 player scenario was implemented on a 16 m x 24 m field. A score was recorded by handballing the ball through the goals (width: 1.5 m). Each player was assigned to a team, which remained the same for both conditions.

Prior to commencing the small-sided games, the participants completed a warm up incorporating general running drills, flexibility, and football activities. This warm up was based on a typical team sports warm up, as outlined in previous research (Zois *et al.*, 2011). The two conditions were conducted on the same training day one week apart as part of regular skills training in the pre-season phase. The warm ups, training stimulus and recovery strategies which are part of the team's weekly routine were matched to prevent difference between testing weeks. The training stimulus (resistance and skills training) over the seven day period leading into the small-sided games were matched closely. Training loads (Session RPE) from each week were compared using the effect size and 95% confidence interval ($ES \pm 95\% CI$) statistic.

4.1.2.3 Methodology

Each participant was instrumented with a tri-axial accelerometer (MinimaxX 2.0; Catapult Innovations, Scoresby, Victoria) to measure external loads during both small-sided games conditions. High reliability of the MinimaxX accelerometer ($CV < 2.0\%$) has been reported previously (Boyd *et al.*, 2011). The vector magnitude which is the instantaneous rate of change in acceleration in three planes of movement (z , y , x) was titled Player load (PL^{3D}) (Boyd *et al.*, 2011), and calculated with the following equation:

$$PLAYERLOAD = \sqrt{\frac{(a_{y1} - a_{y-1})^2 + (a_{x1} - a_{x-1})^2 + (a_{z1} - a_{z-1})^2}{100}}$$

Two modified versions of PL^{3D} , which were developed by the manufacturers of the MinimaxX accelerometers, were also analysed with the aim of minimising the locomotive stimulus to isolate non-locomotor external load such as physical contact. These included PL^{2D} (movement in the medio-lateral (y) and antero-posterior (x) planes only), and PL^{SLOW} (movement in all three planes when velocity was $< 2 \text{ m.s}^{-1}$). Lastly, a fourth accelerometer-derived parameter titled PL^{CO} which used total running

distance as a covariate in the statistical analysis was also compared between conditions.

Time-motion analysis using the GPS component of the MinimaxX 2.0 measured the total distance travelled (metres), the distance covered at high velocity (metres) ($>4.17 \text{ m}\cdot\text{s}^{-1}$), and the percentage of total distance performed at high velocity (Aughey, 2010).

Blood and saliva samples were taken prior to (Pre), immediately post (Post), and 24 hours post small-sided games (24 h) to assess the internal response. These time points were chosen to ensure that the testing did not disrupt the elite athletes' regular schedules, in conjunction with previous research findings in team sports. Ten milliliters of blood was drawn from a forearm vein using a 23-gauge needle equipped with a Vacutainer® tube after the participant had been in a supine position for two minutes. Five milliliters of non-hemolyzed blood was dispersed into a lithium heparin tube. This sample was pipetted into a 1.5 ml microfuge tube then centrifuged (4°C) at $6000 \text{ rev}\cdot\text{min}^{-1}$ for 15 min to split the sample. Plasma was removed and aliquotted into a secondary microfuge tube and stored at -80°C for later analysis of myoglobin. The remaining five milliliters of non-hemolyzed blood was aliquotted into a lithium heparin tube, rolled, and analysed using a blood gas analyser (Sysmex K-800, Japan) to determine hematocrit and haemoglobin, and used to calculate plasma volume changes (Dill & Costill, 1974). Relative plasma myoglobin concentration [Mb] was determined in duplicate using a commercially available enzyme-linked immunosorbent assay (ELISA) kit (Human Myoglobin Enzyme Immunoassay, Oxis International, USA) and plate reader (iMark Microplate absorbance reader. Bio-rad, CA, USA). The CV for this assay was 9.1%. Saliva samples were collected from participants by passively drooling into a plastic sample container. Samples were

frozen at -80°C for subsequent analysis. Salivary cortisol concentration was determined in duplicate using an ELISA kit (Salimetrics, PA, USA) and plate reader (iMark Microplate absorbance reader. Bio-rad, CA, USA). The *CV* for this assay was 4.8%.

Approximately 15 minutes after the conclusion of the small-sided games participants were asked to express their rating of perceived exertion (RPE) using a modified scale (CR10) (Foster *et al.*, 2001). Perceptions of soreness and fatigue were assessed using visual analogue scales (Wewers & Lowe, 1990) Pre, Post and at 24 h.

A single counter-movement jump was measured to assess physical performance on a portable force plate (400 series; Fitness Technology, Adelaide, Australia) Pre, Post, and at 24 h. Before the Pre counter-movement jump the participants performed a 5-minute dynamic warm up consisting of activation, mobility and light plyometric activity, and three practice jumps. Flight time, flight time to contraction time ratio (FT:CT) mean power, peak power, mean force and peak force were calculated using customised software (Ballistic Measurement System; Fitness Technology). Reliability of these variables has previously been reported ($CV = <8.2\%$) (Cormack *et al.*, 2008c). A visual representation of the protocol is displayed in appendix 6.

4.1.2.4 Statistical analysis

Variables were log transformed to reduce bias due to non-uniformity of error and analysed using a customised excel spreadsheet using the meaningful inferences approach (Hopkins *et al.*, 2009). Pearson's product moment correlation coefficient (r) was calculated to express the relationship between the accelerometer variables and other measures. Differences between the C and NC small-sided games were determined using the $ES \pm 95\%CI$ statistic and percentage change to determine the magnitude of any difference. A difference was classified as substantial where there

was a $\geq 75\%$ likelihood that the mean effect was greater than or equal to a small ES (± 0.2). Effects with less certainty were classified as trivial and where the $\pm 95\% CI$ of the ES crossed the boundaries of -0.2 and 0.2 , the effect was reported as unclear (Hopkins *et al.*, 2009).

4.1.3 Results

Training loads (Session RPE) from the NC and C weeks were successfully matched (Figure 4.1).

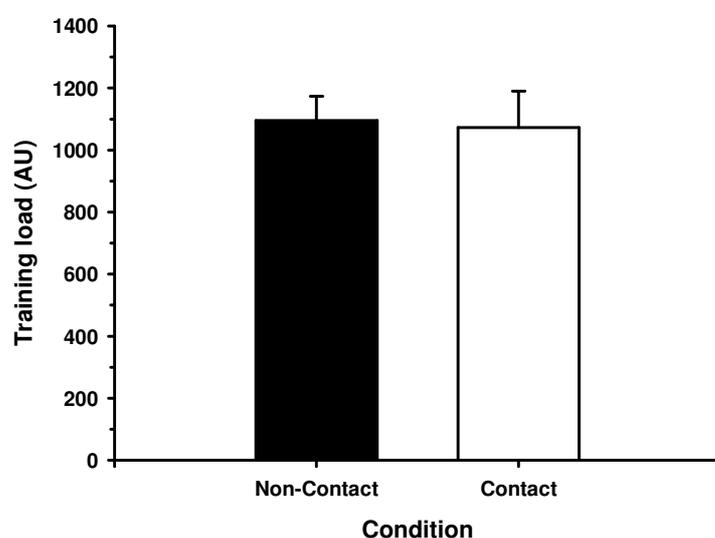


Figure 4.1. Training loads (session RPE) from the week preceding both the non-contact and contact small-sided games condition. All data is expressed as *Mean* \pm *SD*.

Correlations between accelerometer load parameters and GPS measures, and biochemical markers of muscle damage ([Mb]) are displayed in Table 10. Visual representation of these correlations is also displayed in appendix 6. Jump performance immediately post had small to moderate relationships with accelerometer loads (FT:CT: $r = -0.33$ to -0.44 ; peak power: $r = -0.45$ to -0.55 ; mean force: $r = -0.47$ to -0.48). Perceptual measures of muscle fatigue ($r = -0.12$ to -0.55) and soreness ($r = -0.11$ to -0.53), and hormonal responses from salivary cortisol ($r = -0.13$ to -0.47), did not display clear relationships with accelerometer load parameters.

Table 10. Correlations (Pearson's r) between accelerometer derived load parameters, and locomotor variables and Myoglobin concentration [Mb]. Relationships were classified as * moderate ($r = 0.3$ to 0.5); † large ($r = 0.5$ to 0.7); ‡ very large ($r = 0.7$ to 0.9).

Accelerometer load parameters	Total Distance (m)	High velocity running distance (m)	[Mb] Immediately post	[Mb] 24 hours post
PL^{3D}	0.76 ‡	0.31 *	0.28	0.40 *
PL^{2D}	0.68 †	0.21	0.30 *	0.39 *
PL^{SLOW}	0.63 †	0.24	-0.13	0.20

Total distance was higher for NC in comparison to C (10.1%; 0.99 ± 0.71). Similarly, high velocity running distance (24.8%; 0.99 ± 0.68) and percentage of high velocity running (16.5%; 0.76 ± 0.57) were higher for NC (Table 11). Player load was higher for C only when total locomotor distance was used a covariate (PL^{CO}, -11.9%; -0.93 ± 0.68 , Table 11).

Table 11. Accelerometer and GPS parameters from the non-contact and contact conditions are expressed as *Mean±SD*. Differences between conditions were expressed using *ES±95%CI* and percentage change with a qualitative descriptor.

Small-sided games condition	PL^{3D}	PL^{2D}	PL^{SLOW}	PL^{CO}	Total Distance (m)	High velocity running distance (m)	% High velocity running
Non-Contact	221.0±45.21	144.3±30.35	91.0±23.68	207.0±45.21	1556.4±182.71	219.7±79.41	13.8±3.65
Contact	210.7±39.45	140.3±30.72	95.2±37.89	231.5±39.45	1398.9±116.04	165.2±38.72	11.5±2.55
% Difference	4.7	2.8	-4.7	-11.9	10.1	24.8	16.5
<i>ES±95%CI</i>	0.24±0.68	0.13±0.55	-0.18±0.57	-0.93±0.68	0.99±0.71	0.99±0.68	0.76±0.57
Qualitative descriptor	Unclear	Unclear	Unclear	Moderate	Moderate	Moderate	Moderate

Both the NC and C small-sided games displayed an increase in fatigue and soreness immediately post and 24 hours post compared to pre-test values. The increase in fatigue from the NC small-sided game was 54% (0.90 ± 0.50) higher immediately post, and 57.1% (0.98 ± 0.56) higher at 24 hours post compared to the increase from the C small-sides game. Similarly, the increase in soreness following the NC small-sided game was 44.4% (0.63 ± 0.53) higher immediately post, and 69.8% (1.28 ± 0.69) higher at 24 hours post, compared to the increase from the C small-sided game.

Both the NC and C small-sided games displayed an increase in [Mb] immediately post compared to pre-test values, followed by a decrease at 24 hours post which was still above pre-test values (Figure 4.2). Salivary cortisol was decreased immediately post and at 24 hours post for both the NC and C small-sided games, compared to pre-test values (Appendix 6). At 24 hours post, the increase in [Mb] from the NC small-sided game was 27.6% (0.61 ± 0.74) higher than the increase from the C small-sided game. There were no clear differences between small-sided games for [Mb] post, or cortisol immediately post and 24 hours post.

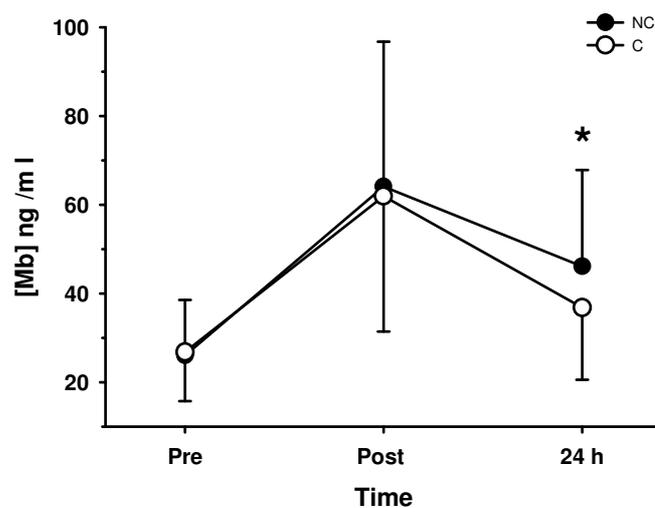


Figure 4.2 Time course changes in Mb concentration. Closed circles are for non-contact (NC), open circles are for contact (C). All data is $Mean \pm SD$. * denotes a moderate effect between the non-contact and contact conditions.

Flight time, and peak power increased immediately post for both the NC and C (Flight time: 4.7%, $ES = 0.83 \pm 0.39$; Peak power: 11.3%, $ES = 0.89 \pm 0.39$) small-sided games. The increases in jump performance immediately post and at 24 hours post did not differ between the NC and C small-sided games.

4.1.4 Discussion

Accelerometer data quantifying external load had large correlations with locomotive distance and moderate correlations with one biochemical marker of muscle damage (Mb) in elite Australian football players during small-sided games. However, accelerometer-derived parameters designed to measure external load could not differentiate between contact and non-contact activity. When movement distance was accounted for, Player Load in the contact small-sided game was higher. Further, very-short duration Australian football small-sided games elicit large increases in muscle damage and the perception of fatigue and soreness in elite players. Elevated feelings of fatigue and soreness, and increased [Mb] during the non-contact condition compared to contact may be a product of increased locomotive activity. In contrast, RPE was higher following the contact condition, suggesting that physical contact increases perceived exertion.

The perceived effort from the Australian football small-sided games used in the testing were equivalent to those reported for elite AF matches (Duffield *et al.*, 2009a), as was the distance per minute covered by players (Aughey, 2010). Relative to time,

the small-sided games stimulus was comparable to matches and tightly controlled, and therefore was an appropriate activity task for this study.

The PL^{3D} parameter was tightly correlated with locomotive parameters during the contact small-sided games. This finding supports strong relationships between accelerometers and velocity ($r = 0.96$ to 0.98) (Rowlands *et al.*, 2007), metabolic cost (Hendelman *et al.*, 2000), HR, and $\dot{V}O_2$ (Fudge *et al.*, 2007) during locomotive activity. Importantly, our results add to this body of knowledge in that we show good correlations between accelerometer-derived player load and intermittent locomotor activity, typical of team sports such as Australian football. Thus accelerometers may provide supplementary information relating to the distance of running performed under conditions where GPS is unavailable. Additionally, moderate relationships existed between PL^{3D} , PL^{2D} and plasma [Mb] immediately and 24 h after contact small-sided games suggesting that these measured external loads are linked to internal responses.

Unlike our study, research in basketball found differences between basketball training drills and matches using accelerometers, however vastly different activities were used (Montgomery *et al.*, 2010). In our study, the two conditions were matched aside from a single rule variation, that being the presence of physical contact. Accelerometer parameters developed by the manufacturers (PL^{3D} , PL^{2D} and PL^{SLOW}) did not identify differences between the non-contact and contact conditions. The PL^{3D} may have been heavily influenced by accelerations in the vertical plane from foot strikes during locomotor activity. When the vertical plane was removed from the analysis (PL^{2D}), differences between the conditions were still unclear, possibly due to frequent accelerations in the antero-posterior plane during forward locomotor activity. Although not significant, the 4.7% higher PL^{SLOW} from the contact condition,

suggests that this parameter supplies different information to PL^{3D} , which was 4.7% higher for non-contact. When total distance was accounted for using covariate analysis (PL^{CO}) accelerometers recorded higher external loads for the contact small-sided games. Thus with further investigation, new accelerometer-derived parameters, capable of identifying the presence of physical contact in the absence of time-motion analysis may be developed.

The addition of deliberate contact in small-sided games resulted in a substantial decrease (10.1%) in the distance covered by players. This could be a consequence of slower play when being tackled and in contested situations, or fatigue from trying to apply and absorb high forces from opposition players. Similarly, high velocity running (24.8%) was substantially higher in the absence of physical contact. The inclusion of deliberate contact thus causes substantial changes in the running performed by players, and this is an important consideration for the design of training drills.

The pattern of [Mb] response to small-sided games was similar to that reported for rugby (Takarada, 2003), and soccer matches (Ascensao, 2008). Concentrations increased from baseline to immediately following small-sided games (135.9%), then reduced at 24 hours, however still remained elevated above pre activity levels (58.5%). These increases were lower than rugby (Post = 1766%; 24 hours post = 266%) and soccer (Post = 871%; 24 hours post = 71%), most likely due to the short total activity time of the small-sided games we employed. The [Mb] was greater following non-contact small-sided games which opposes findings from boxing research where full contact had 86% higher [Mb] compared to shadow boxing (Zuliani *et al.*, 1985). Boxing comprises of predominantly upper body activity whereas Australian football requires large amounts of running. Running activity has a

high eccentric component, which can induce significant micro trauma to muscle structures (Schwane *et al.*, 1983). It is reasonable to suggest that the increase in [Mb] following non-contact small-sided games may be related to higher running activity rather than a direct effect of altered physical contact. Conversely, any differences based on physical contact between conditions may have been masked by the substantial running component of Australian football.

Perceived muscle soreness increased immediately following small-sided games, and decreased at 24 hours post. This is in line with findings following a competitive soccer match, advocating that although short in duration, small-sided games were demanding (Ascensao, 2008). The higher perceived muscle fatigue and soreness after non-contact compared to contact small-sided games suggests that the increase in locomotive activity during the non-contact condition contributes largely to these perceptions. In contrast, perceived exertion was higher for contact small-sided games. This suggests that alternative factors are contributing to this perception. It is possible that activities incorporating physical contact elicits a degree of psychological stress upon the players. Competitive anxiety levels increase substantially during contact compared to non-contact sports possibly due to fear of injury and physical danger (Mellalieu *et al.*, 2004). Furthermore, an increase in perceived exertion can be associated with elevated levels of anxiety (Morgan, 1994).

Although no differences were evident between NC and C small-sided games, both conditions appeared to enhance vertical jump performance. This conflicts with some (Cormack *et al.*, 2008a), but not all (Duffield *et al.*, 2009a) of the findings following Australian football matches. The moderate increase displayed for flight time and peak power from this investigation suggest that the relatively short duration of the small-sided games may have had a potentiating effect, rather than suppressing the central

nervous system. Greater motor unit recruitment and force production may have manifested from the short duration, high intensity small-sided games, thus displaying strong potential as a warm up activity (Zois *et al.*, 2011).

Ambiguous differences in the salivary cortisol response between the NC and C small-sided games suggest that this method was not capable of measuring the stress response of such short duration activity. It was also evident that moderate to small decreases occurred immediately post and at 24 hours post small-sided games, whilst Australian football matches displayed increases both post and 24 hours post (Cormack *et al.*, 2008a). Again, this suggests that the stimulus from small-sided games may be too short to elicit a stress response. It is also common for pre-activity values to be elevated from anxiety related to upcoming performance or fear of blood sampling procedures (Hoffman *et al.*, 2002). Therefore elevated post-activity values may only be shown if the exercise stimulus is more substantial, as with Australian football matches compared to small-sided games.

One limitation of the current research was the non-randomised design which exposes a potential learning or order effect. A priority was placed on attaining high level athletes, therefore we had to forgo a randomised design to fit the testing into the regular training schedule to ensure that their preparation was not interrupted. It was also concluded that as the small-sided games are a weekly feature of the teams training regime, any learning and order effect would be minimised. It should also be acknowledged that SSG can be highly variable. However for the purpose of this research, they provided a controllable stimulus in which to test the hypotheses.

Further research is required to develop accelerometer algorithms, capable of measuring physical contact activity, that are not reliant on locomotor measures. Additionally, the development of specific algorithms, similar to those used in rugby

(Gabbett *et al.*, 2010), for detecting tackles and collisions, would greatly assist in quantifying both the frequency and magnitude of blunt forces applied or received by the player.

4.1.4.1 Practical applications

Although currently unable to identify levels of physical contact, accelerometers may be used as a supplementary objective measure of the external load from Australian football activity, in the absence of regular time-motion analysis systems. Non-contact small sided games appear more demanding for players than those with full-contact. This is an important consideration for training design, as it appears that the locomotor component of Australian football may have a greater affect on the stress experienced by athletes. Subsequently, physical contact represents a key variable for manipulating the training stimulus in Australian football.

4.1.4.2 Conclusions

External load measured from accelerometers was closely linked to total locomotor activity in Australian football. Accelerometers were only capable of differentiating between non-contact and contact Australian football small-sided games when locomotor distance was accounted for in the analysis process. Further comparisons from this research indicated that exercise induced muscle damage, muscle fatigue and muscle soreness, were higher following non-contact Australian football small-sided games. Perceived exertion opposed these findings with higher RPE expressed following contact small-sided games.

CHAPTER 5. STUDY 3

5.1 Quantifying external load in Australian football matches and training using accelerometers

5.1.1 Introduction

The locomotor demands of Australian football matches (Dawson *et al.*, 2004b; Coutts *et al.*, 2009a; Wisbey *et al.*, 2009; Aughey, 2010; Brewer *et al.*, 2010; Aughey, 2011a), and to a lesser extent training (Hahn *et al.*, 1979; Dawson *et al.*, 2004a; Farrow *et al.*, 2008), indicate high physiological and physical stresses on the players (Norton *et al.*, 1999; Dawson *et al.*, 2004c, a). The total distance covered by players in matches has been reported as between 9,500 m to 17,000 m which varies based on playing position. Approximately 3,300 m to 3,800 m of this is at a high velocity ($>4.17 \text{ m}\cdot\text{s}^{-1}$) (Aughey, 2011b) with sprints and hard accelerations executed 0.9 to 1.0 times per minute of playing time (Aughey, 2010; Brewer *et al.*, 2010). Low velocity activities involving changes of direction in congested spaces occur frequently, however horizontal displacement is minimal, therefore common time-motion analysis methods may not accurately represent the load that is placed on the body. Episodes of physical contact such as tackling, bumping, blocking and contested situations when the ball is in dispute are also common (Dawson *et al.*, 2004b). Currently, these activities can be counted and classified, however an objective measure of the load associated with each activity is still to be developed. In Australian football, between 34 to 127 activities may involve physical contact and this varies based on playing position (Dawson *et al.*, 2004c). In rugby and boxing physical contact has shown to contribute substantially to the stresses placed on players (Zuliani *et al.*, 1985;

Takarada, 2003). Indeed, without quantifying all forms of physical stress, the external load of Australian football may be underestimated.

Triaxial accelerometers are a highly responsive motion sensor that measures the frequency and magnitude of body movement in three dimensions. Previous research has proposed that these devices can measure all forms of external load in team sport (Montgomery *et al.*, 2010). Findings from basketball suggested that Player load, which is an accelerometer-derived measure of external load was capable of differentiating loads between a competitive match, modified scrimmage games, and various training drills (Montgomery *et al.*, 2010). In rugby the number and severity of collisions from matches and training was measured using accelerometers (Gabbett *et al.*, 2010). Collisions in training were less frequent and of lower force compared to matches. When playing positions were compared in the same study, the forwards sustained the highest number of collisions. This finding is representative of the forward players' role within the team, and suggests that the accelerometers were a good method for differentiating between playing positions (Gabbett *et al.*, 2010).

Accelerometers are reliable in a laboratory and sports specific setting (Boyd *et al.*, 2011). During Australian football activity, a large relationship between an accelerometer-derived measure of external load (Player load^{3D}), and locomotor distance ($r = 0.63$ to 0.76) was reported (chapter 4), suggesting that in the absence of time-motion analysis, these devices may provide a proxy measure of locomotor load. During the same study, three variations of accelerometer load parameters (Player load^{3D}; Player load^{2D}; Player load^{SLOW}) were used to differentiate non-contact and contact small-sided Australian football games. Player load^{3D} was 4.7% higher for non-contact, however as locomotor distance was 10.1% higher in the non-contact, it was suggested that foot strikes and forward accelerations from running heavily influenced this outcome.

Alternatively, when locomotor distance above $2 \text{ m}\cdot\text{s}^{-1}$ was removed from the analysis, Player load^{SLOW} displayed 4.7% higher load for the contact small-sided game. Although these differences were statistically unclear, it appears that different information is provided by the Player load^{3D} and Player load^{SLOW} parameters.

Although large portions of Australian football involve locomotor activity, there is still a substantial component of other activities performed at lower-velocities that may place significant stress on the players. If not considered, the loads of Australian football activity may be grossly underestimated. Therefore this investigation aimed to describe two forms of external load in AF matches and training using accelerometers. The first being a measure of all external loads (Player load^{3D}), and the second confined to activity performed at low-velocities (Player load^{SLOW}). These comparisons were made between playing positions, playing level, and between common training drills and actual AF matches.

5.1.2 Methods

5.1.2.1 Participants:

Forty Australian football players from one Australian football league team were included in the analysis. Nineteen played at elite level (Age: 25.2 ± 3.8 yrs; height: 1.87 ± 0.06 m; body mass: 87.9 ± 8.6 kg; (*Mean \pm SD*)) and twenty-one at sub-elite level (Age 21.3 ± 2.4 yrs; height 185.3 ± 17.2 cm; body mass 87.7 ± 18.4 kg). Participants were informed of the procedures through a plain language statement, and gave informed consent to participate in this study. All participants were registered players of an elite club training as full time professionals. The study was approved by the university human research ethics committee.

5.1.2.2 Study Design:

Data was collected from 24 matches from the 2008-2009 AFL (elite) premiership season, 29 matches from the 2008-2009 VFL (sub-elite) premiership season. Data was also collected from 32 training sessions where both elite and sub-elite players were involved. Players were allocated to a group (elite or sub-elite) based on where they played the majority of matches. Any observation of a player competing outside of their regular level was not included in the analysis. Match location varied based on the football clubs' fixture over both seasons while training sessions were conducted on a standard Australian football ground. Differences based on playing positions (midfielders, nomadics, deeps, ruckmen) were determined within elite, and within sub-elite playing levels. Analysis between elite and sub-elite for corresponding positions was also conducted. Training analysis was compared between drills, and to elite and sub-elite matches.

5.1.2.3 MinimaxX Accelerometer:

The MinimaxX 2.0 device is 88x50x19 mm, and weighs 67 grams (Catapult Innovations, Scoresby, Victoria). The accelerometer component built into the device is a tri-axial sensor (Kionix: KXP94), which has a full-scale output range of ± 6 g, and an operating temperature range of -40 to 85 °C. The inbuilt power supply has a measuring duration of 5 hours at a sampling rate of 100 Hz.

During match and training activity, the MinimaxX devices were located at the posterior side of the upper torso and held in place using a customized vest designed to minimise movement between the device and the body. The accumulated data from all three axes (anterior-posterior [front to back], medio-lateral [side to side] and cranio-caudal [up and down]) of the MinimaxX was integrated to formulate the vector magnitude. The manufacturers of the MinimaxX accelerometers have titled this

parameter 'Player Load'. The Player load variable has previously been established as highly reliable ($CV = <2\%$) (Boyd *et al.*, 2011). Two variations of this parameter were used to describe external load; 1.) Data from all three vectors which represents total external load and is strongly related to locomotor distance (PL^{3D}) (Boyd *et al.*, 2010); and 2.) Data from all vectors when movement was $<2 \text{ m}\cdot\text{s}^{-1}$ which was used to describe low velocity external load (PL^{SLOW}). Proprietary software (Logan Plus, Version 4.4) was used to download the accelerometer information for analysis. Once downloaded, match and training data was cropped so that only time spent participating in AF activity was included (i.e. all rest periods were removed). Each training drill within a session was analysed separately. All data was expressed per minute of activity time.

5.1.2.4 Positional Analysis:

Players were allocated to one of the following positional categories based on their role within the team:

Midfielders – players who predominantly play as part of the midfield and whose role is to be near the ball at all times and who don't spend time in other positions;

Nomadic – players that are categorised as attackers or defenders, but additionally contribute through the midfield;

Deep forwards and defenders (deeps) – key position players who spend the majority of their time inside the attacking or defensive zones of the ground; and

Ruckmen – players that contest the ruck duels at the centre bounce and around the ground, often resting forward between stints of ruck play.

Although there are slight variations in positional roles and game style between teams, the classifications used in this investigation are relatively standard across most teams.

Positional categories were consistent across the elite and sub-elite matches, and training analysis.

5.1.2.5 Training analysis:

Table 12 presents descriptive information for each of the training drills. More specifically this table presents the number of observations from each playing position, and the number of different players from each position.

Training drills were classified as the following:

Closed skill (closed) – drills that incorporate specific skills of AF such as kicking, handballing and marking (catching the ball) in a pre-determined format that did not require decision making (Farrow *et al.*, 2008),

Open Skill (open) – drills that incorporate specific skills of AF with external pressures to simulate decision making, however do not contain the full competitive requirements of match practice (Farrow *et al.*, 2008),

Tactical – drills that incorporated the specific skills of AF in an unpredictable scenario designed to stimulate the tactical knowledge of the player relative to their own, and the oppositions style of play,

Match practice – the simulation of a match scenario in the training environment.

Small-sided games (SSG) – skill-based training games that are modified to stimulate competitive match scenarios. For this investigation all small-sided games were handball based activities used by most AFL clubs in their training. For details of the SSG protocol, see section 4.1.2.2.

The analysis of closed, open and small-sided games training drills grouped all players together as there were no position specific requirements. The tactical and match practice training drills were analysed separately for each position. The reliability of

each training drill was determined by assessing 3 players from each playing position over two consecutive training sessions. Reliability *CV%* are presented in table 12.

Table 12. Descriptive data and reliability outcomes from the training drill analysis. An observation represents the number of samples collected for each drill within each position, regardless of the individual player.

	Reliability (<i>CV%</i>)	Number of observations per drill/match				Number of players			
		Midfielders	Nomadics	Deeps	Ruckmen	Midfielders	Nomadics	Deeps	Ruckmen
Closed skill	5.0	102	174	96	40	7	13	8	6
Open skills	6.8	31	174	34	17	7	12	9	6
Tactical	5.9	57	51	49	27	7	13	9	6
SSG	3.2	51	72	51	19	8	13	9	4
Match practice	6.4	52	102	41	17	7	13	8	5
Elite matches	-	96	95	30	13	8	13	5	3
Sub-elite matches	-	44	74	25	17	12	16	12	6

5.1.2.6 *Statistical Analysis:*

Parameters were log transformed to reduce bias due to non-uniformity of error and analysed using a customised excel spreadsheet (Hopkins, 2000b; Hopkins, 2007). Differences between playing positions within elite and sub-elite (Eg. elite midfielders vs elite deeps), between playing level within playing position (Eg. elite midfielders vs sub-elite midfielders), between training drills, and between training and matches were evaluated using the effect size (*ES*) statistic with upper and lower 95% confidence intervals (*CI*) and percentage change to determine the magnitude of any difference displayed (Batterham & Hopkins, 2006). Any difference between training and matches that was below the reliability *CV%* was categorised as an unclear outcome. A difference was classified as substantial where there was a $\geq 75\%$ likelihood that the mean effect was greater than or equal to a small effect size (± 0.2) (Batterham & Hopkins, 2006). The magnitude of difference was classified as small 0.2 to 0.6; moderate 0.6 to 1.2; large 1.2 to 2.0; and very large 2.0 to 4.0. Effects with less certainty were classified as trivial and where the $\pm 95\%CI$ of the *ES* crossed the boundaries of -0.2 and 0.2, the effect was reported as unclear.

5.1.3 *Results*

Descriptive data on PL^{3D} and PL^{SLOW} from elite; and sub-elite matches are presented in table 13. Descriptive PL^{3D} and PL^{SLOW} from training are presented in table 14. Differences between training and elite, and sub-elite matches are also presented in table 15 and 16.

5.1.3.1 *Positional comparisons in matches:*

The elite midfielders had higher PL^{3D} compared to nomadics (8.8%; 0.59 ± 0.24), and deeps (34.2%; 1.83 ± 0.39). The elite nomadics (27.9%; 1.42 ± 0.39) and ruckmen (37.2%; 1.27 ± 0.51) were higher than deep. The elite midfielders (13.5%; 0.65 ± 0.37),

nomadics (11.7%; 0.55 ± 0.36) and ruckmen (19.5%; 0.83 ± 0.50) were higher than deeps for PL^{SLOW} .

The sub-elite midfielders recorded higher PL^{3D} compared to nomadics (14.0%; 1.08 ± 0.30), deeps (31.7%; 2.61 ± 0.42) and rucks (19.9%; 0.81 ± 0.55). Sub-elite nomadics (20.6%; 1.45 ± 0.38) and ruckmen (17.4%; 0.57 ± 0.55) were higher than deep. No differences were evident between sub-elite positions for PL^{SLOW} .

5.1.3.2 Elite vs sub-elite matches:

Elite midfielders, nomadics, and rucks displayed higher PL^{3D} compared to the sub-elite equivalent. Similarly, elite midfielders, nomadics, and rucks displayed higher PL^{SLOW} compared to the sub-elite (Table 13).

Table 13. Descriptive $PL^{3D} \cdot \text{min}^{-1}$ and $PL^{SLOW} \cdot \text{min}^{-1}$ from elite and sub-elite matches. Differences were classified as substantial when there was a $\geq 75\%$ likelihood of the effect being greater than the smallest worthwhile change estimated as $0.2 \times$ between subject standard deviation, and classified as small 0.2 to 0.6; moderate 0.6 to 1.2; large 1.2 to 2.0; and very large 2.0 to 4.0.

	Playing position	Elite matches	Sub-elite matches	Difference (%)	Effect size $\pm 95\%$ CI	Qualitative descriptor
$PL^{3D} \cdot \text{min}^{-1}$	Midfielders	16.03 ± 4.21	15.07 ± 2.02	7.8%	0.59 ± 0.29	Small
	Nomadics	14.96 ± 2.35	13.03 ± 2.36	12.9%	0.89 ± 0.25	Moderate
	Deeps	11.01 ± 2.63	10.34 ± 1.59	4.6%	0.20 ± 0.43	Unclear
	Ruckmen	14.91 ± 3.30	12.78 ± 5.49	18.0%	0.67 ± 0.59	Moderate
$PL^{SLOW} \cdot \text{min}^{-1}$	Midfielders	4.19 ± 1.33	3.88 ± 0.88	9.4%	0.52 ± 0.30	Small
	Nomadics	4.21 ± 0.90	3.69 ± 0.65	11.3%	0.68 ± 0.25	Moderate
	Deeps	3.75 ± 0.90	3.81 ± 1.56	0.1%	0.00 ± 0.44	Unclear
	Ruckmen	4.41 ± 0.78	3.81 ± 0.81	14.1%	0.84 ± 0.61	Moderate

5.1.3.3 Training analysis:

In the small-sided games, PL^{3D} was higher than match practice (14.6%; 0.37 ± 0.16), tactical (87.7%; 1.36 ± 0.15), open (48.8%; 1.04 ± 0.18), and closed (43.1%; 1.05 ± 0.15) drills. Match practice had higher PL^{3D} than closed (24.9%; 0.72 ± 0.14), open (29.9%; 0.73 ± 0.18) and tactical (63.9%; 1.12 ± 0.15) drills. Tactical were lower than closed (-23.8%; 0.65 ± 0.14) and open (-20.7%; 0.51 ± 0.16). No difference was present between closed and open drills.

The small-sided games demonstrated higher PL^{SLOW} compared to match practice (84.7%; 1.49 ± 0.16), tactical (67.7%; 1.16 ± 0.15), open (103.3%; 1.77 ± 0.17) and closed (81.3%; 1.38 ± 0.14). Match practice had higher PL^{SLOW} compared to open (10.1%; 0.31 ± 0.17), and lower compared to tactical (9.2%; 0.26 ± 0.15). Tactical drills were higher than closed (8.1%; 0.20 ± 0.13) and open (21.2%; 0.55 ± 0.16). Closed were higher than open (10.8%; 0.34 ± 0.15).

Table 14. Descriptive $PL^{3D} \cdot \text{min}^{-1}$ and $PL^{SLOW} \cdot \text{min}^{-1}$ from training.

Training drill	Playing position	$PL^{3D} \cdot \text{min}^{-1}$		$PL^{SLOW} \cdot \text{min}^{-1}$	
Closed skill	All	10.84	± 2.72	3.39	± 1.54
Open skill	All	10.46	± 3.37	3.03	± 0.9
SSG	All	15.52	± 4.95	6.07	± 3.39
Tactical	Midfielders	9.51	± 3.26	4.23	± 1.42
	Nomadics	8.06	± 3.24	3.58	± 1.35
	Deeps	8.73	± 3.26	3.49	± 1.58
	Ruckmen	5.87	± 2.7	3.27	± 1.16
Match practice	Midfielders	15.34	± 2.84	3.29	± 0.69
	Nomadics	14.30	± 2.89	3.43	± 2.52
	Deeps	11.68	± 3.34	3.20	± 2.59
	Ruckmen	10.62	± 2.57	3.27	± 0.53

5.1.3.4 *Matches vs Training:*

For elite players, only small-sided games and match practice were able to equal or exceed total loads (PL^{3D}) of matches for most positions. Interestingly, for elite deeps PL from small-sided games greatly exceeded PL^{3D} from matches. For elite ruckmen, match practice had a much lower PL^{3D} than matches. Both closed and open skill drills recorded lower PL^{3D} compared to matches for midfielders, nomadic players and ruckmen, with no clear difference for deeps. Regardless of playing position for elite players, tactical drills were lower than PL^{3D} in matches (Table 15).

The small-sided games drills substantially exceeded low-velocity loads (PL^{SLOW}) from matches for all playing positions. Match practice recorded lower PL^{SLOW} compared to matches for all positions. Tactical drills had equivalent PL^{SLOW} to matches for elite midfielders and deeps but were insufficient for nomadics and rucks. Both closed and open skill drills did not simulate the same PL^{SLOW} as matches (Table 16).

Total load (PL^{3D}) from the small-sided games corresponded with sub-elite matches for all positions, with nomadics, deeps and ruckmen substantially exceeding matches. Similarly, PL^{3D} from match practice was equivalent to sub-elite matches for all positions, although in a divergence from elite player's nomadics and deeps substantially exceeded match loads. Tactical, open, and closed drills again did not equate to match loads at sub-elite level aside from the deep position players (Table 15).

Low-locomotor activity (PL^{SLOW}) during small-sided games substantially exceeded matches across all positions. Match practice was lower for PL^{SLOW} from sub-elite matches for midfielders and ruckmen. As with elite ruckmen, PL^{SLOW} was lower for tactical compared to matches for sub-elite. Midfielders were higher during tactical

drills compared to matches. Open and closed drills again were lower than matches for PL^{SLOW} (Table 16).

Table 15. Percentage difference, $ES \pm 95\%CI$, and qualitative descriptor for $PL^{3D} \cdot \text{min}^{-1}$ between training drills and matches at elite and sub-elite level. Differences were classified as substantial when there was a $\geq 75\%$ likelihood of the effect being greater than the smallest worthwhile change estimated as $0.2 \times$ between subject standard deviation.

Drill	Position	Elite			Sub-elite		
		Difference (%)	Effect Size \pm 95% CI	Qualitative descriptor	Difference (%)	Effect Size \pm 95% CI	Qualitative descriptor
Closed Skill	Midfielders	↓33.1%	-1.81±0.15	Large	↓27.1%	-1.48±0.17	Large
	Nomadics	↓26.5%	-1.37±0.15	Large	↓15.6%	-0.77±0.16	Moderate
	Deeps	↑1.3%	0.05±0.32	Unclear	↑6.5%	0.28±0.26	Unclear
	Ruckmen	↓25.8%	-1.23±0.42	Large	↓5.4%	-0.21±0.41	Unclear
Open Skill	Midfielders	↓35.7%	-1.56±0.20	Large	↓29.9%	-1.28±0.21	Large
	Nomadics	↓29.4%	-1.22±0.20	Large	↓18.9%	-0.74±0.21	Moderate
	Deeps	↓2.6%	-0.08±0.31	Unclear	↑2.4%	0.08±0.26	Unclear
	Ruckmen	↓28.6%	-1.13±0.37	Moderate	↓9%	0.29±0.37	Unclear
SSG	Midfielders	↓2.7%	-0.10±0.17	Unclear	↑4.4%	0.15±0.18	Unclear
	Nomadics	↑6.9%	0.23±0.17	Unclear	↑20.7%	0.63±0.18	Moderate
	Deeps	↑47.4%	1.15±0.29	Moderate	↑52.4%	1.39±0.24	Large
	Ruckmen	↑7.9%	0.25±0.35	Unclear	↑35.4%	0.90±0.35	Moderate
Tactical	Midfielders	↓41.4%	-1.94±0.30	Large	↓36.4%	-1.69±0.31	Large
	Nomadics	↓45.4%	-1.37±0.23	Large	↓37.4%	-1.06±0.23	Moderate
	Deeps	↓18.4%	-0.53±0.32	Small	↓14.5%	-0.45±0.30	Small
	Ruckmen	↓59.8%	-2.28±0.48	Very Large	↓48.8%	-1.61±0.47	Large
Match Practice	Midfielders	↓5.4%	-0.31±0.30	Unclear	↑2.6%	0.15±0.33	Unclear
	Nomadics	↓3.1%	-0.13±0.23	Unclear	↑11.2%	0.43±0.24	Small
	Deeps	↑9.1%	0.24±0.35	Unclear	↑14.4%	0.40±0.34	Small
	Ruckmen	↓27.3%	-1.35±0.60	Large	↓7.4%	-0.29±0.57	Unclear

Table 16. Percentage difference, $ES \pm 95\% CI$, and qualitative descriptor for $PL^{SLOW} \cdot \text{min}^{-1}$ between training drills and matches at elite and sub-elite level. Differences were classified as substantial when there was a $\geq 75\%$ likelihood of the effect being greater than the smallest worthwhile change estimated as $0.2 \times$ between subject standard deviation.

Drill	Position	Elite			Sub-elite		
		Difference (%)	Effect Size $\pm 95\% CI$	Qualitative descriptor	Difference (%)	Effect Size $\pm 95\% CI$	Qualitative descriptor
Closed Skill	Midfielders	↓19.2%	-0.72±0.15	Moderate	↓10.0%	-0.36±0.19	Small
	Nomadics	↓17.6%	-0.65±0.15	Moderate	↓7.4%	-0.27±0.14	Small
	Deeps	↓7.1%	-0.23±0.26	Unclear	↓3.2%	-0.12±0.18	Unclear
	Ruckmen	↓22.1%	-0.87±0.30	Moderate	↓9.3%	-0.33±0.28	Small
Open Skill	Midfielders	↓27.9%	-1.33±0.21	Large	↓19.8%	-0.89±0.25	Moderate
	Nomadics	↓26.5%	-1.23±0.21	Large	↓17.4%	-0.82±0.21	Moderate
	Deeps	↓17.2%	-0.69±0.32	Moderate	↓13.7%	-0.65±0.26	Moderate
	Ruckmen	↓30.6%	-1.53±0.57	Large	↓19.2%	-0.86±0.36	Moderate
SSG	Midfielders	↑44.7%	1.02±0.17	Moderate	↑63.1%	1.33±0.20	Large
	Nomadics	↑47.5%	1.07±0.18	Moderate	↑68.4%	1.45±0.17	Large
	Deeps	↑66.3%	1.33±0.25	Large	↑75.9%	1.60±0.19	Large
	Ruckmen	↑39.4%	0.93±0.27	Moderate	↑64.4%	1.35±0.26	Large
Tactical	Midfielders	↑0.8%	0.03±0.29	Unclear	↑11.3%	0.41±0.32	Small
	Nomadics	↓13.2%	-0.39±0.23	Small	↓2.2%	-0.06±0.23	Unclear
	Deeps	↓4.3%	-0.15±0.34	Unclear	↓0.1%	0.00±0.30	Unclear
	Ruckmen	↓25.0%	-1.01±0.49	Moderate	↓12.7%	-0.46±0.48	Small
Match Practice	Midfielders	↓21.7%	-1.21±0.29	Large	↓13.5%	-0.71±0.33	Moderate
	Nomadics	↓16.7%	-0.62±0.23	Moderate	↓6.1%	-0.23±0.24	Unclear
	Deeps	↓12.2%	-0.40±0.36	Small	↓8.3%	-0.31±0.34	Unclear
	Ruckmen	↓25.0%	-1.70±0.61	Large	↓12.6%	-0.75±0.57	Moderate

5.1.4 Discussion

This study was the first to quantify external load in Australian football matches and training using accelerometers. The first major finding from this investigation was that accelerometers detected differences in external load between activities (training drills and matches), playing positions, and from elite to sub-elite competition. Secondly, PL^{3D} displayed similar trends to earlier GPS findings in elite level Australian football matches between positions. It also appears that when low-velocity activity is measured using the PL^{SLOW} parameter, different outcomes are presented. This finding highlights the potential application of accelerometers to measure loads at low-velocities that are currently underestimated. Other major findings were that deep positions did not differ in either parameter between elite and sub-elite, and that small-sided games were the only training drill to provide sufficient external loads compared to matches for all playing positions.

Total external load measured using the PL^{3D} parameter detected differences between positions in Australian football games. This aligns with previous GPS analysis where locomotor distance was highest in midfielders followed by nomadics, ruckmen and deeps (Brewer *et al.*, 2010). Given the strong relationship between total distance from GPS and PL^{3D} ($r = 0.94$) (Aughey, 2011b), these findings suggest that PL^{3D} may be an effective measure of locomotor load in AF matches when other common time-motion analysis methods are unavailable. Different patterns were displayed between playing positions for PL^{SLOW} . When locomotor activity above $2 \text{ m}\cdot\text{s}^{-1}$ was removed, ruckmen displayed higher external loads compared to all other positions. This trend is similar to previous research where ruckmen perform greater quantities of contact-related activities compared to all other playing positions (ruckmen: 173 ± 36 ; midfielders: 119 ± 17 ; centre half forwards and backs: 92 ± 20 ; small forwards and backs: 75 ± 11 ;

and full forwards and backs: 71 ± 19) (Dawson *et al.*, 2004c). Based on these findings it appears that PL^{SLOW} provides alternative information compared to PL^{3D} and time-motion analysis. This finding suggests that with further development, accelerometers may have the potential to measure the load of activities (i.e. agility type movements and physical contact) that are currently misrepresented by time-motion analysis. The low PL^{3D} and PL^{SLOW} for deeps may be associated with reduced running volumes and involvement in play as they are most often required to occupy space in the deep attacking and defensive zones only.

Patterns in sub-elite matches were similar for PL^{3D} with midfielders displaying the highest total external load followed by nomadics, ruckmen and deeps. It appears that the differential in total external load between sub-elite midfielders and other sub-elite positions is larger in comparison to elite players. This may be a reflection of the differing strategies between playing level. For example, in some cases midfielders are required to play larger percentages of game time compared to other positions at sub elite level. On occasions midfielders will rest in the forward or defensive positions before re-entering the midfield.

Elite midfielders, nomadics and rucks, produced higher total external loads compared to sub-elite. This may be a reflection of the higher locomotor activity at the elite level compared to sub-elite (Brewer *et al.*, 2010). Superior running loads in elite matches may be relate to the training status and maturation level of players within each competition (Brewer *et al.*, 2010). Players at the sub-elite level are often younger players who are progressing towards elite level. Running ability may be reduced as a result of these factors. Additionally, a reduction in skill level may also contribute to more contested scenarios in sub-elite matches and less running activity, which may in turn reduce total external loads (PL^{3D}). The PL^{SLOW} parameter was also higher for

elite midfielders, nomadics and deeps, suggesting that the external loads at low-velocities are greater. Possible explanations for this may be related to anthropometrical and strength differences between playing levels (Young *et al.*, 2005), resulting in increased forces being applied to the body.

The only training drill that equalled or exceeded the external loads of matches was small-sided games. Despite GPS analysis demonstrating similar running distances per minute between small-sided games (116-130 m.min⁻¹) (Boyd *et al.*, 2010) and matches (119-135 m.min⁻¹) (Aughey, 2010; Brewer *et al.*, 2010), findings from PL^{SLOW} indicated substantially higher low-velocity external loads in small-sided games compared to matches. This finding illustrates the difficulty in measuring low-velocity activity with time-motion analysis systems. These activities may be better represented by accelerometer-derived measures.

Tactical drills simulated substantially lower total external load (PL^{3D}) compared to matches. However, midfielders and deeps at both elite and sub-elite levels displayed similar PL^{SLOW} values in tactical drills suggesting that low-velocity activities are equivalent to matches. We know that Australian football activities with lower locomotor activity are physiologically less demanding (Boyd *et al.*, 2010). Therefore tactical drills may provide a specific training stimulus without the damaging demands of the running component for these positions. Unfortunately the ruckmen at both elite and sub-elite did not replicate low-velocity locomotor loads during tactical drills. This is a critical observation for the ruckmen as they engage in higher levels of low velocity-locomotor activity in matches compared to other position. The specificity principle suggests that this component requires greater emphasis in training, however this may have been a planned protective strategy to minimise the accumulation of load leading into matches.

Match practice, which becomes a major component of skill and tactical preparation in the later phase of pre-season provided sufficient total external load as indicated by PL^{3D} compared to matches for midfielders, nomadics and deeps. Ruckmen did not attain PL^{3D} values similar to those in matches. This is supported by findings of substantially longer rest periods for ruckmen during training (Dawson *et al.*, 2004c) Findings from PL^{SLOW} suggested that match practice failed to replicate the low-velocity loads of matches across all positions. Again, this may be a planned safety mechanism to prevent impact injuries. Alternatively it may also represent a deficiency in contested situations at training performed in congested spaces. Previous research in American football suggests that contested situations need to be trained to ensure that skeletal muscles can adapt to repeated traumas (Hoffman *et al.*, 2005). Firstly, small-sided games may provide suitable stimulus for this ‘contact adaptation’ theory, whereas the potential shortage of physical contact in match practice may inadequately prepare the players for the blunt forces associated with matches.

As this is the only investigation to date assessing accelerometers in Australian football matches, further investigation is required to develop a greater understanding of how these devices can be utilised. Current parameters such as PL^{SLOW} are limited as satellite access is required to filter the accelerometer data at specific locomotor velocities. Alternative algorithms based purely on accelerometer data would greatly assist with sports played indoors. Additionally, understanding the mechanics of match specific skills such as tackling, may aid the development of systems that can assess the frequency and magnitude of specific actions such as tackling and bumping which involve physical contact.

5.1.4.1 Practical applications

Accelerometers are a useful tool for differentiating external loads in training and matches. Accelerometers have the potential to provide a supplementary measure of low-velocity external load that may be underestimated by current time-motion analysis methods. Small-sided games are an excellent training modality for replicating or often exceeding the external loads of Australian football matches. Particularly for contested activities that are performed in congested spaces at lower-velocities.

5.1.5 Conclusions

The PL^{3D} parameter displayed similar trends to GPS derived data, suggesting that accelerometers may be an easily administered, alternative measure of locomotor activity during indoor activity or in the absence of time-motion analysis. Different outcomes from PL^{SLOW} suggest that accelerometers are a potential measure of low-velocity activity that is currently underestimated. Furthermore, similar patterns between the number of contact-based activities performed within each playing position and low-velocity loads from PL^{SLOW} , indicate that accelerometers may be a potential measure of physical contact activity with further research.

CHAPTER 6. GENERAL DISCUSSION

6.1 Introduction

This thesis investigated the application of accelerometers in the contact team sport, Australian football. This collection of studies began with multiple reliability assessments of the MinimaxX accelerometer for measuring external load (Player load). A concurrent validity assessment followed, which determined the link between accelerometer-derived load parameters (Player load), and locomotor, internal (physiological), perceptual, and physical performance responses, using correlation analysis. In addition, Player load was compared between two modes of Australian football small-sided game training drills (non-contact and contact). The last study compared Player load from matches and training, across designated playing positions, and between elite and sub-elite playing levels. The results from each study have been discussed in the previous chapters. This section will provide an integrated discussion of findings from the thesis.

6.2 Accelerometers as a measurement tool for team sports analysis

Prior to the current research project only two investigations had utilised the MinimaxX accelerometer (Gabbett *et al.*, 2010; Montgomery *et al.*, 2010). Neither of these studies established the reliability of the MinimaxX accelerometer, or the Player load variable. Study one of this thesis was the first investigation of MinimaxX accelerometer reliability (Chapter 3).

6.2.1 Reliability assessments

Earlier models of accelerometers were utilised as a tool for measuring physical activity in the general population. In contrast, the MinimaxX accelerometer was developed as an analysis tool for competitive sports. The intensity of activity in team

sports far exceeds that of daily living activities, therefore reliability testing required more rigorous protocols based on the target environment. Previous research in a laboratory setting employed acceleration ranges of $\leq 1.27 g$ (Nichols *et al.*, 1999; Esliger & Tremblay, 2006; Krasnoff *et al.*, 2008; Van Hees *et al.*, 2009). In comparison, the first study of this thesis subjected the MinimaxX to substantially higher acceleration rates (0.5 to 3.0 g) in a laboratory setting, which were more representative of Australian football activity. Despite these higher acceleration rates, the MinimaxX accelerometer ($CV= 0.91$ to 1.05%), still displayed superior reliability compared to other models of accelerometers ($CV= 0.20$ to 56.20%) (Nichols *et al.*, 1999; Esliger & Tremblay, 2006; Krasnoff *et al.*, 2008; Van Hees *et al.*, 2009).

Similarly, the second section of MinimaxX reliability testing in this thesis also provided an activity stimulus that was of greater intensity than previous accelerometer reliability research. This thesis utilised specific free-living conditions from actual Australian football matches such as walking, running sprinting, agility-based activity and episodes of physical contact. In comparison, previous accelerometer reliability tests in free-living conditions, utilised daily tasks such as walking, running, stair walking, and repeated sit to stand tasks (Powell & Rowlands, 2004; Vanhelst *et al.*, 2010). Maximal oxygen consumption values from previous research indicate that the intensity of team sports activity ($>45 \text{ ml.kg}^{-1}.\text{min}^{-1}$) (Coutts *et al.*, 2003; Impellizzeri *et al.*, 2005; Montgomery *et al.*, 2010) is greater than that of daily activity tasks ($<30 \text{ ml.kg}^{-1}.\text{min}^{-1}$) (Vanhelst *et al.*, 2010). Despite the considerable difference in exercise intensity, again the MinimaxX accelerometer had higher between device reliability ($CV= 1.90\%$) (Study 1, Chapter 3), compared to other models ($CV= 1.79$ to 14.4%) (Nichols *et al.*, 1999; Powell & Rowlands, 2004). This again highlights the superior

sensor technology of the MinimaxX accelerometers compared to previously researched devices.

6.2.2 Efficacy of accelerometers to measure external load in contact team sports

Numerous researchers have stressed the importance of establishing the reliability of a measure when analysing performance (Hopkins, 2000a; Cormack *et al.*, 2008c). Equally, the ability of a system to detect 'real' or practically meaningful differences has also been discussed on several occasions (Hopkins, 2000; Pyne, 2003; Cormack *et al.*, 2008c; Jennings *et al.*, 2010b). As discussed in chapter three, determining the smallest practically important difference in elite athletic performance can help to interpret outcomes more effectively. In some cases the measurement error of a device (noise) is greater than the smallest practically important difference (signal). Therefore only differences in performance that are above the error of the measuring devices can be assumed to be real. Small practically important differences that are below the measurement error of the device may be overlooked (Hopkins, 2000a; Cormack *et al.*, 2008c). The measurement error ($CV = <1.90\%$) of the MinimaxX accelerometer from reliability testing was substantially less than the smallest practically important difference, which was determined using Australian football activity ($CV = 5.88\%$). This finding confirms that the MinimaxX accelerometer is capable of detecting the smallest worthwhile difference in an Australian football setting. A similar assessment of GPS analysis in Australian football reported that the measurement error was greater than the smallest practically important difference (Jennings *et al.*, 2010a). The sensitivity of GPS also decreased over shorter distances at high velocities. With the game of Australian football evoking repeated high intensity activity bouts (Aughey, 2011b), these findings would suggest that meaningful outcomes are difficult to

determine using GPS (Jennings *et al.*, 2010a). This thesis was thus the first to assess the efficacy of accelerometers using the signal to noise approach.

6.3 External load analysis in team sports.

The results from chapter 3 suggest that MinimaxX accelerometers are both reliable and sensitive for measuring team sports activity. Based on these findings comparisons can be made across sports. This thesis implemented a system that was previously used in research assessing the external loads of rugby matches, and basketball training and matches using accelerometers (Cunniffe *et al.*, 2009; Montgomery *et al.*, 2010). Only comparisons between Australian football and basketball were able to be discussed. The rugby analysis used an alternative accelerometer model (SPI Elite; GPSports Systems, Canberra, Australian Capital Territory, Australia). In addition, the researchers did not supply information related to the calculation of this external load parameter.

6.3.1 Comparison across sports

External load during Australian football matches and various training drills was, as expected, different to basketball. Scrimmages in basketball can be compared to Australian football small-sided games as both are modified versions of game play. External load from basketball scrimmages expressed per minute ($20.5 \text{ load}\cdot\text{min}^{-1}$) was ~24% higher compared to Australian football ($15.5 \text{ load}\cdot\text{min}^{-1}$) equivalents. Similarly in matches, basketball load ($30.0 \text{ load}\cdot\text{min}^{-1}$) exceeded Australian football load (12.8 to $14.2 \text{ load}\cdot\text{min}^{-1}$) by ~55% (Figure 6.1).

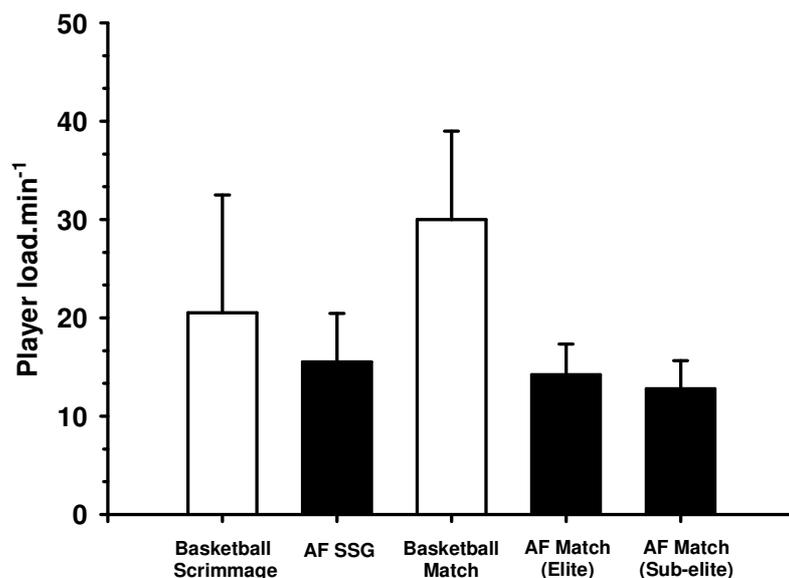


Figure 6.1. Accelerometer-derived external load values from modified games, and actual competitive matches in basketball, and Australian football.

One factor that may contribute to higher external load in basketball is the frequency of efforts compared to Australian football. Efforts above a jogging intensity in basketball occur 7.5 times per minute (Abdelkrim *et al.*, 2007), compared to Australian football which occur 4.8 times per minute (Dawson *et al.*, 2004b). This may induce more frequent acceleration and deceleration activity and greater external loads on the athlete during basketball. A study comparing the mechanical load of an intermittent and steady-state running protocol supports the concept that acceleration and deceleration activity elicit higher forces and increase external loads (Greig *et al.*, 2006). Electromyography was utilised to compare the mechanical load on the lower body during each running protocol. There was greater muscle recruitment during the intermittent protocol, suggesting that structures are under higher mechanical loads compared to steady state activity (Greig *et al.*, 2006). This finding suggests that common time-motion analysis variables such as total locomotor distance may underestimate the load imposed on the athlete during invasion sports such as

basketball. Alternatively, accelerometer-derived external loads may be a proxy measure of external load that is more effective in comparison to other methods such as GPS, during intermittent activity that elicits frequent accelerations and decelerations in confined spaces.

Smaller playing areas in basketball (~28 x 15 m), compared to Australian football (~175 x 120 m) may also contribute to the increase in external load during basketball activity. Field dimensions and player numbers are substantially larger in Australian football compared to basketball. As field dimensions and player numbers increase, involvement in play and ball possession decreases, which in turn may reduce the intensity of team sport activity (Balsom, 1999; Rampinini *et al.*, 2007b). This theory is supported by the increase in energy expenditure (Reilly & Ball, 1984), HR and $\dot{V}O_2$ (Hoff *et al.*, 2002) when participants are in possession of the ball during team sports. Based on these findings it may be proposed that larger field dimensions and player numbers in Australian football reduce each individual's involvement in play, which may decrease the intensity of the activity and therefore result in lower load.

The smaller playing area in basketball decreases the space for movement and increases congestion for players. As a consequence, instances of directional change, possibly as an evasive tactic in congested areas occur repeatedly. This may amplify movement and subsequently forces in the medio-lateral plane in basketball, compared to Australian football which allows for greater areas in which to move.

Playing surfaces may also be a contributing factor to the higher load in basketball compared to the values for Australian football reported in this thesis. Although no comparison between grass and wooden surfaces exist in the literature, braking forces in the antero-posterior plane during running ($3.8 \text{ m}\cdot\text{s}^{-1}$) were higher on a basketball court (0.40 ± 0.10 times body weight) (McClay *et al.*, 1994), compared to three

different natural grass surfaces (0.20 ± 0.08 times body weight) (Stiles *et al.*, 2011).

Forces may be absorbed more by the grass surface of Australian football compared to the wooden floors of basketball.

6.4 Contact vs non-Contact activity

Only two other investigations have compared non-contact and contact activity in sport. The first of these did not involve team sports activity, instead assessing the difference between shadow (non-contact) and contact boxing (Zuliani *et al.*, 1985). The second, which compared a non-contact and contact simulated team sports circuit, was published in the final stages of this thesis and was not able to be included in the literature review (Singh *et al.*, 2011). Rather it was seen as more appropriate to discuss the findings in comparison to the current thesis (Study 2, Chapter 4).

Moderately trained recreational athletes participated in two modified versions of a simulated team sports circuit (as developed by Bishop & Spencer, 2004). Both conditions followed the same protocol as described in section 2.1.5, but the contact condition incorporated additional activities such as tackling and bumping. The activity duration was 4 x 15 repetitions of the circuit with 5 minutes recovery between each period. Perceptual measures, internal responses, and physical performance tests were used to determine differences between the non-contact and contact team sports circuits (Singh *et al.*, 2011).

6.4.1 Perceptual comparisons

Perceived soreness from the small-sided games in this thesis (Study 2, Chapter 4), compared to the team sport circuit conflicted. The contact team sport circuit induced greater perception of soreness immediately post ($\sim 150\%$; $p < 0.05$) and at 24 hours post ($\sim 100\%$; $p < 0.05$) compared to non-contact. Study two of this investigation found that non-contact small-sided games had greater soreness than contact both

immediately post (44.4%; $ES= 0.63\pm 0.53$) and at 24 hours post (69.8%; $ES= 1.28\pm 0.69$) (Chapter 4, Section 4.1.3). Elite professional Australian football players are exposed to contact-based activity on a week to week basis. In comparison, the moderately trained athletes used in the alternative study (Singh *et al.*, 2011), some of who competed in non-contact sports, may express elevated feelings of soreness when required to participate in contact-based activity that may be an unaccustomed form of physical stress.

6.4.2 Biological comparisons

Blood markers of muscle damage were also measured in both investigations. Myoglobin concentration ([Mb]) was substantially higher immediately post (~170%) and at 24 hours post (~50%) for the team sport circuits, compared to the small-sided games. This may be a product of the previously discussed 'contact adaptation' theory (Hoffman *et al.*, 2005) (Study 3; Chapter 5), with elite Australian football players being exposed to, and potentially adapting to contact-based activity, compared to the moderately trained participants of the team-sport circuit study. However, these differences are more likely to be associated with the longer duration of activity in the team sport circuit (60 minutes), compared to the small-sided games (12 minutes). The effect of activity duration is highlighted when [Mb] from these two investigations was standardised per minute of activity time. The small-sided games (~5.0 ng.mL.min⁻¹) were higher compared to the team sports circuits (~3.0 ng.mL.min⁻¹). This discovery emphasises the need for team sports analysis to be conducted relative to activity time. Another interesting observation from the non-contact and contact comparisons was the time-course changes following activity. Both the team sport circuit (Singh *et al.*, 2011) and small-sided games (Study 2, Chapter 4) studies displayed similar trends. Post-activity [Mb] remained elevated above baseline levels following non-contact,

whereas contact returned to pre-levels. The findings from a study of non-contact and contact boxing activity indicated differently with contact activity eliciting higher [Mb] (Zuliani *et al.*, 1985). As discussed in chapter 4, this disparity may be related to higher eccentric loading in the vertical plane of movement from larger running volumes in the team-sport circuit and small-sided games studies. In contrast, elevated [Mb] following boxing activity, are more likely to be a bi-product of blunt forces to the body, rather than running related load.

6.4.3 *Jump testing comparisons*

Jump testing performance was also a feature of both the team-sport circuit and small-sided games investigations. In the current thesis, jump performance following the non-contact and contact small-sided games did not differ (Chapter 4). In contrast, results from the team sports circuits indicated reductions in jump height following contact conditions. The shorter duration of activity from the small-sided games may not have induced enough fatigue, instead having a potentiating effect, with jump performance improving. In comparison the differences seen in the team sports circuits between non-contact and contact may be a consequence of longer activity durations.

6.4.4 *Methodological comparisons*

The activity type and methodology was substantially different in study 2 (Chapter 4) of this thesis, compared to the research using the team-sports circuit (Singh *et al.*, 2011). The team sport circuit study standardised the volume of locomotor activity (4 x 15 repetitions of the circuits) between the two conditions, then subsequently added the activities of physical contact to one condition. In turn, this increased the time taken to complete each circuit, which may contribute to the increased demands for the contact condition. In study two of this thesis, the activity time was standardised (4 x 3 minutes) across both small-sided games conditions.

6.5 Key findings / Practical applications

6.5.1 Study 1: The reliability of MinimaxX accelerometers for measuring physical activity in Australian football

Key findings:

1. MinimaxX accelerometers display high reliability within and between devices, in both a controlled mechanical setting, and sports specific setting.
2. MinimaxX accelerometers are capable of detecting small, practically important differences in Australian football activity.

Practical applications:

1. Sports practitioners can use MinimaxX accelerometers interchangeably between activity bouts, and from one athlete to another, with confidence that any difference above ~2% is a real outcome.

6.5.2 Study 2: Measuring external loads and internal responses of small-sided Australian football games

Key findings:

1. Accelerometer derived vector magnitudes (Player load) display strong relationships with total locomotor distance.
2. In isolation, Player load from accelerometers did not show differences between contact and non-contact small-sided games in Australian football.
3. When Player load was normalised for total locomotor distance, accelerometers recorded higher external loads during Australian football small-sided games with physical contact.

4. A reduction in locomotor activity may occur when physical contact activity is incorporated into Australian football training drills.
5. The concentration of myoglobin was higher during non-contact small-sided games, suggesting that an increase in locomotor activity may cause greater disruption to the muscle structure.
6. Physical exertion during contact small-sided games was perceived to be higher, however feelings of fatigue and muscular soreness were higher for non-contact.

Practical applications:

1. Player load can potentially be used as a supplementary objective measure of total locomotor distance when other time-motion analysis methods are unavailable.
2. Physical contact is a key variable for manipulating Australian football small-sided games.
3. Short duration Australian football small-sided games may have a potentiating effect, and subsequently be an effective warm up activity in Australian football.
4. Short duration, high intensity Australian football small-sided games did not elicit a stress response, and may be an effective form of match specific training.

6.5.3 Study 3: Comparison of external load in Australian football matches and training using accelerometers

Key findings:

1. Differences between playing position, playing level, and between matches and training were observed from various accelerometer-derived measures of external load.
2. Both total and low-velocity external loads in elite matches were higher than sub-elite, except for deep position players.
3. Total external load measured using the Player load parameter displayed similar trends to total locomotor distance from GPS between playing positions.
4. The Player load^{SLOW} parameter appears to provide alternative information compared to locomotor measures from time-motion analysis.
5. Small-sided games were the only training drill that at least equalled both total and low-velocity external load from actual competitive matches.

Practical applications:

1. Accelerometers are a reliable tool that provides supplementary and alternative information related to external loads in Australian football activity.
2. Small-sided games are an excellent training modality for achieving the external loads of Australian football matches, particularly for activities performed at low-velocities in confined spaces.

CHAPTER 7. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This thesis was one of the first to investigate accelerometers in contact team sports such as Australian football. As with the majority of field-based projects, limitations were evident. There is a large scope for further research.

A broad limitation of this thesis was the use of a single elite professional Australian football team, which limits the ability for generalisation of these outcomes. Factors such as tactics and game plan, and differences in athlete physiology between elite teams may produce contrasting results. Cross-team research is difficult in the elite sporting environment as competition between teams is fierce and collaboration challenging. In future, a collaborative approach may be taken in conjunction with the governing body of Australian football (Australian football League, AFL). A project of this type would need to be outsourced to a non-aligned research group with de-identification of the data from respective teams being the highest priority.

A limitation of study one was that reliability testing of the MinimaxX accelerometers did not exceed 3.0 *g*. Whilst this was significantly advanced from previous research (<1.27 *g*), and encompassed ~95% of accelerometer values in Australian football activity, higher acceleration rates (up to ~6.0 *g*) do occur during matches. In addition to this was the absence of within-device reliability in a randomised dynamic setting. An identical human trial for repeated testing of the same device is most likely impossible given the sensitivity of accelerometers compared to gross human movement. Future research requires the use of mechanical equipment with a higher output, and possibly one that is capable of producing repeatable trials of random dynamic movement. Such equipment was not accessible during this research.

Numerous team-sport investigations are limited to testing in the training environment, as a consequence of rules and regulations, athlete compliance and general practical issues such as time constraints, and logistics. Although the use of small-sided games allowed for a tightly controlled scenario to compare non-contact and contact activity, the outcomes from study two of this thesis may not directly apply to actual Australian football matches. Study two required many different measures, some of which were invasive, which did not allow for this testing to be conducted during competitive matches. Substantially smaller playing fields (384 m²), and shorter activity durations (12 min), compared to actual Australian football matches (~15,000 to 18,000 m²; 120 min) were key differences. Whether it is a practice match in the training environment, or during a scheduled premiership fixture, analysis during full ground activity over actual match durations may provide different outcomes to the current findings.

Another limitation of study two was the non-randomised design. This was a consequence of the target population, with a precedence placed on recruiting elite professional Australian football players. Testing was required to be incorporated into team skill's training, and as such, all participants were required to complete the same tasks. This eliminated the possibility of randomisation. Best efforts were made to eliminate learning or order effect by matching the loads of each training week leading into the testing, this was successfully achieved with training loads (Session RPE), displaying no differences between weeks. In addition, the small-sided games were trialled leading into the testing period to ensure that the participants understood the rules of the game, and the testing procedures. In future, researchers may choose to target participants at a lower level where the testing can be more easily manipulated.

Methodologies utilised in recent research from rugby league may be expanded on, and developed for Australian football to assist with measuring physical contact. Two separate investigations developed a system of recognising isolated episodes of physical contact such as the collisions and impacts from tackles and hit-ups in rugby union (Cunniffe *et al.*, 2009; Gabbett *et al.*, 2010). This may be more challenging in Australian football compared to rugby league, as the direction of collisions from bumps and tackles will differ. Collisions in rugby league most often occur front-on, while Australian football collisions can come from all angles. Further, there are more distinct patterns during and after impacts in rugby league, with the tackled player being put to ground or held followed by a play the ball, allowing for reference movements to be used to assist with impact analysis. This presents a challenge for researchers wishing to examine Australian football collisions as the mechanics and subsequent movements are less systematic. An integrated approach combining accelerometers with the gyroscopes that are contained within the MinimaxX accelerometers and video-based analysis to reference impacts may facilitate this process. The ability to detect collisions would better enable researchers to assess if any potential links exist between physical contact, external load and injuries during competitive matches. Using similar methodology to previous research in rugby union (Takarada, 2003) may help determine if the collisions that occur during matches have adverse affects on muscle structure following matches.

Study two also failed to utilise heart rate analysis, which is employed regularly in team sports to measure the cardiovascular response. Previous accelerometer research has assessed the relationship between heart rate and accelerometer parameters, as part of validity assessments (Matthews & Freedson, 1995; Welk & Corbin, 1995). Integrated accelerometer and heart rate systems for predicting energy expenditure are

also common in the literature (Eston *et al.*, 1998; Strath *et al.*, 2002; Fudge *et al.*, 2007). At the time of testing, a heart rate system capable of providing valid and reliable information was unavailable. The substantial contribution of the cardiovascular system to team-sports such as Australian football is such that this research warrants further investigation. Relationships between Player load and heart rate may help to further understand the value of accelerometer-derived load parameters.

Further analysis within each individual axis of the accelerometer (*x*: medio-lateral; *y*: anterior-posterior; *z*: cranio-caudal) may also assist in profiling the activity of team-sports. Numerous applications for this analysis method exist, such as measuring the lateral activity in basketball in comparison to Australian football. Substantially greater activity in the medio lateral axis possibly indicates larger volumes of activities such as shuffling, and cutting. In turn, this may influence the types of activity that are used to prepare the athletes to perform in competition. Isolated analysis of activity in the vertical plane during team sports is another potential application of accelerometers. This may provide some indication of the load that occurs during locomotor activities. Currently, time-motion analysis systems mis-represent locomotor loads, as activity in confined spaces is underestimated because horizontal displacement is low. The frequency and magnitude of each foot strike will contribute to locomotor loads, therefore a system that accounts for locomotor activity of all forms may provide a useful tool for determining team sports loads.

REFERENCE

- Abdelkrim NB, El Fazaa S & El Ati J. (2007). Time-motion analysis and physiological data of elite under-19-year-old basketball players during competition. *Brit J Sport Med* **41**, 69-75; discussion 75.
- Achten J & Jeukendrup AE. (2003). Heart rate monitoring: Applications and limitations. *Sports Med* **33**, 517-538.
- Ali A & Farrally M. (1991). Recording soccer players' heart rates during matches. *J Sports Sci* **9**, 183-189.
- Allen DG, Westerblad H & Lannergren J. (1995). The role of intracellular acidosis in muscle fatigue. *Adv Exp Med Biol* **384**, 57-68.
- Anderson GS & Rhodes EC. (1989). A review of blood lactate and ventilatory methods of detecting transition thresholds. *Sports Med* **8**, 43-55.
- Appleby B & Dawson B. (2002). Video analysis of selected game activities in Australian Rules Football. *J Sci Med Sport* **5**, 129-142.
- Ascensao A. (2008). Biochemical impact of a soccer match - analysis of oxidative stress and muscle damage markers throughout recovery. *Clin Biochem* **41**, 841-851.
- Aughey R. (2010). Australian Football player workrate: evidence of fatigue and pacing? *Int J Sports Physiol and Perf* **5**, 394-405.
- Aughey R. (2011a). Increased high intensity activity in elite Australian football finals matches. *Int J Sports Physiol and Perf* **Accepted**.
- Aughey RJ. (2011b). Applications of GPS technologies to field sports. *Int J Sports Physiol and Perf* **Accepted**.
- Ball K. (2006). Kicking and injury. *AFL coaches conference, Melbourne, Australia*.
- Balsom PD. (1999). *Precision Football*. Polar Electro Oy, Kempele, Finland.
- Bangsbo J. (1994). The physiology of soccer with special reference to intense intermittent exercise. *Acta Physiol Scand* **151**, 1-156.
- Bangsbo J, Nørregaard L & Thosøe F. (1991). Activity profile of competition soccer. *Can Jou Sport Sci* **16**, 110-116.
- Barbero-Alvarez JC, Coutts A, Granda J, Barbero-Alvarez V & Castagna C. (2009). The validity and reliability of a global positioning satellite system device to assess speed and repeat sprint ability (RSA) in athletes. *J Sci Med Sport* **13**, 232-235

- Batterham AM & Hopkins WG. (2006). Making meaningful inferences about magnitudes. *Int J Sports Physiol and Perf* **1**, 50-57.
- Bishop D. (2001). Evaluation of the Accusport Lactate Analyser. *Int J Sports Med* **22**, 525-530.
- Bishop D, Spencer M, Duffield R & Lawrence S. (2001). The validity of a repeated sprint ability test. *J Sci Med Sport* **4**, 19-29.
- Borg G. (1998). *Borg's Perceived Exertion and Pain Scales*. Human Kinetics, Champaign, Illinois.
- Boyd L, J., Gallagher EL, Ball K, Stepto NK & Aughey RJ. (2010). Practical application of accelerometers in Australian football. *Journal of Science and Medicine in Sport (Australian Conference of Science and Medicine in Sport, Queensland)* **13**, e14-e15.
- Boyd LJ, Ball K & Aughey RJ. (2011). The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *Int J Sports Physiol and Perf* **6**, 311-321.
- Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P & Krstrup P. (2009). High intensity running in English FA Premier League soccer matches. *J Sports Sci* **27**, 159-168.
- Brancaccio P, Lippi G & Maffulli N. (2010). Biochemical markers of muscular damage. *Clin Chem Lab Med* **48**, 757-767.
- Braun WA & Dutto DJ. (2003). The effects of a single bout of downhill running and ensuing delayed onset of muscle soreness on running economy performed 48 h later. *Eur J Appl Physiol* **90**, 29-34.
- Brewer C, Dawson B, Heasman J, Stewart G & Cormack SJ. (2010). Movement pattern comparisons in elite (AFL) and sub-elite (WAFL) Australian football games using GPS. *J Sci Med Sport* **13**, 618-623.
- Buchheit M, Lepretre PM, Behaegel AL, Millet GP, Cuvelier G & Ahmaidi S. (2009). Cardiorespiratory responses during running and sport-specific exercises in handball players. *J Sci Med Sport* **12**, 399-405.
- Burgess DJ, Naughton G & Norton KI. (2006). Profile of movement demands of national football players in Australia. *J Sci Med Sport* **9**, 334-341.
- Byrne C & Eston R. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance *J Sports Sci* **20**, 417-425.
- Carling C, Bloomfield J, Nelsen L & Reilly T. (2008). The role of motion analysis in elite soccer: contemporary performance measurement techniques and work rate data. *Sports Med* **38**, 839-862.

- Caswell SV & Deivert RG. (2002). Lacrosse Helmet Designs and the Effects of Impact Forces. *J Athl Training* **37**, 164-171.
- Cavagna G, Saibene F & Margaria R. (1961). A three-directional accelerometer for analyzing body movements. *J Appl Physiol* **16**, 191.
- Clarkson PM, Nosaka K & Braun B. (1992). Muscle function after exercise-induced muscle damage and rapid adaptation. *Med Sci Sports Exerc* **24**, 512-520.
- Cleak MJ & Eston RG. (1992). Muscle soreness, swelling, stiffness and strength loss after intense eccentric exercise. *Brit J Sport Med* **26**, 267-272.
- Coe D & Pivarnik JM. (2001). Validation of the CSA accelerometer in adolescent boys during basketball practice. *Pediatr Exerc Sci* **13**, 373-379.
- Cormack SJ, Newton RU & McGuigan MR. (2008a). Neuromuscular and endocrine responses of elite players to an Australian rules football match. *Int J Sports Physiol and Perf* **3**, 359-374.
- Cormack SJ, Newton RU, McGuigan MR & Cormie P. (2008b). Neuromuscular and endocrine responses of elite players during an Australian rules football season. *Int J Sports Physiol and Perf* **3**, 439-453.
- Cormack SJ, Newton RU, McGuigan MR & Doyle TLA. (2008c). Reliability of Measures Obtained During Single and Repeated Countermovement Jumps. *Int J Sports Physiol and Perf* **3**, 131-144.
- Coutts A, Reaburn P & Abt G. (2003). Heart rate, blood lactate concentration and estimated energy expenditure in a semi-professional rugby league team during a match: a case study. *J Sports Sci* **21**, 97-103.
- Coutts AJ & Duffield R. (2008). Validity and reliability of GPS devices for measuring movement demands of team sports. *J Sci Med Sport*.
- Coutts AJ, Quinn J, Hocking J, Castagna C & Rampinini E. (2009a). Match running performance in elite Australian Rules Football. *J Sci Med Sport*.
- Coutts AJ, Rampinini E, Marcora SM, Castagna C & Impellizzeri FM. (2007). Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. *J Sci Med Sport* **12**, 79-84.
- Coutts AJ, Rampinini E, Marcora SM, Castagna C & Impellizzeri FM. (2009b). Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. *J Sci Med Sport* **12**, 79-84.
- Crisafulli A, Pittau G, Lorrain L, Carcassi AM, Cominu M, Tocco F, Melis F & Concu A. (2006). Poor reliability of heart rate monitoring to assess oxygen uptake during field training. *Int J Sports Med* **27**, 55-59.

- Crouter SE, Albright C & Bassett DR, Jr. (2004). Accuracy of polar S410 heart rate monitor to estimate energy cost of exercise. *Med Sci Sports Exerc* **36**, 1433-1439.
- Cunniffe B, Proctor W, Baker JS & Davies B. (2009). An evaluation of the physiological demands of elite rugby union using global positioning system tracking software. *J Strength Cond Res* **23**, 1195-1203.
- Dawson B, Hopkinson R, Appleby B, Stewart G & Roberts C. (2004a). Comparison of training activities and game demands in the Australian Football League. *J Sci Med Sport* **7**, 292-301.
- Dawson B, Hopkinson R, Appleby B, Stewart G & Roberts C. (2004b). Player movement patterns and game activities in the Australian Football League. *J Sci Med Sport* **7**, 278-291.
- Dawson B, Hopkinson R, Appleby B, Stewart G & Roberts C. (2004c). Player movement patterns and game activities in the Australian Football League. *J Sci Med Sport* **7**, 278-291.
- Dencker M & Andersen LB. (2006). Accelerometer-measured daily physical activity related to aerobic fitness in children and adolescents. *J Sports Sci* **29**, 887-895.
- Deutsch MU, Kearney GA & Rehrer NJ. (2007). Time - motion analysis of professional rugby union players during match-play. *J Sports Sci* **25**, 461-472.
- Deutsch MU, Maw GD, Jenkins DJ & Reaburn PRJ. (1998). Heart rate, blood lactate and kinematic data of elite colts (under-19) rugby union players during competition. *J Sports Sci* **16**, 561-570.
- Di Salvo V, Baron R, Tschan H, Calderon Montero FJ, Bachl N & Pigozzi F. (2006a). Performance Characteristics According to Playing Position in elite Soccer. *Int J Sports Med* **28**, 222-227.
- Di Salvo V, Collins A, McNeill B & Cardinale M. (2006b). Validation of Prozone[®]: A new video-based performance analysis system. *Int J Perform Anal Sport* **6**, 108-119.
- Di Salvo V, Gregson W, Atkinson G, Tordoff P & Drust B. (2009). Analysis of high intensity activity in Premier League soccer. *Int J Sports Med* **30**, 205-212.
- Dill DB & Costill DL. (1974). Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J Appl Physiol* **37**, 247-248.
- Dobson BP & Keogh WL. (2007). Methodological Issues for the Application of Time-Motion Analysis Research. *Str Con Jou* **29**, 48-55.
- Doherty M, Smith PM, Hughes MG & Collins D. (2001). Rating of perceived exertion during high-intensity treadmill running. *Med Sci Sports Exerc* **33**, 1953-1958.

- Duffield R, Coutts AJ & Quinn J. (2009a). Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. *J Strength Cond Res* **23**, 1238-1244.
- Duffield R, Coutts AJ & Quinn J. (2009b). Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. *J Strength Cond Res* **23**, 1238-1244.
- Duffield R & Drinkwater EJ. (2008). Time-motion analysis of Test and One-Day international cricket centuries. *J Sports Sci* **26**, 457-464.
- Duma SM, Manoogian SJ, Bussone WR, Brolinson PG, Goforth MW, Donnenwerth JJ, Greenwald RM, Chu JJ & Crisco JJ. (2005). Analysis of real-time head accelerations in collegiate football players. *Clin Jou Sport Med* **15**, 3-8.
- Duthie G, Pyne D & Hooper S. (2003a). Applied physiology and game analysis of rugby union. *Sports Med* **33**, 973-991.
- Duthie G, Pyne D & Hooper S. (2005). Time motion analysis of 2001 and 2002 super 12 rugby. *J Sports Sci* **23**, 523-530.
- Duthie G, Pyne D & Hooper SL. (2003b). The reliability of video based time motion analysis. *Jou Hum Mov Stud* **44**, 259-272.
- Edgecomb SJ & Norton KI. (2006). Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian Football *J Sci Med Sport* **9**, 25-32.
- Edgercomb SJ & Norton KI. (2006). Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian Football *J Sci Med Sport* **9**, 25-32.
- Edwards S. (1993). High performance training and racing. In *The Heart Rate Monitor Book*, 8th edn, ed. Edwards S, pp. 113-123. Feet Fleet Press, Sacramento, CA.
- Eklom B. (1986). Applied physiology of soccer. *Sports Med* **3**, 50-60.
- Elloumi M, Maso F, Michaux O, Robert A & Lac G. (2003). Behaviour of saliva cortisol [C], testosterone [T] and the T/C ratio during a rugby match and during the post-competition recovery days. *Eur J Appl Physiol* **90**, 23-28.
- Eniseler N. (2005). Heart Rate and Blood Lactate Concentrations as Predictors of Physiological Load on Elite Soccer Players During Various Soccer Training Activities *J Strength Cond Res* **19**, 799-804.
- Esliger DW & Tremblay MS. (2006). Technical reliability assessment of three accelerometer models in a mechanical setup. *Med Sci Sports Exerc* **38**, 2173-2181.

- Esposito F, Impellizzeri FM, Margonato V, Vanni R, Pizzini G & Veicsteinas A. (2004). Validity of heart rate as an indicator of aerobic demand during soccer activity in amateur soccer players. *Eur J Appl Physiol* **93**, 167-172.
- Eston RG, Rowlands AV & Ingledeew DK. (1998). Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities. *J Appl Physiol* **84**, 362-371.
- Farrow D, Pyne DB & Gabbett T. (2008). Skill and Physiological Demands of Open and Closed Training Drills in Australian Football. *Int J Sports Sci Coach* **3**, 489-499.
- Filaire E, Bernain X, Sagnol M & Lac G. (2001). Preliminary results on mood state, salivary Testosterone:Cortisol ratio and team performance in a professional soccer team. *Eur J Appl Physiol* **86**, 179-184.
- Florida-James G & Reilly T. (1995). The physiological demands of Gaelic football. *Brit J Sport Med* **29**, 41-45.
- Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P & Dodge C. (2001). A new approach to monitoring exercise training. *J Strength Cond Res* **15**, 109-115.
- Fudge BW, Wilson J, Easton C, Irwin L, Clark J, Haddow O, Kayser B & Ptiladis YP. (2007). Estimation of Oxygen Uptake during Fast Running Using Accelerometry and Heart Rate. *Med Sci Sports Exerc* **39**, 192-198.
- Gabbett T, Jenkins D & Abernethy B. (2010). Physical collisions and injury during professional rugby league skills training. *J Sci Med Sport* **14**, 210-215.
- Gabbett TJ. (2005). Science of rugby league football: a review. *J Sports Sci* **23**, 961-976.
- Gabbett TJ & Domrow N. (2007). Relationships between training load, injury, and fitness in sub-elite collision sport athletes. *J Sports Sci* **25**, 1507-1519.
- Gebruers N, Vanroy C, Truijien S, Engelborghs S & De Deyn P. (2010). Monitoring of physical activity after stroke: a systematic review of accelerometry-based measures. *Arch Phys Med Rehabil* **91**, 288-297.
- Godsen R, Carroll T & Stone S. (1991). How well does the polar vantage XL heart rate monitor estimate actual heart rate. *Med Sci Sports Exerc* **23**, S14.
- Gonzalez-Alonso J, Mora-Rodriguez R & Below PR. (1997). Dehydration markedly impairs cardiovascular function in hyperthermic endurance athletes during exercise. *J Appl Physiol* **82**, 1229-1236.
- Gonzalez-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T & Nielsen B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol* **86**, 1032-1039.

- Gray AJ & Jenkins DG. (2010). Match analysis and the physiological demands of Australian football. *Sports Med* **40**, 347-360.
- Green JM, McLester JR, Crews TR, Wickwire PJ, Pritchett RC & Lomax RG. (2006). RPE association with lactate and heart rate during high-intensity interval cycling. *Med Sci Sports Exerc* **38**, 167-172.
- Greig MP, McNaughton LR & Lovell RJ. (2006). Physiological and mechanical response to soccer-specific intermittent activity and steady-state activity. *Res Sports Med* **14**, 29-52.
- Hahn A, Taylor N, Hunt B, Woodhouse T & Schultz G. (1979). Physiological relationships between training activities and match play in Australian Football rovers. *Sports Coach* **3**, 3-8.
- Haneishi K, Fry AC, Moore CA, Schilling BK, Li Y & Fry MD. (2007). Cortisol and stress responses during a game and practice in female collegiate soccer players. *J Strength Cond Res* **21**, 583-588.
- Hansen BH, Kolle E, Dyrstad SM, Holme I & Anderssen SA. (2011). Accelerometer-Determined Physical Activity in Adults and Older People. *Med Sci Sports Exerc* **E-Pub ahead of print**.
- Hendelman D, Miller K, Baggett C, Debold E & Freedson P. (2000). Validity of accelerometry for the assessment of moderate intensity physical activity in the field. *Med Sci Sports Exerc* **32**, S442-449.
- Herman L, Foster C, Maher MA, Mikat RP & Porcari JP. (2006). Validity and reliability of the session RPE method for monitoring exercise training intensity. *S Afr J Sport Med* **18**, 14-17.
- Hill-Haas S, Coutts A, Dawson B & Rowsell G. (2009). Time-motion characteristics and physiological responses of small-sided games in elite youth players: The influence of player number and rule changes. . *Journal of Strength and Conditioning Research* **E-publication ahead of print**.
- Hill-Haas S, Coutts A, Rowsell G & Dawson B. (2008). Variability of acute physiological responses and performance profiles of youth soccer players in small-sided games. *J Sci Med Sport* **11**, 487-490.
- Hoff J, Wisløff U, Engen LC, Kemi OJ & Helgerud J. (2002). Soccer specific aerobic endurance training. *Brit J Sport Med* **36**, 218-221.
- Hoffman JR. (2002). Endurance training In *Physiological aspects of sport training and performance*, ed. Bahrke MS, pp. 109-119. Human Kinetics, Champaign.
- Hoffman JR, Kang J, Ratamess NA & Faigenbaum AD. (2005). Biochemical and hormonal responses during an intercollegiate football season. *Med Sci Sports Exerc* **37**, 1237-1241.

- Hoffman JR, Maresh CM, Newton RU, Rubin MR, French DN, Volek JS, Sutherland J, Robertson M, Gómez AL, Ratamess NA, Kang J & Kraemer WJ. (2002). Performance, biochemical, and endocrine changes during a competitive football game. *Med Sci Sports Exerc* **34**, 1845-1853.
- Hopkins WG. (2000a). Measures of reliability in sports medicine and science. *Sports Med* **30**, 1-15.
- Hopkins WG. (2000b). Reliability from consecutive pairs of trials (Excel spreadsheet), A new view of statistics. Available at: <http://www.sportsci.org/InternetSocietyforSportScience>.
- Hopkins WG. (2007). A spreadsheet to compare means of two groups. *Sportscience* **11**, 22-23 ([sportsci.org/2007/inbrief.htm#xcl2](http://www.sportsci.org/2007/inbrief.htm#xcl2)).
- Hopkins WG, Marshall SW, Batterham AM & Hanin J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Med Sci Sports Exerc* **41**, 3-13.
- Howe CA, Staudenmayer JW & Freedson PS. (2009). Accelerometer prediction of energy expenditure: vector magnitude versus vertical axis. *Med Sci Sports Exerc* **41**, 2199-2206.
- Impellizzeri FM, Marcora SM, Castagna C, Reilly T, Sassi A, Iaia FM & Rampinini E. (2006). Physiological and performance effects of generic versus specific aerobic training in soccer players. *Int J Sports Med* **27**, 483-492.
- Impellizzeri FM, Rampinini E, Coutts AJ, Sassi A & Marcora SM. (2004). Use of RPE-based training load in soccer. *Med Sci Sports Exerc* **36**, 1042-1047.
- Impellizzeri FM, Rampinini E & Marcora SM. (2005). Physiological assessment of aerobic training in soccer. *J Sports Sci* **23**, 583-592.
- Ispirlidis I, Fatouros IG, Jamurtas AZ, Nikolaidis MG, Michailidis I, Douroudos I, Margonis K, Chatzinikolaou A, Kalistratos E, Katrabasas I, Alexiou V & Taxildaris K. (2008). Time-course of changes in inflammatory and performance responses following a soccer game. *Clin J Sport Med* **18**, 423-431.
- Jacobs I. (1986). Blood lactate. Implications for training and sports performance. *Sports Med* **3**, 10-25.
- Jakicic JM, Winters C, Lagally K, Ho J, Robertson RJ & Wing RR. (1999). The accuracy of the TriTrac-R3D accelerometer to estimate energy expenditure. *Med Sci Sports Exerc* **31**, 747-754.
- Jennings D, Cormack SJ, Coutts A, Boyd L, J. & Aughey R. (2010a). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *Int J Sports Physiol and Perf* **5**, 328-341.

- Jennings D, Cormack SJ, Coutts A, Boyd LJ & Aughey R. (2010b). Variability of GPS units for measuring distance in team sport movements. *Int J Sports Physiol and Perf* **In Press**.
- Jeukendrup AE, Hesselink MK & Kuipers H. (1997). The Conconi test. *Int J Sports Med* **18**, 393-396.
- Johnston T, Sproule J, McMorris T & Maile A. (2004). Time-motion analysis and heart rate response during elite male field hockey: Competition versus training. *Jou Hum Mov Stud* **46**, 189-203.
- Kozey SL, Lyden K, Howe CA, Staudenmayer JW & Freedson PS. (2010). Accelerometer Output and MET Values of Common Physical Activities. *Med Sci Sports Exerc*.
- Kraemer WJ, French DN, Paxton NJ, Häkkinen K, Volek JS, Sebastianelli WJ, Putukian M, Newton RU, Rubin MR, Gómez AL, Vescovi JD, Ratamess NA, Fleck SJ, Lynch JM & Knuttgen HG. (2004). Changes in exercise performance and hormonal concentrations over a big ten soccer season in starters and nonstarters. *J Strength Cond Res* **18**, 121-128.
- Kraemer WJ, Spiering BA, Volek JS, Martin GJ, Howard RL, Ratamess NA, Hatfield DL, Vingren JL, Ho JY, Fragala MS, Thomas GA, French DN, Anderson JM, Hakkinen K & Maresh CM. (2009). Recovery from a national collegiate athletic association division 1 football game: Muscle damage and hormonal status. *J Strength Cond Res* **23**, 2-10.
- Krasnoff JB, Kohn MA, Choy FK, Doyle J, Johansen K & Painter PL. (2008). Interunit and intraunit reliability of the RT3 triaxial accelerometer. *J Phys Act Health* **5**, 527-538.
- Krustrup P, Mohr M, Steensberg A, Bencke J, Kjaer M & Bangsbo J. (2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc* **38**, 1165-1174.
- Lamb KL, Eston RG & Corns D. (1999). Reliability of ratings of perceived exertion during progressive treadmill exercise. *Brit J Sport Med* **33**, 336-339.
- Laukkanen RMT & Virtanen PK. (1998). Heart rate monitors: state of the art. *J Sports Sci* **16**, S3-7.
- Le Bris R, Billat V, Auvinet B, Chaleil D, Hamard L & Barrey E. (2006). Effects of fatigue on stride pattern continuously measured by an accelerometric gait recorder in middle distance runners. *Jou Sport Med Phys Fit* **46**, 227-231.
- Leger L & Thivierge M. (1988). Heart Rate Monitors: Validity, Stability and Functionality. *Phys Sportsmed* **16**, 143-151.

- Levine JA, Baukol PA & Westerterp KR. (2001). Validation of the Tracmor triaxial accelerometer system for walking. *Med Sci Sports Exerc* **33**, 1593-1597.
- Lothian F & Farrally M. (1994). A time-motion analysis of women's hockey. *Jou Hum Mov Stud* **26**, 255-265.
- Macleod H, Morris J, Nevill A & Sunderland C. (2009). The validity of a non-differnetial global positioning system for assessing player movement patterns in field hockey. *J Sports Sci* **27**, 121-128.
- Matthews CE & Freedson PS. (1995). Field trial of a three-dimensional activity monitor: comparison with self report. *Med Sci Sports Exerc* **27**, 1071-1078.
- McClay IS, Robinson JR, Andriacchi TP, Frederick EC, Gross T, Martin P, Valiant G, Williams KR & Cavanagh PR. (1994). A profile of ground reaction forces in professional basketball. *Jou App Biomech* **10**, 222-236.
- McInnes SE, Carlson JS, Jones CJ & McKenna MJ. (1995). The physiological load imposed on basketball players during competition. *J Sports Sci* **13**, 387-397.
- Mellalieu SD, Hanton S & O'Brien M. (2004). Intensity and direction of competitive anxiety as a function of sport type and experience. *Scand J Med Sci Sport* **14**, 326-334.
- Mizrahi. J, Verbitsky. O & Isakov. E. (2000). Effect of fatigue on leg kinematics and impact acceleration in long distance running. *Human Movement Sciences* **19**, 139-151.
- Montgomery PG, Pyne D & Minahan CL. (2010). The Physical and Physiological Demands of Basketball Training and Competition. *Int J Sports Physiol and Perf* **5**, 75-86.
- Moreira A, Arsati F, Arsati YBOL, Da Silva DA & De Araujo VC. (2009). Salivary cortisol in top-level professional soccer players. *Eur J Appl Physiol* **106**, 25-30.
- Morgan WP. (1994). Psychological components of effort sense. *Med Sci Sports Exerc* **26**, 1071-1077.
- Nichols JF, Morgan CG, Sarkin JA, Sallis JF & Calfas KJ. (1999). Validity, reliability, and calibration of the Tritrac accelerometer as a measure of physical activity. *Med Sci Sports Exerc* **31**, 908-912.
- Nielsen OB, de Paoli F & Overgaard K. (2001). Protective effects of lactic acid on force production in rat skeletal muscle. *J Physiol* **536**, 161-166.
- Norton K, Craig NP & Olds TS. (1999). The Evolution of Australian Football. *J Sci Med Sport* **2**, 389-404.

- Osgnach C, Poser S, Bernardini R, Rinaldo R & Di Prampero PE. (2010). Energy costs and metabolic power in elite soccer: A new match analysis approach. *Med Sci Sports Exerc* **42**, 170-178.
- Petersen C, Pyne D, Portus M & Dawson B. (2009). Validity and reliability of GPS units to monitor cricket-specific movement patterns. *Int J Sports Physiol and Perf* **4**, 381-393.
- Portas MD, Harley JA, Barnes CA & Rush CJ. (2010). The validity and reliability of 1-Hz and 5-Hz global positioning systems for linear, multidirectional, and soccer-specific activities. *Int J Sports Physiol and Perf* **5**, 448-458.
- Portas MD, Harley JA, Barnes CA & Rush CJ. (2011). The validity and reliability of 1-Hz and 5-Hz global positioning systems for linear, multidirectional, and soccer-specific activities. *International Journal of Sports Physiology & Performance* **5**, 448-458.
- Powell SM, Jones DI & Rowlands AV. (2003). Technical variability of the RT3 accelerometer. *Med Sci Sports Exerc* **35**, 1773-1778.
- Powell SM & Rowlands AV. (2004). Intermonitor variability of the RT3 accelerometer during typical physical activities. *Med Sci Sports Exerc* **36**, 324-330.
- Puhl J, Greaves K, Hoyt M & Baranowski T. (1990). Children's Activity Rating Scale (CARS): description and calibration. *Res Q Exerc Sport* **61**, 26-36.
- Pyke FS & Smith RS. (1975). *Football: The scientific way*. University of Western Australia Press, Nedlands, WA.
- Pyne D. (2003). Interpreting the results of fitness testing. In *International Science and Football Symposium*. Victorian Institute of Sport, Melbourne, Australia.
- Pyne DB, Boston T, Martin DT & Logan A. (2000). Evaluation of the Lactate Pro blood lactate analyser. *Eur J Appl Physiol* **82**, 112-116.
- Rampinini E, Bishop D, Marcora SM, Ferrari Bravo D, Sassi R & Impellizzeri FM. (2006). Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *Int J Sports Med*, DOI: 10.1055/s-2006-924340.
- Rampinini E, Coutts AJ, Castagna C, Sassi R & Impellizzeri FM. (2007a). Variation in Top Level Soccer Match Performance. *Int J Sports Med*.
- Rampinini E, Impellizzeri FM, Castagna C, Abt GA, Chamari K, Sassi A & Marcora S. (2007b). Factors influencing physiological responses to small-sided soccer games. *J Sports Sci* **25**, 659-666.

- Rampinini E, Impellizzeri FM, Castagna C, Coutts AJ & Wisloff U. (2009). Technical performance during soccer matches of the Italian Serie A league: effect of fatigue and competitive level. *J Sci Med Sport* **12**, 227-233.
- Rampinini E, Sassi A & Impellizzeri FM. (2005). Reliability of heart rate recorded during soccer training. *Science and Football V: The proceedings of the fifth world congress on science and football*.
- Reilly T & Ball D. (1984). The net energetic cost of dribbling a soccer ball. *Res Q Exerc Sport* **55**, 267-271.
- Reilly T & Thomas V. (1976). A motion analysis of workrate in different positional roles in professional football match-play. *Jou Hum Mov Stud* **2**, 87-97.
- Rogers DM, Olson BL & Wilmore JH. (1995). Scaling for the VO₂-to-body size relationship among children and adults. *J Appl Physiol* **79**, 958-967.
- Rontu JP, Hannula MI, Leskinen S, Linnamo V & Salmi JA. (2010). One-repetition maximum bench press performance estimated with a new accelerometer method. *J Strength Cond Res* **24**, 2018-2025.
- Rowlands AV. (2007). Accelerometer assessment of physical activity in children: an update. *Pediatr Exerc Sci* **19**, 252-266.
- Rowlands AV, Stone MR & Eston RG. (2007). Influence of speed and step frequency during walking and running on motion sensor output. *Med Sci Sports Exerc* **39**, 716-727.
- Rowlands AV, Thomas PW, Eston RG & Topping R. (2004). Validation of the RT3 triaxial accelerometer for the assessment of physical activity. *Med Sci Sports Exerc* **36**, 518-524.
- Sato K, Smith SL & Sands WA. (2009). Validation of an accelerometer for measuring sport performance. *J Strength Cond Res* **23**, 341-347.
- Schulz S, Westerterp KR & Bruck K. (1989). Comparison of energy expenditure by the doubly labeled water technique with energy intake, heart rate, and activity recording in man. *Am J Clin Nutr* **49**, 1146-1154.
- Schwane JA, Johnson SR, Vandenakker CB & Armstrong RB. (1983). Delayed-onset muscular soreness and plasma CPK and LDH activities after downhill running. *Med Sci Sports Exerc* **15**, 51-56.
- Seaward BL, Sleamaker RH, McAuliffe T & Clapp JF, 3rd. (1990). The precision and accuracy of a portable heart rate monitor. *Biomed Instrum Techn* **24**, 37-41.
- Sheppard JM, Gabbett TJ & Stanganelli LC. (2009). An analysis of playing positions in elite men's volleyball: considerations for competition demands and physiologic characteristics. *J Strength Cond Res* **23**, 1858-1866.

- Singh TK, Guelfi KJ, Landers G, Dawson B & Bishop D. (2011). A comparison of muscle damage, soreness and performance following a simulated contact and non-contact team sport activity circuit. *J Sci Med Sport* **In Press**.
- Skinner JS, Hutsler R, Bergsteinova V & Buskirk R. (1973). The validity and reliability of rating scale of perceived exertion. *Med Sci Sports Exerc* **5**, 94-96.
- Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B & Goodman C. (2004). Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. *J Sports Sci* **22**, 843-850.
- Spencer M, Rechichi C, Lawrence S, Bishop D, Dawson B & Goodman C. (2002). Time-motion analysis of elite field hockey during several games in succession: a tournament scenario. *J Sci Med Sport* **5**, 33.
- Stamford BA. (1976). Validity and reliability of subjective ratings of perceived exertion during work. *Ergonomics* **19**, 53-60.
- Steele BG, Holt L, Belza B, Ferris S & Buchner DM. (2000). Quantitating Physical Activity in COPD Using Triaxial Accelerometer. *Chest* **117**, 1359-1367.
- Stiles VH, Guisasola IN, James IT & Dixon SJ. (2011). Biomechanical response to changes in natural turf during running and turning. *Jou App Biomech* **27**, 54-63.
- Strath SJ, Bassett DR, Jr., Thompson DL & Swartz AM. (2002). Validity of the simultaneous heart rate-motion sensor technique for measuring energy expenditure. *Med Sci Sports Exerc* **34**, 888-894.
- Stroyer J, Hansen L & Klausen K. (2004). Physiological profile and activity pattern of young soccer players during match play. *Med Sci Sports Exerc* **36**, 168-174.
- Sumukadas D, Laidlaw S & Witham MD. (2008). Using the RT3 accelerometer to measure everyday activity in functionally impaired older people. *Aging Clin Exp Res* **20**, 15-18.
- Takarada Y. (2003). Evaluation of muscle damage after a rugby match with special reference to tackle plays. *Brit J Sport Med* **37**, 416-419.
- Terbizan D, Dolezal B & Albano C. (2002). Validity of seven Commercially Available Heart Rate Monitors. *Meas Phys Educ Exerc Sci* **6**, 243-247.
- Thompson D, Nicholas CW & Williams C. (1999). Muscular soreness following prolonged intermittent high-intensity shuttle running. *J Sports Sci* **17**, 387-995.
- Tsivgoulis SD, Papagelopoulos PJ, Efstathopoulos N, Papadakis NC, Kampanis NA, Christakis DG & Katonis PG. (2009). Accelerometry for evaluation of gait pattern in healthy soccer athletes. *J Int Med Res* **37**, 1692-1700.

- Tumilty D. (1993). Physiological characteristics of elite soccer players. *Sports Medicine* **16**, 80-96.
- Van Hees VT, Slootmaker SM, De Groot G, Van Mechelen W & Van Lummel RC. (2009). Reproducibility of a triaxial seismic accelerometer (DynaPort). *Med Sci Sports Exerc* **41**, 810-817.
- Vanhelst J, Theunynck D, Gottrand F & Beghin L. (2010). Reliability of the RT3 accelerometer for measurement of physical activity in adolescents. *J Sports Sci* **28**, 375-379.
- Veale JP, Pearce AJ & Carlson JS. (2007). Player movement patterns in an elite junior Australian Rules Football Team: An exploratory study. *J Sci Med Sport* **6**.
- Vincent HK & Vincent KR. (1997). The effect of training status on the serum creatine kinase response, soreness and muscle function following resistance exercise. *Int J Sports Med* **18**, 431-437.
- Welk GJ, Blair SN, Wood K, Jones S & Thompson RW. (2000). A comparative evaluation of three accelerometry-based physical activity monitors. *Med Sci Sports Exerc* **32**, S489-S497.
- Welk GJ & Corbin CB. (1995). The validity of the Tritrac-R3D Activity Monitor for the assessment of physical activity in children. *Res Q Exerc Sport* **66**, 202-209.
- Welk GJ, Schaben JA & Morrow JR, Jr. (2004). Reliability of accelerometry-based activity monitors: a generalizability study. *Med Sci Sports Exerc* **36**, 1637-1645.
- Wewers ME & Lowe NK. (1990). A critical review of visual analogue scales in the measurement of clinical phenomena. *Res Nurs Health* **13**, 227-236.
- Wisbey B, Montgomery PG, Pyne DB & Rattray B. (2009). Quantifying movement demands of AFL football using GPS tracking. *J Sci Med Sport* **13**, 531-536.
- Young WB, Newton RU & Doyle TLA. (2005). Physiological and anthropometric characteristics of starters and nonstarters and playing positions in elite Australian Rules Football: a case study. *J Sci Med Sport* **8**, 333-345.
- Zois J, Bishop DJ, Ball K & Aughey RJ. (2011). High-intensity warm-ups elicit superior performance to a current soccer warm-up routine. *J Sci Med Sport*.
- Zuliani U, Bonetti A, Franchini D, Serventi G, Ugolotti G & Varacca A. (1985). Effect of boxing on some metabolic indices of muscular contraction. *Int J Sports Med* **6**, 234-236.

APPENDIX 1: Information for participants form

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate in the research project titled:

“Accelerometry in Team Sports: Investigating the Physical Demands of Australian Rules Football”

This project is being conducted by a student researcher Luke Boyd as part of a PhD study at Victoria University/Western Bulldogs under the supervision of Dr Rob Aughey, and Dr Kevin Ball, from the School of Sport and Exercise Science, and Centre for Ageing, Rehabilitation, Exercise and Sport.

The project will be assessing the following:

- The reliability of MinimaxX accelerometers for assessing the physical loading placed upon players in Australian football matches,
- The trends associated with player load in Australian football matches,
- The difference between contact and non-contact activity during modified training games in Australian football.

What will I be asked to do?

- Wear an accelerometer unit fixed into a vest on the upper back during Australian football matches,
- Wear a heart rate monitor around the chest,
- Participate in two modified Australian football games involving various intensities of running, including maximal sprints, changes of direction, accelerating, decelerating and jumping,
- Perform a vertical jump and repeated sprint ability test following the completion of the modified games,
- Complete a suitable warm up routine prior to commencing the modified games and exercise testing,
- Allow blood samples to be taken from the forearm both before and after the modified games,
- Express your perceived effort and levels of fatigue and soreness following the modified games,
- Complete a suitable recovery routine following completion of the testing.

What will I gain from participating?

As a participant in this research project you will be contributing to the development of knowledge regarding the physical demands of Australian football. This information will be utilised to determine the effects of physical contact on performance and physical status of the athletes and help to design preparation and recovery strategies to enhance performance.

How will the information I give be used?

The information you provide to the researcher (through personal details and the results of your participation in the project) will be kept strictly confidential. Only group data will be reported and presented, not individual. These data may be presented through written publication, posters and conference presentations.

Your personal information will not be passed onto any people or organisations other than the principal investigators.

What are the potential risks of participating in this project?

The associated risks with participation in the study are:

- Injury obtained from the Australian football matches, modified games, or exercise tests,
- Adverse effects from the blood sampling procedures,
- Feelings of intimidation when performing Australian football specific activity, and exercise tests in front of a group of observers,
- Feelings of psychological discomfort from the blood sampling procedure,
- Feeling pressured by others to participate in the research project.

Access to medical staff will be available at all testing sessions. Any psychological issues that arise can be discussed with Dr Mark Andersen, from Victoria University, Faculty of Arts, Education, and Human Development, Ph. 99195413.

How will this project be conducted?

Upon arrival you will be asked to read a description of the research project and sign a consent form. You will then be fitted with a vest in which the accelerometer unit will be stored. A warm up protocol will be completed prior to commencing the testing. Once this is complete you will be taken through the requirements of the modified AF game, including the rules and regulations. The actual testing will now commence. You will be asked to compete to the best of their ability during the modified game, which will be 4x7.5 minute periods of play with 4 minutes recovery between each period. Following the completion of the testing, each participant will be required to complete a vertical jump and repeated sprint test to the best of their ability. Blood samples will then be taken and perceived efforts, fatigue and soreness levels will then be recorded. A recovery routine will then follow.

Who is conducting the study?

Victoria University - Centre for Ageing, Rehabilitation, Exercise and Sport & Western Bulldogs Football Club

Principal Researcher:

Dr Robert Aughey
 Email: robert.aughey@vu.edu.au
 Contact No: 9919 5551

PhD Candidate:

Luke Boyd
 Email: lukeboyd23@bigpond.com
 Contact No: 0417135476

Any queries about your participation in this project may be directed to the Principal Researcher listed above.

If you have any queries or complaints about the way you have been treated, you may contact the Secretary, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4781.

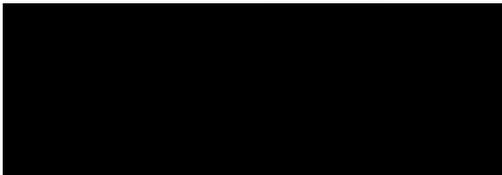
Please note that your participation in this project is voluntary, that is, it is not compulsory by virtue of your membership with the club. Should you have any concerns about the conduct of this research project, please contact:

The Secretary

University Human Research Ethics Committee
Victoria University, PO Box 14428
Melbourne, 8001
Telephone no: 03-9919 4710

Thank you for reading this statement and if you have any concerns or queries, please do not hesitate to contact Dr Rob Aughey on 9919 5551. Alternatively the address for written correspondence is: Dr Rob Aughey, School Exercise and Sport Science, PO Box 14428, Melbourne, Victoria, 8001 Australia or robert.aughey@vu.edu.au

Thank you for agreeing to assist us with our research.



Dr Robert Aughey PhD
School of Human Movement, Recreation and Performance
Victoria University

APPENDIX 2: Participants consent form

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a research program:

“Accelerometry in Team Sports: Investigating the Physical Demands of Australian Rules Football”

The project will be conducted by Luke Boyd, and Dr Rob Aughey. The project will aim to:

- Test the reliability of MinimaxX accelerometers for assessing player load in Australian football matches;
- Describe the trends associated with player load in Australian football matches;
- Assess the difference between contact and non-contact activity during modified training games in Australian football.

As a participant you will be asked to wear a MinimaxX accelerometer device during matches and training. In the match component you will wear either 1 or 2 MinimaxX accelerometer device during actual Australian football matches. In the training component you will participate in a simulated handball game based on the skills of Australian football. This game will involve running at varied intensities with multiple high intensity efforts often at maximal exertion and involving rapid changes of direction, skill related activity such as kicking, handballing and marking, and activity requiring physical contact such as tackling, bumping, blocking and contested situations. The MinimaxX devices will be worn on the upper back and a heart rate monitor around the chest. Small blood samples will be taken from the forearm before and after the game, and a series of exercise tests will be conducted before and after the game. As part of the project you may be subject to physical risks in relation to injury. Both warm up and recovery procedures have been developed to minimise this risk. Medical staff will be available at all time during the testing. The information gathered from this project will

be valuable in developing a greater understanding of the demands of team sports performance, more specifically the contribution of physical contact based activity.

CERTIFICATION BY SUBJECT

I, _____

of _____

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the study: "*Accelerometry in Team Sports: Investigating the Physical Demands of Australian Rules Football*" being conducted at Victoria University by: Dr Rob Aughey, and Luke Boyd.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by **Luke Boyd** and that I freely consent to participation involving the below mentioned procedures:

- Wear an accelerometer unit fixed into a vest on the upper back during Australian football matches,
- Wear a heart rate monitor around the chest,
- Participate in two modified AF games involving various intensities of running, including maximal sprints, changes of direction, accelerating, decelerating and jumping,
- Perform a vertical jump and sprint test following the completion of the modified games,
- Complete a suitable warm up routine prior to commencing the modified games and exercise testing,
- Allow blood samples to be taken from the forearm both before and after the modified games,
- Express your perceived effort and levels of fatigue and soreness following the modified games,
- Complete a suitable recovery routine following completion of the testing,
- Allow the current information to be used in the research project,
- Allow previously collected data through the MinimaxX devices to be used in the research project.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

I have been informed that the information I provide will be kept confidential.

Signed:

Date:

Any queries about your participation in this project may be directed to the researcher
Dr Rob Aughey on 9919 5551.

If you have any queries or complaints about the way you have been treated, you may contact the Secretary, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4781

APPENDIX 3: Medical Questionnaire



MEDICAL QUESTIONNAIRE

Responses to this questionnaire will be kept strictly confidential. The responses from this questionnaire will provide the investigators with appropriate information to establish suitability of your participation in this study. Anyone who is currently carrying a musculo-skeletal injury or has a history of past, serious musculo-skeletal injuries may be excluded from the study for health and safety reasons.

Please complete the following preliminary questionnaire.

Name: _____

Age: _____ (years)

Weight _____ (kg): _____

Height

(cm) _____ Sex: _____

Are you currently undertaking any form of regular exercise? YES NO

(If yes, briefly describe the type and amount (i.e. Frequency, duration) of exercise you perform)

Are you a smoker? YES NO

Has anyone ever told you that you:

- | | | | |
|-----------------------------|-----|----|------------|
| • are overweight? | YES | NO | DON'T KNOW |
| • have high blood pressure? | YES | NO | DON'T KNOW |
| • have a heart murmur? | YES | NO | DON'T KNOW |
| • are asthmatic? | YES | NO | DON'T KNOW |
| • are Haemophiliac? | YES | NO | DON'T KNOW |
| • have type 2 diabetes? | YES | NO | DON'T KNOW |

- heart palpitations (sensation of abnormally fast and/or irregular heart beat)?

YES	NO	DON'T KNOW
-----	----	------------
- episodes of fainting, collapse or loss of consciousness?

YES	NO	DON'T KNOW
-----	----	------------
- abnormal bleeding or bruising?

YES	NO	DON'T KNOW
-----	----	------------
- gastrointestinal problems?

YES	NO	DON'T KNOW
-----	----	------------

Have you, or anyone of your family a history of cardiovascular disease?

YES NO

(e.g. Heart attack, chest pain, stroke, rheumatic vascular disease)

If YES,

please elaborate: _____

Have you ever suffered any musculoskeletal injury?

YES NO

If YES,

please elaborate: _____

Have you suffered any musculoskeletal injury in the last 6 months?

YES NO

If YES,

please elaborate: _____

Do you have any allergies (including to medications)

YES NO DON'T KNOW

If YES,

please elaborate: _____

I believe the information I have provided to be true and correct.

Signed: _____

Date: _____

COMMENTS ON MEDICAL EXAMINATION (where appropriate):

APPENDIX 4: Participant Details

Table 17. Study 1 – Details of participants in the field assessment section. (Chapter 3)

Participant No.	Height (cm)	Mass (kg)	Age	
			Years	Months
1	183	80	22	9
2	187	83	23	1
3	182	78	18	7
4	179	82	23	2
5	177	84	21	11
6	190	92	19	4
7	182	80	21	5
8	175	73	18	10
9	187	83	23	2
10	174	82	20	6
<i>n</i>	10	10	10	10
<i>Mean</i>	181.6	83.0	23.0	2.0
<i>SD</i>	5.4	4.8	2.0	3.5

Table 18. Study 2 – Details of elite Australian football players who participated in the small-sided games. (Chapter 4)

Participant No.	Age	Height (cm)	Mass (kg)
1	20	193	87
2	30	199	108
3	27	195	104
4	22	186	83
5	26	187	86
6	27	182	83
7	27	190	92
8	20	185	82
9	20	196	85
10	20	199	93
11	18	195	86
12	23	183	82
13	27	184	90
14	28	188	99
15	23	188	86
16	28	190	85
17	27	186	82
18	21	184	89
19	26	181	82
<i>n</i>	19	19	19
<i>Mean</i>	24.2	189.0	88.6
<i>SD</i>	3.6	5.7	7.6

Table 19. Study 3 – Australian football players who participated in elite matches. (Chapter 5)

Participant No.	Age	Height (cm)	Mass (kg)
1	20	193	87
2	30	199	108
3	27	195	104
4	22	186	83
5	26	187	86
6	27	182	83
7	27	190	92
8	23	183	82
9	27	184	90
10	28	188	99
11	23	188	86
12	28	190	85
13	27	186	82
14	21	184	89
15	25	181	82
16	31	188	89
17	23	200	95
18	23	196	101
19	24	186	88
20	19	185	75
21	23	187	84
22	20	185	81
23	32	177	85
24	31	180	83
25	27	180	82
26	21	178	74
27	21	186	82
28	32	182	87
29	24	199	106
<i>n</i>	29	29	29
<i>Mean</i>	25.2	187.1	87.9
<i>SD</i>	3.8	6.2	8.6

Table 20. Study 3 – Australian football players who participated in sub-elite matches.
(Chapter 5)

Participant No.	Age	Height (cm)	Mass (kg)
1	23	187	97
2	20	192	92
3	22	188	85
4	21	192	95
5	20	196	85
6	20	199	93
7	18	195	86
8	21	192	81
9	25	197	93
10	20	195	92
11	23	191	88
12	23	200	95
13	19	185	75
14	20	185	81
15	19	199	95
16	27	211	110
17	23	178	68
18	19	184	81
19	20	179	83
20	21	174	85
21	23	183	86
22	21	185	86
23	23	183	83
24	23	187	85
25	23	188	80
26	19	182	78
27	19	183	81
28	18	177	75
29	20	175	79
30	22	176	71
31	23	177	83
32	23	174	79
33	28	178	83
34	18	188	90
35	21	187	84
36	18	202	80
37	20	199	101
<i>n</i>	37	37	37
<i>Mean</i>	21.2	187.6	85.5
<i>SD</i>	2.4	9.0	8.4

APPENDIX 5: Ethics Approval

MEMO



A NEW
SCHOOL OF
THOUGHT.

TO Dr Rob Aughey
School of Sport & Exercise Science
Footscray Park Campus

DATE 21/12/2009

FROM Prof Carolyn Noble
Deputy Chair
Arts, Education & Human Development Human
Research Ethics Subcommittee

SUBJECT Ethics Application – HRETH 09/206

Dear Dr Aughey,

Thank you for submitting your application for ethical approval of the project:

HRETH09/206 Accelerometry in team sports: investigating the physical demands of Australian rules football.

The proposed research project has been accepted and deemed to meet the requirements of the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007)', by the Chair, Faculty of Arts, Education & Human Development Human Research Ethics Committee. Approval has been granted from 21/12/2009 to 02/01/2011.

Continued approval of this research project by the Victoria University Human Research Ethics Committee (VUHREC) is conditional upon the provision of a report within 12 months of the above approval date (by **21/12/2010**) or upon the completion of the project (if earlier). A report proforma may be downloaded from the VUHREC web site at: <http://research.vu.edu.au/hrec.php>

Please note that the Human Research Ethics Committee must be informed of the following: any changes to the approved research protocol, project timelines, any serious events or adverse and/or unforeseen events that may affect continued ethical acceptability of the project. In these unlikely events, researchers must immediately cease all data collection until the Committee has approved the changes. Researchers are also reminded of the need to notify the approving HREC of changes to personnel in research projects via a request for a minor amendment.

If you have any queries, please do not hesitate to contact me on 9919 2917.

On behalf of the Committee, I wish you all the best for the conduct of the project.

Prof Carolyn Noble

Chair

Faculty of Arts, Education & Human Development Human Research Ethics Committee

APPENDIX 6: Supplementary information

Review of literature – GPS research summary:

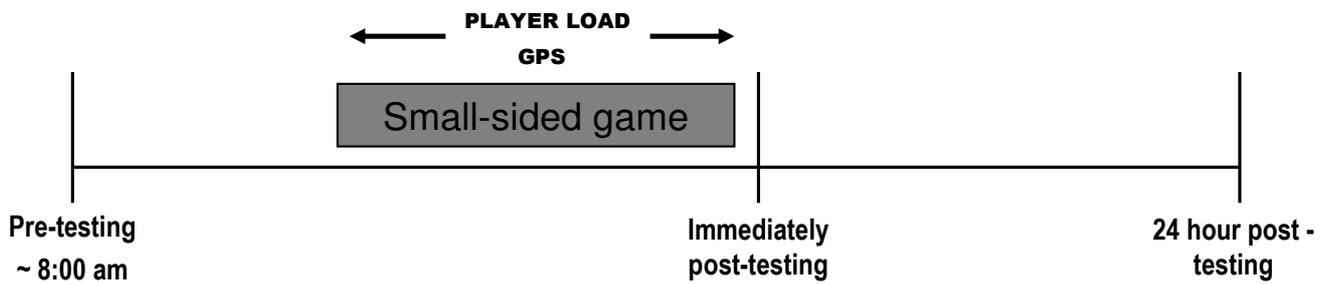
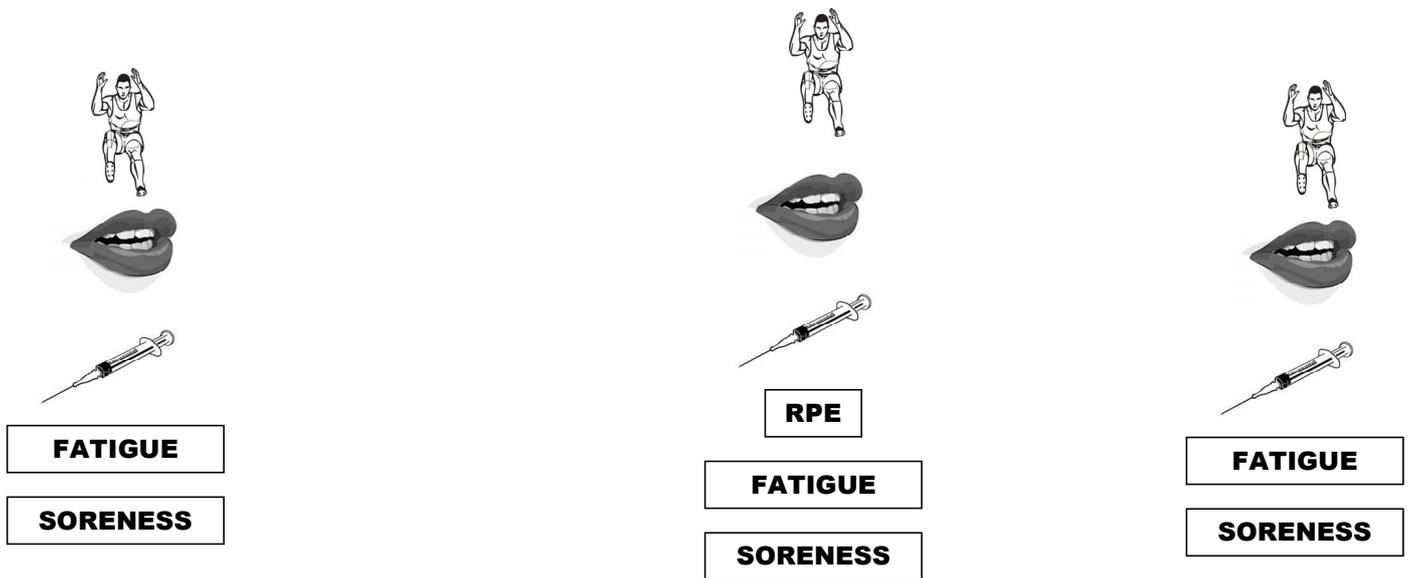
Reliability

Study	GPS make/model	Sampling rate	Task	Criterion measure	Variable	Reliability
Edgecomb& Norton (2006)	GPSports (SPI 10)	1 Hz	Continuous running	Trundle wheel	Distance (meters)	Intra device: CV = 5.5%
Petersen (2009)	GPSports (SPI 10)	1 Hz	Continuous walking, jogging, running, and striding	Athletics track	Distance (meters)	Intra device: CV = 0.4 to 1.5%
Coutts & Duffield (2008)	GPSports (SPI 10)	1 Hz	Team sports locomotor circuit	Measuring tape	Distance (meters)	Inter device: CV = 6.4 to 32.4%
	GPSports (SPI Elite)	1 Hz	Team sports locomotor circuit	Measuring tape	Distance (meters)	Inter device: CV = 4.3 to 15.4%
	GPSports (WiSPI)	1 Hz	Team sports locomotor circuit	Measuring tape	Distance (meters)	Inter device: CV = 11.5 to 20.4%
Barbero-Alvarez <i>et al.</i> , (2009)	GPSports (SPI Elite)	1 Hz	Repeat sprint (7x30 m)	Measuring tape	Velocity (m.s ⁻¹)	Intra device: CV = 1.2 to 1.7%
Petersen (2009)	GPSports (SPI Pro)	5 Hz	Continuous walking, jogging, running, and striding	Athletics track	Distance (meters)	Intra device: CV = 0.3 to 2.9% Inter device: CV = 1.5%
	Catapult Innovations (MinimaxX 2.0)	5 Hz	Continuous walking, jogging, running, and striding	Athletics track	Distance (meters)	Intra device: CV = 1.2 to 2.6% Inter device: CV = 1.3%
	GPSports (SPI Pro)	5 Hz	20 to 40 m sprints	Athletics track	Distance (meters)	Intra device: CV = 2.3 to 9.3%
	Catapult Innovations (MinimaxX 2.0)	5 Hz	20 to 40 m sprints	Athletics track	Distance (meters)	Intra device: CV = 15.8 to 30.0%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.5)	5 Hz	10 to 40m - walking, jogging, running, sprinting	Measuring tape	Distance (meters)	10 m: CV = 22.8 to 39.5% 40 m: CV = 6.6 to 9.3% Sprinting: CV = 9.2 to 39.5% Walking & jogging: CV = 6.6 to 23.3%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.5)	5 Hz	40 m slalom course	Measuring tape	Distance (meters)	Jogging, striding & sprinting: CV = 7.9 to 10% Walking: CV = 11.5 to 15.2%
Portas <i>et al.</i> , (2011)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Sport-specific movement patterns	Trundle wheel	Distance (meters)	CV = 3.08 to 7.71%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Team sports locomotor circuit	Measuring tape	Distance (meters)	Intra device: CV = 3.6% Inter device: CV = 11.1%
Jennings <i>et al.</i> , (2010b)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Competitive hockey matches	-	Distance (meters)	Inter device: CV = 10.3%

Validity

Study	GPS make/model	Sampling rate	Task	Criterion measure	Variable	Validity
Edgecomb& Norton (2006)	GPSports (SPI 10)	1 Hz	Continuous running	Trundle wheel	Distance (meters)	Overestimated by 4.8%
Coutts & Duffield (2008)	GPSports (SPI 10)	1 Hz	Team sports locomotor circuit	Trundle wheel	Distance (meters)	Underestimated by 4.1%
	GPSports (SPI Elite)	1 Hz	Team sports locomotor circuit	Trundle wheel	Distance (meters)	Overestimated by 2.0%
	GPSports (WiSPI)	1 Hz	Team sports locomotor circuit	Trundle wheel	Distance (meters)	Overestimated by 0.7%
Macleod <i>et al.</i> , (2009)	GPSports (SPI Elite)	1 Hz	Sport-specific movement patterns	Trundle wheel	Distance (meters)	-0.1 to 2.5 m
	GPSports (SPI Elite)	1 Hz	Sport-specific movement patterns	Timing light gates	Velocity (m.s ⁻¹)	-0.03 to 0.05 m.s ⁻¹
Petersen <i>et al.</i> , (2009)	GPSports (SPI Pro)	5 Hz	Continuous walking, jogging, running, and striding	Athletics track & time	Velocity (m.s ⁻¹)	<i>SEE</i> = 1.7 to 3.8%
	Catapult Innovations (MinimaxX 2.0)	5 Hz	Continuous walking, jogging, running, and striding	Athletics track & time	Velocity (m.s-1)	Overestimation of 3.2%
	GPSports (SPI Pro)	5 Hz	20 to 40 m sprints	Athletics track & time	Velocity (m.s ⁻¹)	<i>SEE</i> = 0.5 to 3.7%
	Catapult Innovations (MinimaxX 2.0)	5 Hz	20 to 40 m sprints	Athletics track & time	Velocity (m.s-1)	Underestimation of 3.8%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.0)	5 Hz	10 to 40 m walking, jogging, running, striding & sprinting	Measuring tape	Distance (meters)	<i>SEE</i> = 2.9 to 10.5%
Portas <i>et al.</i> , (2011)	Catapult Innovations (MinimaxX 2.5)	5 Hz	50 m walking, jogging, running, striding & sprinting	Trundle wheel	Distance (meters)	<i>SEE</i> = 14.9 to 23.8%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.0)	5 Hz	40 m slalom course	Measuring tape	Distance (meters)	<i>SEE</i> = 9.8 to 30.9%
Portas <i>et al.</i> , (2011)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Sport-specific movement patterns	Trundle wheel	Distance (meters)	Overestimation of ~ 1%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.0)	5 Hz	Team sports locomotor circuit	Trundle wheel	Distance (meters)	<i>SEE</i> = 8.9 to 11.7%
Portas <i>et al.</i> , (2011)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Game simulated course	Trundle wheel	Distance (meters)	Underestimation of -0.6 to 15.8%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.0)	5 Hz	Team sports locomotor circuit	Trundle wheel	Distance (meters)	<i>SEE</i> = 2.2 to 4.4%
Portas <i>et al.</i> , (2011)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Game simulated course	Trundle wheel	Distance (meters)	No systematic over- or underestimation
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.0)	5 Hz	Team sports locomotor circuit	Trundle wheel	Distance (meters)	<i>SEE</i> = 3.8%
Portas <i>et al.</i> , (2011)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Game simulated course	Trundle wheel	Distance (meters)	Underestimation of -3.7%
Jennings <i>et al.</i> , (2010a)	Catapult Innovations (MinimaxX 2.0)	5 Hz	Team sports locomotor circuit	Trundle wheel	Distance (meters)	<i>SEE</i> = 1.5 to 2.2%
Portas <i>et al.</i> , (2011)	Catapult Innovations (MinimaxX 2.5)	5 Hz	Game simulated course	Trundle wheel	Distance (meters)	Underestimation of 1%

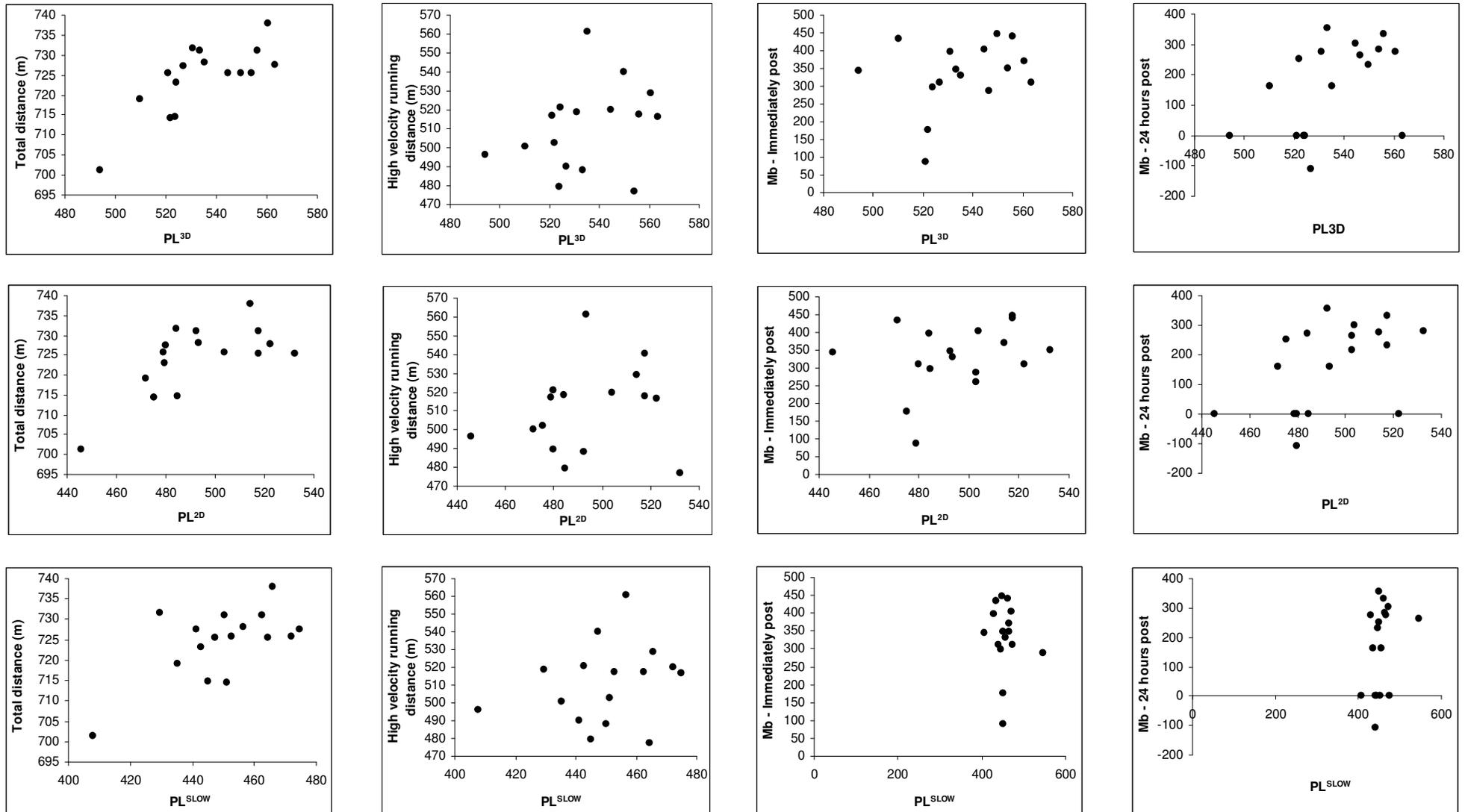
Study 2 - Schematic diagram of protocol:



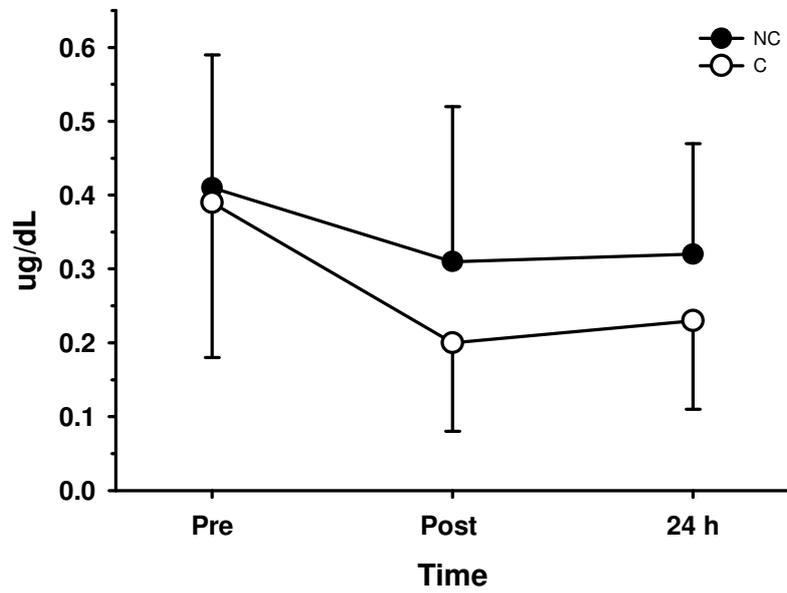
Legend:

- Jump testing – 
- Saliva testing – 
- Blood testing – 

Study 2 – Correlations between accelerometer and GPS variables.



Study 2 – Cortisol results



Time course changes in Cortisol concentration. Closed circles are for non-contact (NC), open circles are for contact (C). All data is $Mean \pm SD$. * denotes a moderate effect between the non-contact and contact conditions.