

GPS Analysis of Elite Level Hockey

Submitted by

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Doctor of philosophy

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ABSTRACT

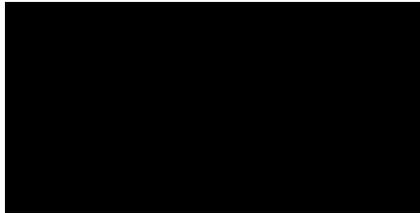
This thesis investigated the suitability of Global Positioning System (GPS) to assess activity profiles in elite hockey. Study one established validity and reliability of GPS units (1 and 5 Hz) to assess distance during movement's common to team sport. Measurement accuracy decreased as speed increased in both straight line and change of direction (COD) courses. Difference between criterion and GPS measured distance ranged from 9.0 – 32.4%. Higher sampling rates improved validity regardless of distance and locomotion. Reliability improved as distance travelled increased but decreased as speed increased. Total distance (TD) over the team-sport circuit exhibited the lowest variation (Coefficient of variation (CV) 3.6% at 1 and 5Hz), while sprinting over 10 m demonstrated the highest (CV 77.2% at 1 Hz). Study two examined the variability between GPS units. Differences ($\pm 90\%$ CI) between the units ranged from $9.9 \pm 4.7\%$ - $11.9 \pm 19.5\%$ for straight line running, $9.5 \pm 7.2\%$ - $10.7 \pm 7.9\%$ in COD courses and $11.1 \pm 4.2\%$ in the team-sport circuit. Similar variability was displayed for TD ($10.3 \pm 6.2\%$) and High Speed Running Distance (HSR) (10.3 ± 15.6) during match play. It is recommended players wear the same GPS unit for each exercise session. Study three compared activity profiles of national and international hockey players. International players covered more TD (13.9%) and HSR (42.0%) than sub-elite players. Less running was performed during the second half in both competitions (TD = 6.1–7.5%). Study four investigated the influence of multiple games on exercise intensity during an international hockey tournament. Two levels of comparison were made; (a) data from subsequent matches were compared to match 1 and (b) data from each match compared to a tournament average (TA). The amount of HSR was maintained as the tournament progressed. When compared to the TA, defenders showed more variation in each match. All positions showed lower movement outputs when the

team won by a large margin. It was possible for elite team sport athletes to maintain exercise intensity when playing six matches in a period of nine days.

STUDENT DECLARATION

“I, Denise Jennings declare that the PhD thesis entitled “GPS analysis of elite level hockey” 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”.

Signature:



Date: 8 August, 2013

ACKNOWLEDGEMENTS

I thought this section would be the easiest to write, free flowing thank-you's to everyone who helped me along the way. Surely the university has a document or policy on what should be included, which font to use, the line spacing, who to include and the word limit. Alas, this is the creative aspect of the document, your own style, is that why it is so difficult? A PhD thesis was once described to me as the process of hitting your head against a brick wall until your supervisors and examiners deem that you have done it enough times to break through the wall. Needless to say, there are a few bruisers. They will heal; the resilience and achievement will remain.

Over the last 5 years there have been a number of constants. These include, supervisors, colleagues, friends, and of course, family.

To my two supervisors, Rob and Aaron, who's extensive, knowledge and support has been invaluable. For different reasons you both have been an integral part of the last 5 and a bit years from inception to completion. The experiences I have had over this time have taught me many things, not only professionally but personally. You have challenged, helped and most of all supported me through the duration of this thesis. I thank you both for the time and effort you have devoted to me and the ongoing support you have shown to assisting me in completing this thesis. I look forward to maintaining this relationship for many years to come.

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ABBREVIATIONS

GENERAL

CT	Champions Trophy
FIH	International Hockey Federation
AHL	Australian Hockey League
MSFT	Multistage Fitness Test
ATP	Adenosine Tri-Phosphate
AF	Australian Football
°	Degrees
s	Seconds
min	Minutes
mm	Millimetres
g	Gram
kg	Kilogram
h	Hour
y	Year

LOCOMOTOR ANALYSIS:

UNITS

GPS	Global position system
Hz	Hertz
dGPS	Differential Global position system
WAAS	Wide Angle Augmentation System
HDOP	Horizontal Dilution of Position
CBT	Computer Based Tracking
COD	Change of Direction
TD	Total Distance

HSR	High Speed Running
LSR	Low Speed Running
VHSR	Very High Speed Running
TMA	Time-motion Analysis
TA	Tournament Average
m	metres
Km	kilometres
m.min ⁻¹	metres per minute
km.h ⁻¹	kilometres per hour
m.s ⁻¹	metres per second

STATISTICAL:

TEM	Technical error of the measurement
TE	Typical error
CV%	Co-efficient of variation
SD	Standard deviation
SEE%	Standard error of the estimate
SWC	Smallest worthwhile change
CI	Confidence Interval
ES	Effect Size
ICC	Intra-class correlation coefficient

CARDIOVASCULAR**UNITS**

VO _{2max}	Maximum oxygen consumption	ml·kg ⁻¹ ·min ⁻¹
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PUBLICATIONS

The following publications are presented in support of this thesis:

Publications arising directly from this thesis:

1. Jennings, D., Cormack, S.J., Boyd, L.J., Coutts, A., Aughey, R (2010) The validity and reliability of GPS units for measuring distance in team sport specific running patterns, *Int J Sports Physiol Perform*, 5:328-341(Study 1; Chapter 3)
2. Jennings, D., Cormack, S.J., Coutts, A., Aughey, R (2010) Variability of GPS units for measuring distance in team sport movements, *Int J Sports Physiol Perform*, 5(4):565-9 (Study 2; Chapter 4)
3. Jennings, D., Cormack, S.J., Coutts, A., Aughey, R (2011) International field hockey players perform more high intensity running than national level counterparts, *J Strength Cond Res*, 26(4):947-952, April 2012 (Study 3; Chapter 5)
4. Jennings, D., Cormack, S.J., Coutts, A., Aughey, R (2012) GPS analysis of international field hockey tournament, *Int J Sports Physiol Perform*, 7(3):224-31 (Study 4; Chapter 6)

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CHAPTER 1. INTRODUCTION

Hockey is a competitive sport requiring prolonged, high-intensity intermittent exercise that has origins dating back to 2000 BC in Asia. As a sport, hockey was spread around the world by English soldiers and sailors while carrying out their duties in expanding and defending the British Empire, and early colonial Australia was no exception. By 1900 AD there were already a number of local men's hockey clubs scattered throughout the states and competitive hockey was being played in private girl's schools in Australia. The first men's association, the South Australian Hockey Association, was formed in 1903. In 1910, the All Australian Women's Hockey Association was created as the national association for women's hockey and in 1925 the men's hockey national body; the Australian Hockey Association was established (Jaensch, Jones, & Nairn, 2003). Today, hockey is a mass participation sport played in every continent of the world, with many nations competing in the three major international competitions - The Olympic Games, World Cup and Champion's Trophy (CT).

A number of significant rule changes have occurred that have improved various aspects of play concerned with issues such as safety, officiating and the speed of the game. Rule changes in hockey have dramatically transformed the game over the past 50 years and are governed by the International Hockey Federation (FIH). The modern game of hockey is now much different from what was played in the early 1900's (Craig, 1979). Examples of such changes include the introduction of common rules for men and women (1975) and the abolition of the off-side rule (1998). More significantly, changes to the playing surface (from grass to artificial grass) and the creation of an unlimited substitution rule, have both likely influenced the physical and technical demands of hockey match play.

At the elite level, hockey is physically demanding, requiring players to have a high level of aerobic fitness, as well as the capacity to perform short-duration, high-intensity efforts (Spencer et al., 2004). In order to cope with the physical demands of match play, training is complex and challenging, as the players are required to develop many facets of physical fitness (e.g., speed, agility, strength, power and aerobic capacity) and skill. As in all competitive sports, hockey coaches are dedicated to improving their teams' performance by optimising training practises specific to their sport.

Hockey shares many tactical and structural similarities with soccer which allows for good comparison between sports. In contrast to soccer however, the volume and quality of research, investigating various aspects of performance in hockey is limited. At the elite level there have been relatively few studies that have provided information on activity patterns and player performance, especially since the more recent rule changes. The most significant of which is the unlimited substitution rule which may have altered the speed and nature of the game (Boyle, Mahoney, & Wallace, 1994; Lythe & Kilding, 2011; Spencer, et al., 2004). The scarcity of research in this area suggests that there is little known about the physical requirements of modern hockey, even at the elite level of competition.

The majority of previous peer-reviewed research in hockey has examined the incidence and type of injuries in training, skill development, tactics and match play as well as the anthropometric and physical characteristics of players (Table 1.1). However, relatively little attention has been given to identifying the differences in physical outputs, activity patterns or physiological responses during match play between various playing positions or standards of competition (Lythe & Kilding, 2011; Macutkiewicz & Sunderland, 2011; Spencer, et al., 2004). Furthermore, no

studies have been completed on players competing at the elite level of competitions of international significance

Table 1-1: Hockey studies divided into topic groups. Reproduced from (Podgórski & Pawlak, 2011)

Theme group	No of publications	Percent (%)
Anthropometrics	14	6 . 7
Biochemistry	32	15 . 4
Injuries	36	17 . 3
Nutrition	7	3 . 4
Physiology	43	20 . 7
Psychology	40	19 . 2
Tactics	36	17 . 3
Total	208	100 . 0

(i.e. The Olympic Games, World Cup and Champions Trophy [CT]). These are played in a round robin or tournament format which may elicit very distinct physical requirements and physiological demands. Currently, no studies have investigated changes in activity patterns during elite level tournament play.

Central to the development of effective training programs for elite level hockey is an understanding of the physical demands and unique activities of the game (Reilly & Borrie, 1992). Much of the information relating to the development of specific training programs or competition demands available to elite players, coaches and scientists is based on relatively few studies. Moreover, the research that has attempted to quantify the activity profiles of hockey match play has a number of limitations (Spencer et al., 2004). Methodological issues such as a lack of information on the reliability of the analysis method, low sample size, and the investigation of one player in a position during each match rather than the requirements of a position for a whole

match may limit these studies. Research is yet to compare time–motion analysis between different levels of elite competition or throughout an international tournament. It is possible that due to the differences in physical fitness and skill between positional sub-groups or playing abilities that the physical match profiles may vary accordingly. Therefore, in order to provide relevant data for the design of specific training programs, there is a need for greater data collection of various playing positions at all playing levels.

Monitoring athletes during competition to develop an understanding of physical and technical demands has evolved considerably since the early methods were pioneered (Pollard, 2002). Indeed, current methods have become extremely sophisticated and are now being applied to a range of sports. Until recently, quantification of player activity profiles has been difficult as it has required manual analysis with only one player being analysed at a time (Roberts, Trewartha, & Stokes, 2006). However, with recent technological developments there are now many systems that can analyse activity patterns of multiple players simultaneously. For example, micro-technology applications incorporating gyroscopes, magnetometers and tri-axial accelerometers have been increasingly used to assess and analyse sporting performances. The use of global positioning system (GPS) receivers are being increasingly applied to a range of sporting applications. Recent advances in this system now enable units to be worn during competition and training, providing detailed information about activity patterns of athletes. This technology has provided an alternate data acquisition method to video-based time-motion analysis when determining the demands of training and competition in real time as well as potentially overcoming some of the limitations associated with traditional methods (Liebermann et al., 2002; Peterson, Pyne, Portus,

& Dawson, 2009). This is a distinct advantage compared to the time consuming video-based time-motion analysis systems.

This technology is now widely used in team sport and has led to an increase in the use of GPS to investigate specific speeds and distances travelled during training and competition. However, this has been prior to the establishment of the measurement validity and reliability of these GPS devices. As yet, the value of GPS for the assessment of athlete activity profiles in team sport remains unclear and there has been insufficient published data to establish the reliability, validity and practicality of this application (Dobson & Keogh, 2007).

This thesis aims to determine which aspects of GPS derived data are valid and reliable for use when describing activity profiles in team sport, and specifically elite level hockey. An additional aim is to quantify differences between national and international competition as well as examine activity profile variations during an elite international tournament.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Introduction

The following section reviews the research methods used to determine activity profiles of team sports. This review focussed primarily on methods used in hockey, however some additional methods utilised in other team sports are also discussed. The literature reviewed will be from prior to the publication of the four experimental chapters. More recently published literature will be examined in the general discussion section.

2.2 Hockey

2.2.1 Introduction

Hockey originated in primitive form, thousands of years before the first Olympic matches, in 776 B.C. The sport evolved through Roman-influenced Europe and developed derivatives in Germany (Kolbe), Holland (Het Kolven), France (Hocquet) and Ireland (Hurling). The first hockey association was formed in 1873 and international field hockey competitions were played by men as early as 1895 (Reilly & Borrie, 1992). At present there are 64 ranked women's teams and 68 ranked men's teams in the world and hockey is a formal sport in both the Commonwealth and Olympic Games. Other significant international tournaments at the elite level include the World Cup and CT.

In Australia, field hockey has approximately 145,000 registered players from 880 clubs. In addition to players registered with clubs, hockey is played extensively in Australian schools and at a recreational level bringing the total participants close to 200,000. The Australian Hockey League (AHL) is the highest standard of domestic competition and provides a pathway to international representation.

Despite its widespread popularity, there has been relatively little information and research conducted on the physical and physiological demands of hockey. The following literature review consists of searches for scientific studies on hockey hosted on a number of available databases. They were obtained by browsing for publications on a variety of topics in the PubMed and EBSCO host databases, which included Academic Search Premier, SPORT Discus, and MEDLINE. Key words included in this search were, field hockey, movement patterns, GPS, time-motion analysis, activity profile, competition and tournament. Often referred to as field hockey to differentiate it from ice hockey, within Australia and other Commonwealth nations, the term hockey is used. For the purpose of this thesis, hockey will be used throughout.

2.2.2 The game of hockey

Hockey is played between two teams of eleven players, including a goalkeeper. The field of play is rectangular (91.4 m long and 55 m wide, Figure 2.1) and a match consists of two, 35 minute halves. The object of the match is to hit the ball (approximately 9 inches in circumference) into the opponent's goal using specially shaped sticks that are 36 - 42 inches in length.

A significant rule of hockey is that for a goal to be scored the ball must touch an attacking player's stick inside of the attacking circle (a 16 yard semi-circle around the goal). Additionally, penalty corners, which are an important goal scoring set-piece opportunity, are awarded for infringements by the defenders inside the circle. These two factors make getting the ball into this area a key objective for the attacking team.

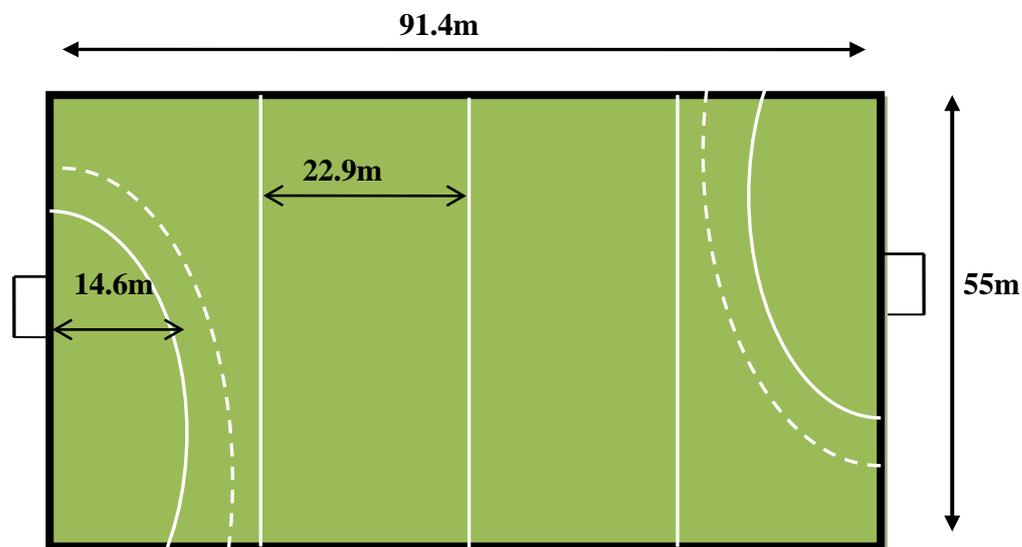


Figure 2.1: Dimensions of hockey field (reproduced from www.dsr.wa.gov.au/hockeydimensions)

The playing positions of hockey can be divided into three broad groups; strikers, midfielders and defenders. More specifically, positions can be defined using five categories; goalkeepers, fullbacks, halves, inside forwards and forwards with each position positional area having specific roles and activities. For the purpose of this review the positional group of the strikers consists of the three forwards, while the midfielders consist of two inside forwards as well as the centre half, and defenders contain the two outside half-backs as well as the two full backs. Many similarities exist between field hockey and soccer, making comparisons between sports possible. These include positional formations, number of players as well as similarities in field

size and match duration. Although there are many options, a typical hockey team formation is a goal keeper, two fullbacks, three halves, two inside forwards and three strikers (Figure 2.2).

Over the past four decades a number of significant modifications to the structure of hockey have transpired. In the 1970s the playing surface changed from grass to artificial turf significantly altering the pace and style of the game (Reilly & Borrie, 1992). In recent times, the most significant changes have been the removal of the off-side rule and the introduction of unlimited interchange. Although it is possible that these changes may have facilitated fast-paced, continuous play and altered the tactical and physiological requirements of the game (Spencer, et al., 2004), the magnitude of effect is not yet known.

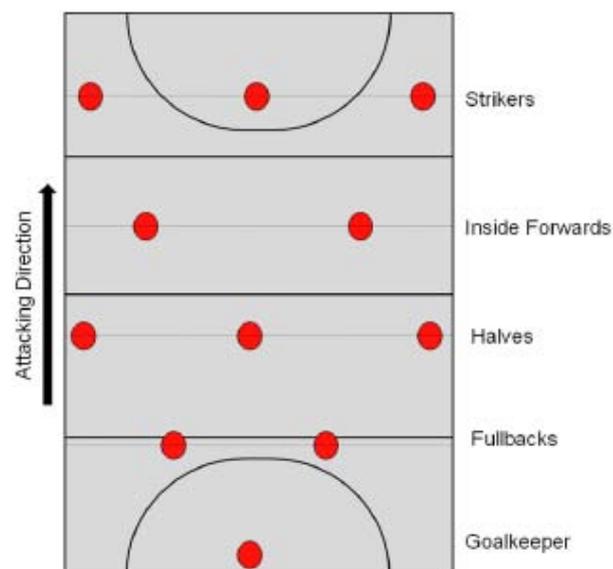


Figure 2.2: Typical positional formation in hockey.

2.2.3 *The physiological capacity of hockey players*

Hockey is a sport that demands a combination of high muscular strength, power, speed and flexibility, as well as high aerobic and anaerobic capacities (Reilly & Borrie, 1992). The physical capabilities of hockey players have been measured using

both field and laboratory tests. Field tests such as the multi-stage fitness test (MSFT) and Yo-Yo intermittent recovery tests, sprint tests, agility and anaerobic capacity tests, as well as tests of muscular strength and power are most commonly used (Gore, 2000).

This group of tests can be separated into two distinct categories; capacity tests assessing players underlying physiological capabilities and performance tests. Both laboratory and field tests have advantages and disadvantages for application in hockey. At the elite level, laboratory based capacity tests such as the assessment of maximal oxygen uptake ($\dot{V}O_{2max}$) is common (Spencer, Bishop, Dawson, & Goodman, 2005). The advantage of this test is that it measures oxygen uptake directly and scientists can be more confident that the athlete provides a maximal effort. However, the exercise protocol with this test is not specific to hockey, due for example, to the intermittent nature of hockey during match play, and the physiological cost of accelerating, decelerating and changing direction which is not captured in this test (Osganach, 2009). The contribution of these actions to the total energy expenditure should not be ignored when attempting to assess physiological or performance characteristics specific to hockey. Consequently, it may be appropriate to perform more frequent changes of motion in testing batteries for hockey players. Due to this, field based tests are more widely adopted in hockey (Reilly & Borrie, 1992; Spencer, et al., 2004).

In contrast, the MSFT and Yo-Yo intermittent recovery tests require accelerations and decelerations and may be more appropriate. In addition, these tests offer several other advantages of laboratory based tests. For example, a large number of people can be tested at once; they are cost effective and require little specialized equipment to perform. Results are commonly used to assess players' adaptations to training, identify talent, predict match running capacity and assess player capacities allowing

for the prescription of training programs (Castagna, Impellizzeri, Chamari, Carlomagno, & Rampinini, 2006).

Like other sports that require prolonged high-intensity, intermittent exercise, hockey has a large reliance on the aerobic pathways for energy provision (Reilly & Borrie, 1992). Although aerobic metabolic pathways provide the majority of energy, anaerobic activity is highlighted during the more crucial moments of the match that contribute directly to winning possession of the ball as well as the scoring or conceding of goals. Hockey is referred to as an intermittent team sport due to the pattern of repeated short bursts of high intensity activity interspersed with active and passive recovery. Such a pattern requires lactate removal and rapid regeneration of phosphocreatine (PCr) stores to allow for sustained performance (Tomlin & Wenger, 2001).

Muscular strength in hockey is required to strike the ball, tackle and also tolerate physical impacts with other players. Moreover, anaerobic power is also important in accelerating the body during short movements and changing direction quickly. Indeed, players who can sustain a high work-rate throughout a match may gain an advantage over equally skilled players whose energy can approach depletion towards the end of a game or after a series of high intensity efforts, resulting in reduced physical performance (Reilly, Bangsbo, & Franks, 2000).

Published research on the physical demands of hockey is limited, especially relating to recent and elite competition. Regardless, research from other team sports has shown that the aerobic system is important for facilitating recovery between high-intensity efforts in field sports and is related to performance during prolonged high-intensity running exercise (Helgerud, Engen, Wisløff, & Hoff, 2001; Sirotic & Coutts, 2007). However, few studies have directly measured $\dot{V}O_{2\max}$ in male hockey players,

particularly at the elite level (Lythe & Kilding, 2011; Spencer, et al., 2004). Descriptive information from the Indian national team reported that average $\dot{V}O_{2\max}$ was $54.4 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and $53.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for junior players and senior players, respectively (Cych, 2006). Interestingly, slightly higher values were measured in the junior players in that study, this may have been due to lower body mass, although this information was not included in the results. No information was provided in regard to the timing of testing in relation to different squads preparations as this may have influenced the fitness of subjects, limiting the application of this information.

A study of Australian international players reported higher $\dot{V}O_{2\max}$ values ($57.9 \pm 3.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Spencer, et al., 2004). The higher fitness of these players may have been due to the increased professionalism of international teams as well as a greater emphasis on a systematic use of sports science to develop training regimes (MacLeod, Bussell, & Sunderland, 2007). The higher fitness of these players is also an indication of the increase in athleticism in international hockey over the last 5 – 10 years; a trend that has also been reported in other team sports such as soccer (Bangsbo, Mohr, & Krstrup, 2006) and rugby union (Quarrie & Hopkins, 2007). Aerobic capacities have improved with semi-elite Australian national league level players also showing higher $\dot{V}O_{2\max}$ values ($62.1 \pm 2.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Harvey, Naughton, & Graham, 2009). Recently, high values were also reported by New Zealand national team members ($64.9 \pm 1.9 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). These players were in the final stages of preparation for a major tournament and had been training consistently for a number of months, and as a consequence were likely to be in peak fitness (Lythe & Kilding, 2011).

2.3 Time-motion analysis

Time–motion analysis provides an objective yet non-invasive method for quantifying the activity profiles of an athlete during match play. Such analyses may provide a

valuable insight into the physical work demands and activity profiles of a chosen sport. This information has been used for, and is considered a fundamental requirement for the development of physical training programs (Duthie, et al., 2003). Feedback from motion analysis also has the capacity to set benchmarks for desirable on-field physical performance and can assist in quantifying the changes in sports, competition levels and performances over time (Williams, Lee, & Reilly, 1999).

Time-motion studies have provided information on the mode, frequency, and duration of player activities in sports such as soccer (Bangsbo, et al., 2006; Bangsbo, Nørregaard, & Thosøe, 1991; Burgess, Naughton, & Norton, 2006; Krstrup, Mohr, Ellingsgaard, & Bangsbo, 2005), rugby union (Duthie, Pyne, & Hooper, 2003a; Sirotic, Coutts, Knowles, & Catterick, 2009), rugby league (Estell, Lord, Barnsley, Shenstone, & Kannagara, 1996; Gabbett, 2005) and Australian football (AF) (Appleby & Dawson, 2002; Aughey, 2010; Brewer, Dawson, Heasman, Stewart, & Cormack, 2010; Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010; Dawson, Hopkinson, Appleby, Stewart, & Roberts, 2004b). These studies have allowed insights into the activity profiles of these respective competitions. Commonly reported variables in previous studies, include total distance covered, specific distances covered and time spent in various speed zones (Dawson, Hopkinson, Appleby, Stewart, & Roberts, 2004a; Dawson, et al., 2004b; Deutsch, Kearney, & Rehrer, 2007; Duthie, Pyne, & Hooper, 2005; Spencer et al., 2005), length, time and frequency of efforts (Bangsbo, et al., 1991; Duthie, et al., 2005), and work to rest ratios including time between maximal efforts (Dawson, et al., 2004a, 2004b; Spencer, et al., 2004). This information has also been suggested to be used to improve the specificity and focus of training to promote enhanced physiological adaptations to improve match performance (Dawson, et al., 2004b; Spencer, et al., 2004).

Time-motion analysis in hockey has determined the activity profile of both female (Gabbett, 2010; Lothian & Farrally, 1994; MacLeod, et al., 2007) and male players (Lythe & Kilding, 2011; Spencer, et al., 2004), the number of repeat sprints performed in competition (Spencer, et al., 2004) as well as the differences in motion between two halves of a game. Changes in activity profiles of hockey players have also been analysed between consecutive games (Spencer, et al., 2004). A variety of measurement systems and methods have been used to document time and motion activity in team sports. The following section will focus on two specific methods: video-based and automated systems.

2.3.1 Video-based time-motion analysis systems

The majority of time-motion investigations in hockey have used observational techniques to evaluate the overall physical activity associated with match-play by recording and analysing the many different activities for the players observed (Spencer, et al., 2004). Early approaches focused on the use of hand notation systems for the recording of activity patterns, where player movements were tracked on a scale plan of the pitch. More refined systems were then developed using coded commentaries of activities recorded on audio tape, in conjunction with measurements based on stride length and frequency taken from video recordings to evaluate the total distance (TD) covered for the duration of a match (Dobson & Keogh, 2007). Whilst the early studies that employed these methods revealed important information about the demands of hockey, the complexity and large amount of time required for coding, analysing and interpreting the output inhibited their use by performance analysts (Lythe & Kilding, 2011). Furthermore, these methods did not allow real-time analysis and were extremely labour-intensive in terms of the capture and analysis of data (Carling, Bloomfield, Nelsen, & Reilly, 2008). These original techniques were also

restricted to the analysis of a single player, therefore limiting the practical application of research projects.

A later method of filming and analysis utilised two or three fixed cameras (Reilly & Gilbourne, 2003). This allows for a combined view with the cameras covering the complete playing area and their fields of view overlapping facilitating the tracking of players from one camera's view to the next. Player motion was then subjectively categorised while watching the video playback. This can be performed by one, but usually two operators. The first operator watching the video, calling changes in motion of a single player, with the second operator inputting the events manually into a computer with purpose built software (Edgecomb & Norton, 2006; Spencer, et al., 2004). Computer-based tracking (CBT) relies on ground markings and reference points that translate to markers on a miniaturized, calibrated version of the playing field (Edgecomb & Norton, 2006). This method utilises a stylus or movements of a mouse which correspond to the linear distance travelled by the player to estimate activity profiles. The validity and reliability of this method is discussed in the following section. Although each method used different techniques, they fundamentally measured the same variables, namely, the activity profile of players.

Alternative methods for measuring activity profiles have included video footage taken from overhead views of the pitch for computer-linked analysis of the movements of the whole team and synchronized cameras positioned to overlook each half of the pitch; activities are then calculated using trigonometric principles (Edgecomb & Norton, 2006). Both notation and motion analysis techniques provide a valuable source of feedback to coaches and players, specifically regarding the physical requirements of match play.

Activity profiles of players within a team have been established according to the intensity, duration, and frequency of classified activities (e.g., walking, moving sideways or backwards, jogging, cruising, and sprinting). Movement classification systems were originally documented in the soccer literature (Reilly & Thomas, 1976) and recently modified for use in other team sports such as rugby (Deutsch, Maw, Jenkins, & Reaburn, 1998; Docherty, Wenger, & Neary, 1988) and hockey (MacLeod, et al., 2007; Spencer, et al., 2004). Each movement was coded as one of six speeds of locomotion and depending on the sport assessed, game specific movements and involvements were also identified (Duthie, et al., 2003a; Macutkiewicz & Sunderland, 2011). For example, hockey time-motion analysis studies have included lunging as part of the analysis (MacLeod, et al., 2007). Rugby time-motion analysis studies have also included game specific movements identifying three states of non-running intensive exertion (rucking / mauling, tackling, and scrummaging), and three discrete activities (kicking, jumping, passing) (Sirotic, et al., 2009).

Whilst there is no strict consensus in time-motion research on motion categories, there are common modes of movement used in studies across different sports. In a study of elite men's hockey using a video-based time-motion analysis system, player motion was coded into five distinct categories. These were defined as follows (Spencer, et al., 2004):

1. Standing: motionless.
2. Walking: motion, but with both feet in contact with the ground at the same time at some point during the gait cycle.
3. Jogging: motion with an airborne phase, but with low knee lift

4. Striding: vigorous motion with airborne phase, higher knee lift than jogging (included skirmishing movements of rapid changes of motion, forwards / backwards/ laterally).
5. Sprinting: maximal effort with a greater extension of the lower leg during forward swing and a higher heel lift relative to striding.

Difficulties exist when comparing data from studies using different classification systems. For example, some studies have combined the motions of sprinting and striding (or high-intensity efforts) into one category and utilised different speed zones to define these high intensity categories. This may impact the distance recorded for these zones (Mayhew & Wenger, 1985; McKenna, Patrick, Sandstrom, & Chennells, 1988; Meir, Arthur, & Forrest, 1993). Furthermore, different methods have been used to document motion activity (i.e. manual charting, audio recording, video recording and computer tracking), which may influence the accuracy of results (Spencer, et al., 2004).

2.3.2 Reliability of video-based analysis systems

Reliability is an assessment of the consistency of a measure and is usually determined by testing and then retesting individuals under the same conditions (Atkinson & Nevill, 2001). For a measurement system or testing procedure to be useful in assessing athletic performance, it needs to be able to reproduce consistent and reliable data (Duthie, Pyne, & Hooper, 2003b). There are numerous statistical procedures used to determine the reliability of a system or test (Atkinson & Nevill, 2001; Hopkins, 2000). Ideally, a combination of statistical procedures including the technical error of measurement (TEM) and correlation analysis, each with corresponding confidence intervals, should be used (Pyne, 2003). This can also be expressed in relative terms as a coefficient of variation (CV). The information obtained from these reliability

measures will allow sport scientists to interpret the smallest worthwhile change, or changes independent of *'technological, biological and systematic'* error (Atkinson & Nevill, 2001). The ability to identify a *'real'* change in these measures enables sports scientists to more accurately assess performance, evaluate player qualities, the effects of interventions and prescribe training. This type of analysis is especially important for elite level athletes when small, meaningful changes may be lost with traditional approaches to statistical analyses (Hopkins, 2000).

The reliability of video-based time–motion analysis methods has been determined for many team sports (Coutts & Reaburn, 2000; Dawson, et al., 2004b; Duthie, et al., 2003b; Krstrup & Bangsbo, 2001; Martin, Smith, Tolfrey, & Jones, 2001; Williams, et al., 1999). These studies reveal wide variations in the level of test-retest reliability between both the time–motion analysis methods used, but these have been estimated from a number of statistical methods. Since a number of human testers are used in manual video-based time-motion analysis, most researchers determine their own reliability statistic (intra- and inter observer) as part of the study methodology. Intra and inter-observer reliability assessments are common practice as human testers are required to collect and analyse data. These variations may also be related to the typically low sample size used for assessment which may be due to the time consuming nature of this work. Differences in durations of matches analysed as well as the inconsistency in time elapsed between testing and re-testing may also add to the surrounding issues when assessing this aspect of reliability. Additionally, manual time–motion studies may be influenced by an observer's knowledge of the game, focus of attention, level of arousal and anticipation of game-specific events during each analysis occasion (Duthie, et al., 2003b).

The intra-tester reliability of video-based motion-analysis has been determined from international male hockey players during match play. In that study, observers visually categorized players' movements into standing, walking, jogging, striding and sprinting. To determine the reliability, half the match was analysed twice for five players, by the same observer. The typical error (TE), expressed as a coefficient of variation (CV), was 5.9-10.2% (mean = 7.8%) for the frequency of movement and 5.7-9.8% (mean 8.1%) for duration of movement (Spencer, et al., 2004).

In order to provide accurate information for specialised training programs and to accurately describe match profiles, time-motion measurement systems need to be able to reproduce consistent and reliable data. A tracking system with poor measurement reliability is of little practical benefit for coaches and scientists, as small variations in match running performance between players or matches cannot be detected. Indeed, in a study that examined the reliability of a video-based analysis system during a rugby union match, moderate to poor reliability for total duration of activities with a CV of 5.8-11.1% were reported (Duthie, et al., 2003b). Further, a TEM of 4.3-13.6% for the frequency of individual activities, indicating good-to-poor reliability were also reported (Duthie, et al., 2003b). Interestingly, when analysing movement distance at different intensities using a computer based tracking system, low-intensity activities demonstrated a good level of reliability (4.0-6.0 TEM%), and measures of high-speed movements demonstrated only a moderate-to-poor level (6.5-13.2 TEM%) of reliability (Sirotic & Coutts, 2009). The increased measurement error at higher speeds may be due to the difficulty in assessing these brief and high intensity efforts as they occur over short distances. Better reliability is more commonly observed in lower speed activities performed over longer distances.

In comparison, the total frequency of activities during 10 minutes of futsal match-play movement patterns had a TEM of 5.0% for video-based analysis indicating good to moderate reliability for notational analysis (Doğramaci & Watsford, 2006). However the comparison between studies is difficult due to variations in the sample time used to calculate the TEM. The lower TEM's in the futsal study may be due to the lower total sampling time, compared to the 80 mins of a rugby union match used by Duthie et al (2003).

The poor reliability of these methods, especially at higher speeds, along with the logistical limitations (i.e. time consuming data collection procedures and the requirement for extensive post hoc data analysis) has led to the development of semi-automated tracking systems (e.g. Prozone Sports Ltd®, Leeds, UK; & Amisco Pro, Sport-Universal Process, Nice, France) and microtechnologies, including GPS.

2.3.3 Automated systems

Advances in technology have allowed new methods of assessing the activity profiles of players in soccer, including the multiple-camera method (Di Salvo, Collins, McNeill, & Cardinale, 2006; Edgecomb & Norton, 2006; Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007). These multi-player tracking systems are based on integrated computer and video technology and are currently the most widely used commercial tracking systems in professional European soccer. Systems were developed to further increase accuracy (sampling rate > 10 Hertz (Hz)), and reduce labour in the recording and analysis stage. Multiple cameras (6 to 12) are strategically positioned to simultaneously observe the playing surface, umpire, ball and all players involved in the match activity (Rampinini et al., 2007). Optical character recognition technology detects 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). In comparison to other video-based time-motion analysis systems, a distinct advantage of this system is the capture of player movement in real-time. However, operators are required to manage the system during capturing periods (Di Salvo et al., 2007; Rampinini, Coutts, et al., 2007).

2.3.3.1 Reliability of automated tracking systems

Relatively little information exists regarding the reliability of automated tracking systems, with the majority of studies examining soccer-specific activity. Intra- and inter-operator reliability was assessed for the Prozone automated camera tracking system (Prozone Sports Ltd®, Leeds, UK) during a soccer match. Two trained observers tracked five randomly selected professional soccer players on two separate occasions. Intra-observer reliability for TD (CV = 1.0%) was high, as was the distances covered in each velocity band (CV= <1.2%). Similar to the previous video-based analysis systems, at high speeds the reliability decreased (CV= 2.4%) (Bradley et al., 2009). Inter-observer reliability showed similar tendencies, with lower intensity activities (CV= 1.2%) more reliable, compared to sprinting (CV= 3.5%). Although reliability decreased at higher velocities, this variation was below that deemed to be an acceptable level for team sports analysis.

2.3.3.2 Validation of automated tracking systems

Despite the widespread popularity of semi-automated player tracking devices, there is relatively little information regarding the validity of these systems. Validation of the same system (Prozone Sports Ltd®, Leeds, UK) was carried out using a series of runs, of known distance performed at different velocities in different parts of two separate stadiums (Di Salvo, et al., 2006). Straight, curved and turning runs (90 degree (°)) were performed at velocities ranging from 1.95 to 6.38 m.s⁻¹. 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., 2006). Straight line activities were the most accurate, with turning activities being more difficult to measure (Table 2.1). Sprinting activity ($>25 \text{ km}\cdot\text{h}^{-1}$) however, as reported in the previous reliability study was not validated. Unfortunately, failure to accurately measure this type of maximal activity may underestimate the true locomotor demands of matches (Duthie, Pyne, Marsh, & Hooper, 2006).

Multi-player tracking systems such as AMISCO and Pro Zone generally require the permanent installation of several cameras fixed in optimally calculated positions to cover the entire surface of play. Being a fixed camera set up, usually at the playing stadium of the home team, the use of the system at other venues and training facilities is not possible, limiting valuable data collection to competition matches only (Carling, et al., 2008).

Table 2-1: Statistical measure of absolute reliability for velocity over four 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 (2010).

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

A further limitation of these systems is the high financial cost (Di Salvo, et al., 2006). This restricts the use of automated systems to elite sporting organisations. To overcome the costs of multiple camera systems, GPS systems have been suggested as a viable alternative for time-motion analysis (Witte & Wilson, 2004).

2.4 Global Positioning System

The global positioning system (GPS) is a navigation system that uses up to 27 operational satellites in orbit around earth. First developed for the U.S. military, GPS became fully operational in the mid-1990s (Witte & Wilson, 2004). Increasingly, GPS has been used for aviation, marine, recreational and more recently in the sporting environment. It allows the tracking of a change in position (displacement) of an object (e.g. an athlete) in real-time. As yet however, the usefulness of this application to team sport analysis remains unclear as there has not been sufficient published data to establish the reliability, validity and practicality of 1 and 5 Hz GPS systems.

One advantage of GPS over semi-automated analysis systems is that GPS devices can now be worn during competition and training. A further benefit is the systems portability. Rather than a fixed camera with a specific stadium, this system can be used at different competition and training venues, providing a more extensive information about the activity profile of athletes. Information from these devices is derived using satellites orbiting the earth. The satellites first set the clock in the GPS receiver by synchronising it with the atomic clock in the satellite. The satellites then constantly send information (at the speed of light) about exact time to the GPS receiver. By calculating the displacement between the signal (satellite) and the receiver (GPS unit), the exact position can be determined. This calculation utilizes a doppler frequency calculation, whereby the phase-shift difference between the

satellite and an oscillator-produced signal within the receiver is measured (Schutz & Herren, 2000). By calculating the distance to at least four satellites, the exact position can be trigonometrically determined (Cunniffe, Proctor, Baker, & Davies, 2009). Figure 2.3 shows the satellites signals being detected by a GPS unit. This is the basis on which non-differential GPS, differential GPS (dGPS) and Wide-Angle Augmentation System GPS (WAAS-enabled GPS) work. However, dGPS and WAAS-enabled GPS have some distinctive differences, which improve their level of precision.

In an attempt to improve position determination accuracy for aviation, the satellite based WAAS-enabled system was developed (Witte & Wilson, 2005). This system employs the same principles as dGPS, with receivers in known locations being used to correct the error in the individual satellite data (Witte & Wilson, 2005).

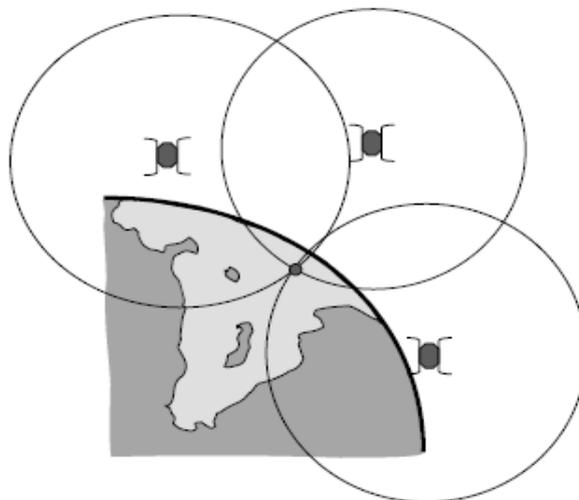


Figure 2.3: GPS unit scanning for and locking into 3 of 27 satellite signals (Larsson, 2003).

The correction data is then sent to an additional Geostationary Earth Orbit Satellite, which in turn transmits the correction data to the standard GPS receiver in the form of a pseudo-range code (Witte & Wilson, 2005). The limitations of newer GPS units are

their costs and design as they are bulkier and less portable than traditional GPS units. These factors preclude the use of these in team sport environments.

Differential GPS requires that one of the receivers is located at a station of known position (the “base” station), while the other is at an unknown location or “receiver station”. The stationary receiver then compares their fixed position to the position given by the satellites to the GPS unit. The correction signals are then sent from these receivers via radio waves to the GPS unit via a differential receiver (Larsson & Henriksson-Larsen, 2001). The GPS unit is then able to re-calculate the correct position of each satellite and therefore its position on earth more accurately than a standard GPS unit (Schutz & Herren, 2000). The application and potential use of these systems for studies of locomotion was performed over an orienteering course, where one participant was tracked over a predetermined course (Larsson, 2003). One of the major disadvantages of the dGPS technique is that speed can only be measured in an environment in which access to the satellites is not obstructed by urban landscapes, tall skyscrapers, tunnels, stadium roofs or roofs that overhang playing surfaces (Schutz & Herren, 2000). Since elite team sports competition often takes place in stadiums, a further methodological consideration that is most often ignored is the potential horizontal dilution of position error that may occur as a function of building structures near the playing field (Williams & Morgan, 2009).

2.4.1 Horizontal dilution of position

The horizontal dilution of position (HDOP) is a reflection of the geometrical arrangement of satellites and is related to both the accuracy and quality of the signal. Values can range between 1 and a maximum value of 50, with an ideal HDOP of 1 indicating that one satellite is directly overhead with the remainder equally spaced around the horizon (Witte & Wilson, 2004). Higher values show a situation where

satellites are tightly clustered overhead and a maximum value of 50 indicating that the position fix is unreliable (Witte & Wilson, 2005). When reporting GPS data, authors should attempt to quantify and report both HDOP and estimates of the number of satellites to provide readers with a clearer understanding of the quality of data presented.

2.4.2 Application of GPS to team sport

There is a growing body of literature examining the use of GPS for time-motion and player analysis. Specifically, GPS technology is used by many sports to quantify the activity profile of players during training and competition. The development of GPS units, designed for athlete tracking, have provided an alternate data acquisition method to determine the demands of training and competition in real time with the potential to overcome some of the limitations associated with traditional methods (Liebermann, et al., 2002; Peterson, et al., 2009). Until recently, measurement and quantification of player activity profiles has been difficult as it has required manual analysis with only one player being analysed at a time (Roberts, et al., 2006). The GPS system automatically tracks and stores the movement patterns of individuals. Multiple players can be tracked at the same time, with data collection automated. This is a distinct advantage compared to video-based time-motion analysis.

The GPS receivers worn by players during training and competition draw on signals sent from at least four satellites located in the atmosphere. Using this information, the receivers are able to calculate and store data on position, time and velocity. Early units weighed approximately four kilograms (kg), and thus could not be used in athletic settings (Larsson, 2003). The current size of the receiver has decreased from initial models to the point of being appropriate for use in sporting environments. Units are approximately 67- 76 grams (g), and 48 mm x 20 mm x 87 mm in size, the size of

a small mobile phone. Current GPS devices can withstand heat, moisture and potential impact which can be applied in team sport environments. Devices are typically worn in custom made harnesses or built into playing garments located in the centre area of the upper back slightly superior to the shoulder blades at approximately the level of thoracic vertebrae (T1). This ensures that range of movement through the upper body and torso are not limited and provides clear unrestricted reception to antennas located at the top of the units.

The application of GPS technology in sporting settings utilizes the same principles for position calculation as does navigational GPS units, with the unit's operating initially at 1 Hz. The first commercially available GPS device designed specifically for use in sporting environments became available in 2003 (Edgecomb & Norton, 2006). At present, two commercial manufacturers are commonly used in elite sports environments and time-motion research (i.e. Catapult and GPSports). With the production of sport-specific GPS hardware and software, information from GPS units has increasingly been used to assess the activity of players training and competition. The accompanying software allows analysis of the GPS signal, which can provide the athlete with information such as distances covered, speed achieved as well as frequency and durations of efforts performed. Indeed, GPS technology has the potential to provide a more comprehensive, accurate and automated examination of player movements in invasion style team sports (e.g., hockey, rugby union, rugby league, soccer and Australian Football).

Position data can now be collected at a 5 Hz sample rate during match play and training. This increase in sample rate may enhance the validity and reliability of GPS for team sport applications. Few studies have investigated the reliability and validity of GPS technology for the assessment of activities performed in team sport (Barbero

Álvarez, Coutts, Granda, Barbero Álvarez, & Castagna, 2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, Morris, Nevill, & Sunderland, 2009; Peterson, et al., 2009). Additionally, most studies have assessed the validity and reliability of these GPS devices with distance and positional data recorded at 1 Hz, (Barbero Álvarez, et al., 2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009). Only recently, have researchers used 5 Hz data (Peterson, et al., 2009).

2.4.3 Reliability of GPS for use in team sports

A growing body of research exists on the use of GPS devices for the measurement of physical activity but only very limited research to date has applied GPS to team sport time-motion analysis. However, only a small number of studies have investigated the reliability of GPS technology for the assessment of team sport movement patterns (Barbero Álvarez, et al., 2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009; Peterson, et al., 2009). Additionally, relatively few studies have assessed the reliability of these GPS devices with distance and positional data recorded at 5 Hz, (Peterson, et al., 2009). The reliability of GPS to determine human locomotion is influenced by a number of factors including, sample rate, velocity and duration of movement, as well as the type of task performed.

The increase in the application of GPS technology to investigate activity patterns in team sports in training and competition has largely occurred prior to the establishment of variables that are reliable and valid. Fast bowler movement patterns in one day cricket (Peterson, et al., 2009) and distance and intensity measures in tennis (Reid, Duffield, Dawson, Baker, & Crespo, 2008) have been described, yet surprisingly no reliability data reported for the devices in these studies.

Interest in GPS monitoring of hockey is growing. Information collected by conditioning and sports science personnel using GPS data attempts to quantify the activity demands of training and competition (Gabbett, 2010). However, the reliability and validity of this methodology for use in hockey has yet to be established. It is prudent therefore, to assess the reliability and validity of GPS measurements over sport-specific distances and locomotion patterns to determine the measurement error. Once the technology is deemed to be accurate and reliable and the measurement error is less than the within-player variability, sports science practitioners can confidently use the GPS measurements to estimate game distances and player movement velocities.

2.4.4 Sample rate

The sample rate refers to the speed at which a GPS unit can collect movement information (Coutts & Duffield, 2010). The sample rate may impact on the quality of the data collected, with a higher sampling rate potentially allowing for the collection of more accurate movement data. A 1-Hz GPS unit, for example, collects only one position measurement each second. These units may miss critical data and be unable to accurately detect changes in running distances at higher velocities. (Coutts & Duffield, 2010). To investigate this, three 1 Hz GPS units were used to estimate distance and speed in a linear running protocol at varying velocities. This information was then compared against timing gates over 10 trials (Portas, Rush, Barnes, & Batterham, 2007). Results suggested that the error for GPS distance measurements varied by the velocity of the trial. Specifically, the mean percentage error, equivalent to CV, was highest during running at 22.5 km·h⁻¹ (5.64%; 2.82 m) and lowest (0.71%; 0.36 m) at the slowest velocity of 6.45 km·h⁻¹. Similar findings were also found for non-differential GPS, with 1 Hz units reported to be accurate and reliable for

measuring linear distance at low velocities (Townshend, Worringham, & Stewart, 2008). Interestingly, in this study it was suggested that the sampling frequency of 1 Hz meant that the number of actual values collected within each 10-m section ranged from a single value during the highest speeds to as many as nine data samples during slow walking (Townshend, et al., 2008).

2.4.5 Assessment of distance and speed using GPS

Critical movements for performance in team sports are the ability to maximally accelerate, decelerate and change direction at speed over a short distance (Dobson & Keogh, 2007). Several studies have reported that increased sprint and repeated-sprint performance, (Coutts, Russell, & Sirotic, 2005; Duthie, et al., 2006; Impellizzeri et al., 2008; Rampinini, Impellizzeri, Castagna, Coutts, & Wisløff, 2009) particularly with the ball, are important for team performance (Rampinini, et al., 2009). Due to the short nature of sprints in the team sport (Dawson, et al., 2004b), the ability to accelerate is likely to be more important than a player's top speed (Young, Benton, Duthie, & Pryor, 2001). It is therefore necessary to be able to accurately measure these characteristics in match play.

Accurate determination of player speed is an important component of time-motion analysis and can increase the specificity of strength and conditioning programs. An early GPS study assessed velocity using a bicycle ridden around a running track, comparing GPS speed to a custom-made speedometer. The cycling tasks were conducted at a range of velocities from 10 - 35 km·hr⁻¹ and over both a straight and curved path (Witte & Wilson, 2004). The speed determined by the GPS receiver was within 0.2 m·s⁻¹ of the criterion speed measured for 45% of the values with a further 19% lying within 0.4 m·s⁻¹ for the linear path. However, an underestimation of speed

occurred when the cyclist followed a curved path and at higher speeds, and movement error increased when a curve of smaller radius was followed (Witte & Wilson, 2004).

The application of GPS to the team sport context is a logical progression for sport scientists and coaches aiming to measure activity profiles. However, the accuracy of GPS when assessing rapid changes in speed (accelerations and decelerations) and direction is still evolving. An initial study investigated the use of this technology for use in AF (Edgecomb & Norton, 2006). The study had two aims, the first of which was to compare GPS against another computer based tracking system (CBT), and the second to assessing validity of GPS distance against a calibrated trundle wheel pedometer. Results indicated that GPS overestimated the actual distance, as measured by the calibrated trundle wheel, by 4.8%, indicating a systematic error in the tracking system. There was also, 5.8% difference when CBT was compared to the calibrated trundle wheel (Edgecomb & Norton, 2006). However, the distances used only ranged from 128 to 1,386 m, which is much less than most team sports such as hockey where typical distances range from 8,000 to 10,000 m (Lythe & Kilding, 2011). In relative terms, a potential difference of 5.8% may equate to over 500 m in a hockey match.

There is presently limited information regarding the validity and reliability of the various GPS devices for measuring movement during high-intensity, intermittent exercise. To quantify these changes of speed and direction, researchers compared GPS derived distance to the criterion (128.5 m) distance covered during a team sport specific circuit. In agreement with previous research (Edgecomb & Norton, 2006), the 1 Hz GPS units in this study demonstrated a good level of reliability for the total measured distance (Coutts & Duffield, 2010). However, the CV was poor for both high speed running (11.2–32.4%) and very high speed running (11.5–30.4%). Additionally, frequently short sprints and brief maximal accelerations of >1 s are

completed in team sports, it was suggested that at high speeds, (for example running distance at velocities $>20 \text{ km}\cdot\text{h}^{-1}$) may be missed by GPS devices with a 1 Hz sampling rate.

Only two studies have examined the validity and reliability of 5 Hz GPS devices (Coutts & Duffield, 2010; Peterson, et al., 2009). In an investigation assessing cricket-specific movement patterns, results demonstrated that 5 Hz devices have an acceptable validity and reliability for estimating longer distances (600–8,800 m) in walking and striding activities (i.e., $\text{CV} < 3\%$), but were poor (i.e., $\text{CV} > 15\%$) for shorter sprints of between 20 to 40 m (Peterson, et al., 2009). The second study confirmed these results, reporting even larger errors for high speed tennis specific court based movements over short distances (i.e., $\text{CV} < 30\%$) (Duffield, Reid, Baker, & Spratford, 2009).

At present, the efficacy of these devices for assessing activity profiles for team sport specific requirements is not well understood.

2.4.6 Changes of Direction (COD)

In addition to rapid changes in speed, the ability to change direction is also important in team sport (Duthie, et al., 2006). For example, in a study investigating the physical demands of premier league soccer, players performed the equivalent of 726 ± 203 turns during the match; 609 ± 193 of these being of 0° to 90° to the left or right. (Bloomfield, Polman, & O'Donoghue, 2007;). Furthermore, more than half the number of sprints performed in AF involved at least one change of direction (Dawson, et al., 2004b). Accordingly, it is logical that coaches and scientists should be able to quantify these demands. However, changes in motion rather than changes in direction have been investigated in hockey. Changes in movement were recorded and classified into motion categories (standing, walking, jogging, striding, and sprinting). In elite

women's hockey, changes in motion occurred every 3 s (MacLeod, et al., 2007). In contrast, elite male hockey players had a change in motion every 5.5 s during the match play (Spencer, et al., 2004). Differences may exist due to the different number of movement categories used, with the female hockey study utilising six categories, including lunging, whereas male hockey studies have used five. To date, no time-motion analysis research performed in hockey has incorporated changes of direction into their investigations. This may be due to the time consuming nature of video-based time-motion analysis with the collection of another variable amplifying data analysis. It would be useful for sports science practitioners to be able to use GPS to have the capacity to accurately identify changes of direction.

A critical component of changing direction is the ability to accelerate and decelerate. A study investigating the accuracy of GPS to determine accelerations and decelerations that occurred during cycling, found that the transition from acceleration to deceleration was not smooth or accurate. The authors concluded that this was a result of the low sampling frequency of GPS as well as the filtering of data that occurs in the GPS software programs (Witte & Wilson, 2004) and asserted that higher sampling frequencies could provide more accurate data on accelerations and decelerations. However, research is required to assess the ability of GPS to accurately measure the acceleration and decelerations and associated changes in direction in team sports such as hockey where these movements are regularly completed.

Sample rate and the speed of movement may also influence the reliability of GPS for assessing COD. Indeed, earlier research has demonstrated that the error of 1 Hz GPS increased during high velocity and /or multidirectional motion (Coutts & Duffield, 2010). More recently, the reliability of soccer specific movements were investigated using both 1 and 5 Hz GPS units over a variety of angles. The authors concluded that

there is “a threshold” for multidirectional motion where, at both 1 and 5 Hz, GPS became less reliable (Portas, et al., 2007). This occurred when the turning angle increased to 180°. This may have implications when attempting to accurately assess team sports involving movements that involve a rapid COD over a variety of different angles, such as hockey.

The reliability of GPS for assessing these changes remains unclear. Nonetheless, it is apparent that the combination of COD, sample rate and speed of movement affects the ability of GPS to reliably detect these movements. Further research is required to identify the reliability of GPS to assess hockey specific movements such as accelerating, decelerating and COD, enabling sport scientists to confidently measure the activity profiles associated with match play.

2.4.7 Validity of distance and speed using GPS

In order to validate the use of GPS in team sports, knowledge of the accuracy and precision of the measurements are essential. Validity can be determined by comparing the new test or method against a previously established “gold standard” (Wilkinson et al, 2009). The most popular method of GPS validity assessment is to compare a known distance or course measured with a tape measure or trundle wheel, to the recorded GPS distance (Aughey, 2011a). Light gates are set up at nominated points to obtain a criterion sprint time for a known distance. The GPS estimated distance for the time taken on each course as measured by the timing gates is then determined using the manufacturer software. The start time for each effort is determined by the first increase above zero on the velocity trace (Peterson, et al., 2009). The time from timing lights is used to indicate the end of the movement for each known distance.

Validation of GPS devices for assessing team sport movements did not occur until 2008 (Coutts & Duffield, 2010; MacLeod, et al., 2009). However, comparison

between studies is difficult due to differences in methodology, type of unit, sample rates and statistical method applied. One of the first studies examining the validity of team sport using non-differential GPS found it was a valid system to assess distance and speeds in a variety of hockey specific activities. Using a hockey specific circuit (Figure 2.4), the authors observed a strong correlation ($r = 0.99$; $P < 0.001$) between the participants speed, as measured by timing gates, and the GPS (MacLeod, et al., 2009). Interestingly, this study showed that GPS was accurate for determining velocity, whereas other studies have shown differing results when assessing short duration, high speed efforts (Coutts & Duffield, 2010). For example, a low sample rate underestimated distance (31%) in high velocity tennis specific drills, whilst the typical errors ranged from 3% to 40% when estimating sprint distances of 20 to 40 m in cricket specific sprint efforts (Peterson, et al., 2009). One reason for the disparity in findings could be found in the differences in methodology between the studies. In the hockey study, the validity of distance and mean speed for four types of hockey specific shuttles, total lap distance, and overall total distance were assessed. What is unclear from this study is the validity and reliability of the individual movement patterns (walking, jogging, cruise, and sprint) that comprised the hockey simulation circuit which, unlike the cricket investigation, were not examined. The $7 \text{ km}\cdot\text{h}^{-1}$ average movement speed, indicating an overall intensity of walking, around the hockey circuit may also have impacted the accuracy of these results. It would be of interest to perform a larger amount of high intensity distance and determine the impact this has on the validity of GPS to assess these movements.

good level of accuracy (<5%) for the actual measured distance. When investigating distances common to cricket, the validity of the 1 Hz unit used ranged from 0.5% to 2.1% during walking to striding locomotion, respectively. Interestingly, estimation of running had more than twice the error of walking, jogging or striding (Peterson, et al., 2009). This may be due to the 1 Hz sample rate not being able to detect higher intensity movements.

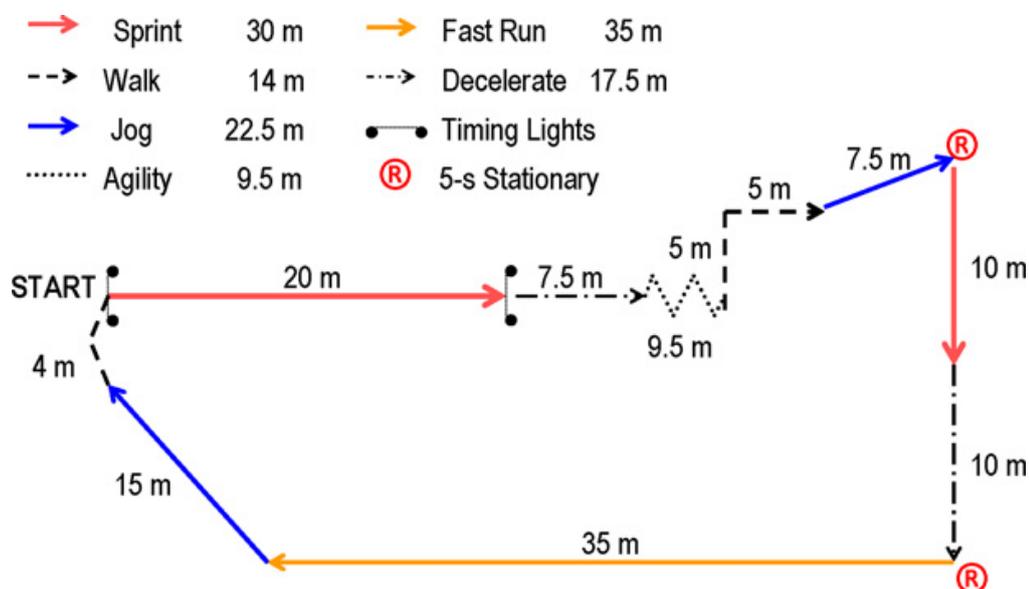


Figure 2.5: Diagram of simulated team sport running circuit. Reproduced from Coutts & Duffield (2010).

A 5 Hz sample rate may enhance the validity and of GPS for team sport applications. In a study examining the validity of 5 Hz GPS devices for assessing cricket-specific movement patterns demonstrated some interesting results (Peterson, et al., 2009). It was established that 5 Hz devices have an acceptable validity for estimating longer distances (600–8800 m) in walking and striding activities (i.e., CV < 3%), but were poor (i.e., CV >15%) for shorter sprints of between 20 to 40 m.

Under- and over-estimations of criterion distance with various GPS devices have been reported. Studies have investigated the length and type of movement (COD), the model of GPS device being used, and more importantly, speed of movement (Edgecomb & Norton, 2006; MacLeod, et al., 2009). At present the majority of findings suggest that the 5 Hz systems display higher accuracy and reliability compared to 1 Hz (Coutts & Duffield, 2010; Peterson, et al., 2009). However, the effectiveness of these devices for assessing movement specific to team sports such as hockey is not well understood.

2.4.8 Limitations of GPS

Although GPS can be used for a variety of applications it does have some limitations for use with team sport. First, the signal from the satellites to the GPS units can be interrupted by the atmosphere and local obstructions such as buildings which may cause the signal to bounce around rather than being directly transmitted to the unit (Schutz & Herren, 2000). Signals sent from the satellite to the GPS unit can also drop out for periods of time, causing incomplete data sets (Duncan, Badland, & Mummery, 2009). These limitations may cause errors in the calculation of the distance of the satellites from the GPS unit (Larsson & Henriksson-Larsen, 2001) and most likely explain some of the measurement error reported in previous validation studies.

Another potential limitation is the constant changing orientation, positioning and identity of the satellites over time. This may make research conditions difficult to standardise when using GPS. To assess the influence of this, trials of a known distance using a hockey specific circuit were conducted on different days at 9:00, 13:00, and 16:00 and compared to GPS distance. No differences existed between TD measures, suggesting satellite positioning at different times of the day did not affect the validity of the system (MacLeod, et al., 2009). In contrast however, in a study

investigating the stability of GPS distance measures over four consecutive days, participants completed identical running circuits of a known distance wearing 1 Hz GPS units. While the GPS and known distance were highly correlated ($ICC = 0.99$), the difference across the four GPS trials ($p < 0.0001$; $ES = 0.20$) showed a lack of measurement stability (Wissell, Williams, & Lorenzen, 2010). This work demonstrated there are major limitations when using GPS for the assessment of team sport specific movements during training session occurring on consecutive days or during matches completed over multiple days within a tournament scenario.

2.5 Time-motion analysis in hockey

Time-motion analysis provides an objective yet non-invasive method for quantifying activities and movements of athletes during match play (Duthie, et al., 2003a). In time-motion analysis, movement patterns, distance covered, mean speeds, levels of “exertion” and work-to-rest ratios can be established by quantifying the time spent performing different activities. Existing studies have generally established the activity profiles by calculating the distances travelled in pre-determined motion categories (standing, walking, jogging, striding, and sprinting) as well as frequency of occurrence for each activity for players in a variety of positions. Time-motion analysis can also provide valuable information regarding the fatigue during matches (Aughey, 2010; Mohr, Krstrup, & Bangsbo, 2003; Sirotic, Knowles, Catterick, & Coutts, 2011) and/or the activity profiles of different levels of competition (Brewer, et al., 2010; Mohr, Krstrup, Andersson, Kirkendall, & Bangsbo, 2008; Sirotic, et al., 2009). The use of GPS as an analysis tool allows extensive performance data to be generated within a few hours after the completion of training or match. However, as previously described, the number of variables and scope of data collected may be limited by the accuracy of the system. This is especially relevant for the assessment of high intensity

activities, which appear to be more important to team performance and success than the total distance travelled (Mohr et al, 2003; Di Salvo, 2009).

In comparison to other team sports, there have been relatively few attempts to determine the activity profile of high level hockey (Gabbett, 2010; Lothian & Farrally, 1994; MacLeod, et al., 2007; Spencer, et al., 2004). Although the most recent hockey-specific time-motion studies have provided a basic understanding of the activity profiles of hockey, gaps in the literature and limitations to individual studies exist (Lythe & Kilding, 2011). Early investigations into the activity profiles in hockey categorised it as aerobically demanding with frequent though brief repeated high intensity efforts superimposed (Reilly & Borrie, 1992). At the elite level there have been relatively few studies that have provided information on activity patterns and player performance, especially since some of the more recent rule changes have been made.

2.5.1 Activity profile of female hockey

While there is relatively little research on time-motion analysis of male hockey, there is a larger body of knowledge in female hockey that can assist in understanding the male version of the game. In general it has been reported that elite female hockey players travel between 3,400 – 9,500 m during a match (Gabbett, 2010; Macutkiewicz & Sunderland, 2011), with regular changes in activity and velocity. Video-based time-motion analysis investigating the physical demands of female national league players determined that between 78 - 84% of activity was accounted for with low intensity movements (Lothian & Farrally, 1994). This differed to club level female players who covered on average $3,901 \pm 552$ m over the duration of a game with the majority of time spent performing low intensity movements (97.4%) and only 2.6% accounting for high intensity activities. However, a major limitation of that study was that player

movement was only recorded every 15 s and time spent performing discrete activities were not recorded. This may have caused an underestimation of both total distance covered and the amount of high intensity activity performed.

More recently, it was reported that high intensity activity accounted for $7.9 \pm 1.2\%$ of total playing time in female English national league players (MacLeod, et al., 2007). Different movement classification systems were used in the more recent study with six motion categories utilised rather than the five previously employed. As well as this, Lothian and Farrally (1994) defined hockey skill related motions of trapping, dribbling and passing as high intensity activities, even though they may be performed at a low intensity. These methodological differences may have influenced the amount of high intensity activity recorded. Finally, in the years between the two studies, there were some significant rule modifications such as the use of continuous substitutions and the elimination of the offside rule which may also have influenced activity patterns. Recently, GPS technology has been used to objectively quantify movement in team sports (Cutts & Duffield, 2010) and more specifically in hockey (Gabbett, 2010; Lythe & Kilding, 2011; Macutkiewicz & Sunderland, 2011). Indeed, GPS technology was recently used to quantify the activity profile of elite female hockey players in the Australian Hockey League (AHL) (Gabbett, 2010) and English national league (Macutkiewicz & Sunderland, 2011). On average, AHL players covered 6,600 m (range: 3,400 – 9,500 m) in the match, a considerably greater distance than previously reported for female players using video-based time-motion analysis systems. However, although more distance was covered, time spent in low- to moderate speed activities was similar to previous work. Notably, these periods of lower speed exercise were interspersed with frequent bouts of high-acceleration and high-velocity movement activities (Gabbett, 2010). Similar distances were found in

the English women's national league, with players covering on average $5,541 \pm 1,144$ m. It was reported that forwards spent a greater percentage of time running, fast running, and sprinting than midfielders and defenders (Macutkiewicz & Sunderland, 2011). This differed to the AHL study where, midfielders spent more time and covered greater distances in high intensity running (i.e. $> 5 \text{ m}\cdot\text{s}^{-1}$) than strikers and defenders. The differences in activity profiles reported in these studies may have been due to different playing styles utilised in each league, team and positional tactics. The number of substitutions used within matches analysed was only reported in the English national league study, making comparisons problematic. The continuous substitution rule, and the substitution strategies resulting from this, has been shown to impact activity patterns (Macutkiewicz, 2011). The two studies also employed a different number of velocity bands when classifying movements, with the English national league study utilising six bands compared with five for the AHL study. When the velocity bands were collapsed to form exercise intensity groupings differences were also observed. These groupings differentiated between low ($0-1.67 \text{ m}\cdot\text{s}^{-1}$ vs $0-1 \text{ m}\cdot\text{s}^{-1}$), medium ($1.67-4.17 \text{ m}\cdot\text{s}^{-1}$ vs $1-5 \text{ m}\cdot\text{s}^{-1}$) and high intensity categories ($4.17-8.19 \text{ m}\cdot\text{s}^{-1}$ vs $>7 \text{ m}\cdot\text{s}^{-1}$). This may have affected the amount of high intensity activity recorded.

2.5.2 Activity profile of male hockey

Time-motion analysis of the 1973 World Cup provided some early data quantifying the distances covered during hockey matches (Wein, 1981). In that study, defenders covered less distance than midfielders, 5,160 m and 6,360 m respectively. The greatest distance covered was recorded by a midfielder playing on the New Zealand team. However, little information was reported on individual playing time and it is unclear if results included players who played for less than 70 mins (Wein, 1981).

Manual video-based time–motion analysis performed during international male hockey demonstrated that players spend most of a match exercising at lower speeds (i.e. standing, walking, jogging), with a small proportion of time (~5.6%) spent at higher speeds (striding and sprinting) and an occasional bout of repeated sprint exercise (Spencer, et al., 2004).

The activity profile of elite male hockey players' has also been assessed using GPS technology during competition. The average total distance (TD) covered per position was $8,160 \pm 428$ m (70 min) and $6,798 \pm 2,009$ m when expressed per player (mean playing time: 51.9 min) (Lythe & Kilding, 2011). The distance per player data is similar to elite female hockey players (Gabbett, 2010) but higher than previous studies in males (Wein, 1981). However, it is difficult to compare this data with other results reported in the literature, due to the number of different movement categorizations (five vs. six), methodology (e.g. GPS, manual video-based analysis) and GPS sample rates (i.e. 1 Hz vs. 5 Hz) employed.

Whilst these studies provide useful information on some of the physical requirements of international field hockey, no studies have investigated the activity demands of national level competition or compared these to the top level international competition. Further, it is possible the game demands have changed in the 5-6 years since some of these studies were completed.

2.5.3 Positional differences

As previously described, hockey categorises players into three distinct positional groups (strikers, midfielders and defenders). Understanding the activity profiles (i.e. distance covered and intensity) specific to each positional role is essential when developing sport-specific training programs.

Given the similarities between soccer and hockey, both positionally and strategically, some useful comparisons can be made between sports. In soccer, there are major individual differences in the physical demands of players, in part related to positional roles within the team. A number of studies have compared playing positions (Di Salvo et al, 2009; Bloomfield et al, 2007; Bangsbo, 1994; Bangsbo et al., 1991; Ekblom, 1986; Reilly & Thomas, 1979). In a study of top-class players, defenders covered less TD and performed less high speed running (HSR) than players in the other positions (Mohr et al., 2003). This was probably closely linked to the tactical roles of the defenders as well as their lower physical capacity (Bangsbo, 1994). In comparison, the attackers covered a distance at a high intensity equal to the midfield players, but sprinted more than the midfield players and defenders (Mohr et al, 2003). In comparison, a more recent study of elite level soccer players, using a semi-automatic computer tracking system (Prozone) investigated the amounts of high speed activities in the English premier league were investigated. Similar to the previous work, the results indicated that differences in total amount of HSR and sprinting existed between positions with the largest amounts of HSR and sprinting associated with wide defenders, attackers and midfield players (both central and wide).

Currently only one study has described the specific activity patterns of positional groups within male international level hockey using GPS (Lythe & Kilding, 2011). In that study, fullbacks were found to be the most unique of the positional groups, covering significantly less total distance than the other positions and performed a greater proportion of distance at low intensity. Similar to the previously mentioned soccer study, fullbacks covered the least TD, performed a greater proportion of distance at low intensity and less distance at moderate and high intensities than other positional groups. For most measures, except distance covered, this data is similar to

that reported in early video-based time-motion hockey studies (Cych, 2006; Spencer, et al., 2004). However, there were a number of limitations to this research. The study used six narrow velocity bands to discriminate between movement speeds and distances. The ability of 1 Hz devices to accurately assess high speed movements may reduce the capacity to accurately report distance covered in narrow speed zones. To reduce this error an increase in sampling rate could be employed and coupled with wider speed zones in future GPS time-motion analysis studies. Advancements in technology may enable further differentiate between positions in elite level hockey.

2.5.4 Activity profile across a match

It is generally accepted that physical performance declines during a match as a consequence of increased fatigue towards the end of the game (Bangsbo, et al., 1991; Mohr, Krstrup, et al., 2003; Mohr, Krstrup, & Bangsbo, 2005; Reilly & Thomas, 1976; Van Gool, Van Gerven, & Boumans, 1988). Several researchers in soccer have observed a reduction in TD covered in the second half when compared to the first (Bangsbo, et al., 1991; Reilly & Thomas, 1976; Van Gool, et al., 1988). This reduction may indicate the development of fatigue in the second half, although TD covered appears not to be the best indicator of physical performance in a match (Mohr, Krstrup, et al., 2003). A number of studies have investigated the amount of high speed running (HSR) and its importance to performance in team sports (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Mohr, Krstrup, et al., 2003; Rampinini, Coutts, et al., 2007). Some studies have reported that the most successful teams (top 5 in the English Premier league) perform less HSR than the bottom 5 teams (Di Salvo, et al., 2009). Indeed, in soccer, HSR can be used to differentiate between the tactical roles of players (Di Salvo, et al., 2007), between elite and sub-elite players

(Mohr, Krstrup, et al., 2003), and is related to the overall success of a team (Rampinini, Coutts, et al., 2007).

Several studies have provided evidence that players' ability to perform high intensity exercise is reduced towards the end of games in both elite and sub-elite soccer (Krstrup, et al., 2005; Krstrup, Mohr, Nybo, et al., 2006; Mohr, Krstrup, et al., 2003; Mohr, et al., 2005; Reilly & Thomas, 1976). It has also been demonstrated that the amount of sprinting and HSR, covered are lower in the second half than in the first half of a soccer game (Bangsbo, 1994; Bangsbo, et al., 1991; Mohr, Krstrup, et al., 2003; Reilly & Thomas, 1976). Further, the players' physical performance was reduced after a period with a large amount of high-intensity exercise during match-play and towards the end of the match, suggesting that fatigue occurs both transiently and at the end of a game (Mohr, Krstrup, et al., 2003).

There are similar findings regarding the decrement of HSR during match play in other elite level team sports. Research in elite level rugby league demonstrated that the ability to perform physical activity during the second half is related to the physical stress of the first half (Sirotic, et al., 2009; Sirotic, Russell, & Coutts, 2005). Furthermore, players who completed more physical activity in the first half showed a decrement in physical performance during the second half in both total intensity of exercise and HSR. Conversely, when a lower physical stress was placed on the players during the first half, second-half total intensity of exercise and HSR exercise was maintained (Mohr, Krstrup, et al., 2003).

In a study of AF players TD, HSR and lower speed activity (LSA) were reduced in the fourth quarter (Coutts, et al., 2010), however, there was not a gradual reduction in exercise intensity during each half as reported by some studies on high-level soccer players (Bradley, et al., 2009; Di Salvo, et al., 2009; Mohr, Krstrup, et al., 2003).

Rather, the TD, sprint distance and HSR distance were reduced following the first quarter and the very high intensity running (VHIR) was reduced during the final quarter. One possible explanation for the differences between the within-match variations in activity profile observed between AF and soccer is that AF allows unlimited interchange of players and is played in four quarters of ~30 min with rest periods. Both the use of the unlimited number of player interchanges during a game along with the regular programmed breaks in play (i.e. quarter time, half-time and three-quarter time) in AF may allow for greater recovery from short-term fatigue. These regular short breaks may allow the players to reduce the metabolic stress and their perception of fatigue, and exercise at higher intensities immediately after the breaks (Marcora & Staiano, 2010; Noakes, 2012).

In comparison to research performed in other elite level team sports, the extent to which HSR has been examined in elite male hockey is limited. In an early study of English national league level hockey, the amount of high-intensity activity performed decreased during the 2nd half (Lothian & Farrally, 1994). In contrast, when each 5 min period of the 1st and 2nd halves were compared during an international match, results suggested no significant decrease in the amount of striding and sprinting that occurred (Spencer, et al., 2004). A more recent investigation of international players using 1 Hz GPS devices supported these findings. Although there was a 4.8 % reduction in TD covered between the 1st and 2nd halves, no change in HSR distances was reported as the match progressed. These results may have been influenced by the different methods of analysis and methodologies used to assess HSR. Six speed zones were used in the later study in an attempt to get a more accurate description of HSR distances. Further research, using currently available 5 Hz GPS devices and

identifying the number of substitutions per match may provide greater insight into the overall and positional HSR activity profiles of elite hockey players.

Although similarities between soccer and hockey exist, recent rule variations have changed the movement characteristics of match play in hockey (Spencer, et al., 2004). Specifically, changes to the playing surface (grass to AstroTurf), the elimination of the offside rule and the introduction of unlimited substitutions have all had an influence on the speed of the game (Lythe & Kilding, 2011; Spencer, et al., 2004). The influence of the number of substitutions may be the most significant rule change in relation to the players' ability to sustain the amount of HSR within a half and across the full match. To date no information exists regarding the effect unlimited substitutions have had on the maintenance of HSR within a match or across a tournament. Investigations into this would enable coaches to develop specific substitution strategies to maximise players HSR output. This in turn could influence specific tactics used during a match.

2.5.5 Activity profile across a tournament

The three major international competitions at the elite level are the Olympic Games, World Cup and Champions Trophy (CT). The CT consists of the top six ranked countries playing a round-robin style tournament, within a period of nine days. This schedule may involve intense periods where teams are required to play up to three matches in four days. With limited time to recover before the next match and an increased importance of match outcomes as the tournament progresses, the ability to maintain exercise intensity across a tournament could be important.

Given that the majority of competition within hockey is performed in tournament scenarios rather than week-to-week competition, no studies have investigated the effect a tournament may have on HSR distances. Research in soccer has investigated

changes in the activity profiles of players over the course of a match or different phases of a season (Di Salvo, et al., 2007; Rampinini, et al., 2009). A recent study examined the effects of three matches in five days in professional soccer, suggesting that the activity profiles were not influenced by the short recovery between matches (Odetoyinbo, Wooster, & Lane, 2009). Similar results were observed when comparing the same top class soccer players over two consecutive matches indicating that activity profiles were not statistically influenced by the short recovery periods between matches (Rey, Lago-Peñas, Lago-Ballesteros, Casais, & Dellal, 2010).

Only one study has examined changes in activity profiles over a tournament scenario in elite hockey players using video-based time-motion analysis. In this study, residual fatigue was evident in subsequent matches when players compete in three field hockey matches within a four-day time period (Spencer, et al., 2005). During the tournament investigated, players increased the time spent standing and reduced the time spent jogging from match 1 to match 3, indicative of fatigue. However, during major international tournaments, more than three matches are played. For example, the CT consists of six matches played over a period of nine days. Thus the changes in activity pattern experienced by players competing in the CT may be even greater than previously reported (Spencer, et al., 2005), although this is yet to be investigated.

Information on the activity profile of players in a single match may provide valuable information on positional profiles in field hockey. However a detailed analysis throughout a tournament could provide a greater insight into the requirements over the duration of such competitions. Previous studies in basketball, soccer and hockey examined the match demands of a tournament by comparing subsequent matches to the first match played. (Montgomery et al., 2008; Rowsell, Coutts, & Reaburn 2007). Whilst this approach provides a comparison with a theoretically 'fatigue-free' baseline

(i.e. match 1), results may be heavily influenced by tactics, opposition, environmental and other factors related to the first match. There is potential benefit in examining individual match activity profiles in comparison to values such as a tournament average or matches displaying the highest level of exercise intensity. Published research on the physical demands of men's hockey is limited, especially relating to recent elite competition and tournament play.

2.5.6 Levels of competition

Time-motion analysis may also provide specific information that can be applied to the physical and game-specific skill preparation of players at different competitive levels or leagues. Such preparation may assist in improving weaknesses in physical and game-specific skill match play between each standard of competition in order to make a more successful transition into the higher playing level. Physical match performance is different between professional soccer players of different competitive levels (Andersson, Randers, Heiner-Moller, Krstrup, & Mohr, 2010; Mohr, et al., 2008). A larger amount of HSR is performed by players at higher competition level games compared with players at moderate levels in both male and female soccer players (Andersson, et al., 2010; Mohr, et al., 2008; Rampinini et al., 2008). In a study of female soccer players, the HSR performed during games in top-class vs. high-level players was compared. The top-class players covered more distance at high intensities compared with the high-level players, which could partly be explained by a superior fitness level in the top-class players (Mohr, et al., 2008). In addition to the fitness level, it has also been shown that the opponent has an impact on exercise intensity and the fatigue development during games (Rampinini, et al., 2008).

In Australia, the AHL is the highest standard of domestic competition and provides a pathway to international representation. The extent to which the activity profiles in the

AHL prepare players to make a successful transition to international competition is not known. Whilst previous studies provide useful information on some of the physical requirements of international hockey, no studies have investigated the activity profiles of national level competition or compared these to the top level international tournaments. Additionally, as HSR is an important discriminator between elite and sub-elite team sport athletes (Mohr, Krstrup, et al., 2003), no studies have investigated differences in HSR between these competition levels.

At present, research into hockey at the elite level is limited. With advancements in micro technologies and the subsequent use of GPS for time-motion analysis of team sport, the ability to perform a more comprehensive analysis is now possible. Utilising 5 Hz GPS devices may provide a more accurate and detailed insight into the activity profiles of hockey players at the elite level. This technology may enable the identification of greater differences between positions, competition levels and be able to define the amounts of HSR performed both from a positional and match perspective with a greater level of precision. Finally, this technology may provide greater understanding into activity profiles of players across an international tournament and accurately identify HSR requirements of positional groups, assessing how these change across a number of consecutive matches. The results of these investigations will allow sport scientist, practitioners and coaches to develop a greater understanding into of the physical requirements of hockey at the elite level enabling the design of sport and position specific training programs.

2.6 Aims

The primary aim of this series of investigations included in this thesis is to determine the reliability and validity of GPS for measuring key variables associated with time-motion analysis common to team sports. A secondary aim is to utilise this tool to

describe and compare the activity profiles of elite male hockey players with regard to playing level and positional roles. Finally, assessing differences in the activity profiles of elite hockey players during an international tournament may enable the development and improve the effectiveness of training strategies and programs that will ultimately optimise performance.

2.6.1 Study 1: The validity and reliability of GPS units for measuring distance in team sport specific running patterns.

- The purpose of this study was to assess the validity and reliability of distance data measured by GPS units sampling at 1 and 5 Hz during movement patterns common to team sports.

2.6.2 Study 2: Variability of GPS units for measuring distance in team sport movements

- The aim of this investigation was to examine the differences in distances measured by two GPS units of the same model worn by the same player while performing movements common to team sports.

2.6.3 Study 3: International field hockey players perform more high intensity running than national level counterparts

- The purpose of this study was to examine several aspects of elite field hockey running performance.
- The three specific aims of this study were to determine: 1) the activity profile of national and international field hockey competitions, specifically the influence of competition level on HSR; 2) if playing position within a level of

competition influences the activity profile; and 3) if the movement characteristics are different between each half of a match.

2.6.4 Study 4: GPS analysis of international field hockey tournament

- This examination was undertaken to determine the influence of multiple games on exercise intensity during a world class hockey tournament.
- The specific aims of this study were to determine: (1) if the mean match intensity changed throughout a tournament, specifically high speed running; and (2) if playing position influences movement output across the tournament.

2.7 Research linking the manuscripts

This research project investigated the suitability of GPS to identify and assess activity profiles within elite male hockey players. To achieve this, four separate research projects were undertaken. Study 1 examined the reliability and validity of GPS to identify and determine specific movement patterns and velocities commonly found in field based team sports (Chapter 3). Additionally, Study 2 (Chapter 4) investigated the difference between GPS units by determining the between unit variability. As a result of the findings from Chapter 3 and 4, specifically the detection of adequately valid and reliable time–motion analysis variables, Chapters 5 investigated the differences in activity profiles between competition levels and positional sub-groups in elite hockey players. Finally, Chapter 6 was undertaken to determine the influence of multiple games on exercise intensity during a world class hockey tournament.

CHAPTER 3. THE VALIDITY AND RELIABILITY OF GPS UNITS FOR MEASURING DISTANCE IN TEAM SPORT SPECIFIC RUNNING PATTERNS

3.1 Introduction

Quantifying the movement demands of team sport players during training and matches provides valuable information that can be used to better understand the demands of competition and develop specific training programs. Until recently, measurement and quantification of player movement demands has been difficult as it has required manual analysis with only one player being analysed at a time (Roberts, et al., 2006). However, with recent technological developments there are now many systems that can analyse movement patterns of many players in team sports simultaneously, including manual and computer-assisted video-based time-motion analysis systems, triangulation of miniature electronic transmitters and GPS devices (Carling, et al., 2008; Dobson & Keogh, 2007). Specifically, GPS technology is used by many sports to quantify movement demands during training and competition (Aughey & Falloon, 2010; Barbero Álvarez, et al., 2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009).

The use of video-based time-motion analysis (TMA) has been well documented (Bradley, et al., 2009; Carling, et al., 2008; Rampinini, Coutts, et al., 2007; Rampinini, et al., 2009), however, there is a growing body of literature examining the use of GPS for game and player analysis (Aughey & Falloon, 2010; Barbero Álvarez, et al., 2010; Coutts, et al., 2010; Peterson, et al., 2009). Indeed, GPS technology has the potential to provide a more comprehensive, accurate and automated examination of player movements in invasion style team sports (e.g. hockey, rugby union, rugby

league, soccer and AF). However, few studies have investigated the reliability and validity of GPS technology for the assessment of team sport movement patterns (Barbero Álvarez, et al., 2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009; Peterson, et al., 2009). Additionally, most studies have assessed the validity and reliability of these GPS devices with distance and positional data recorded at 1 Hz, (Barbero Álvarez, et al., 2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009), with relatively few utilising 5 Hz data (Peterson, et al., 2009).

Technology developments now allow position data to be collected at 5 Hz during match play and training. This increase in sample rate may enhance the validity and reliability of GPS for team sport applications. To date, however, only one study has examined the validity and reliability of 5 Hz GPS devices, assessing cricket-specific movement patterns (Peterson, et al., 2009). The results demonstrated that 5 Hz devices have an acceptable validity and reliability for estimating longer distances (600-8800 m) in walking and striding activities (i.e. CV < 3%), but were poor (i.e. CV >15%) for shorter sprints of between 20 to 40 m (Peterson, et al., 2009). The efficacy of these devices for assessing movement demands specific to team sports such as the football codes is not well understood.

Critical movements to performance in team sports are the ability to maximally accelerate, decelerate and change direction at speed over a short distance (Dobson & Keogh, 2007). For example, AF, soccer, rugby union and hockey players' exhibit similar sprint distances, typically between 10-20 m (Coutts, et al., 2010; Duthie, et al., 2006; MacLeod, et al., 2009; Sirotic, et al., 2009). Several studies have shown that increased sprint and repeated-sprint performance (Dawson, et al., 2004b; Duthie, et al., 2006; Impellizzeri, et al., 2008; Rampinini, Bishop, et al., 2007; Sirotic, et al.,

2009; Spencer, et al., 2004), particularly with the ball (Rampinini, et al., 2009), are important for team performance. In addition, the ability to change direction is important in these sports (Bloomfield, et al., 2007; Duthie, et al., 2006; Mujika, Santisteban, Impellizzeri, & Castagna, 2009). Dawson et al (2004b) investigated players' movement patterns in AF and demonstrated that more than half the number of sprints performed in a match involved at least one change of direction. It is therefore necessary to be able to accurately measure these characteristics in match play. Therefore, the aims of this study were to assess the reliability and validity at both 1 Hz and 5 Hz of the MinimaxX GPS device for the assessment of different movement patterns and distances common to team sport play.

3.2 Methods

Twenty elite Australian football players (mean \pm SD) age, stature and body mass: 24 ± 4 y, 188 ± 7 cm, and 87 ± 9 kg respectively participated in the study. This study conformed to the National Health and Medical Research Council's Statement on Human Experimentation. All athletes gave informed consent following full disclosure of procedures.

3.2.1 Experimental design

This study evaluated the validity and reliability of distance data collected from GPS units at 1 and 5 Hz during movement patterns common to team sports. Specifically, the accuracy of these devices was assessed during straight line running at various speeds, during two COD courses, and during a team sport running circuit. This research design allowed for the assessment of team-sport specific movement patterns of increasing intensities, complexity and specificity. During each trial subjects wore two GPS units (MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia) in a custom made harness with the units located on the right and left scapula,

approximately 25 cm apart. The antennas of each unit were exposed to allow a clear satellite reception. Trials were completed on a grassed AF field, clear of large buildings to enhance satellite reception. The mean \pm SD number of satellites during data collection for the straight line, COD and simulated team sport running circuit were 8.2 ± 0.6 , 8.3 ± 0.4 and 8.2 ± 0.6 , respectively. The HDOP is a reflection of the geometrical arrangement of satellites and is related to both the accuracy and quality of the signal. Values can range between 1 and a maximum value of 50, with an ideal HDOP of 1 indicating that one satellite is directly overhead with the remainder equally spaced around the horizon (Witte & Wilson, 2004). Higher values indicating that the position fix is entirely unreliable (Witte & Wilson, 2005). The mean HDOP during data collection was 1.5 ± 0.28 , 1.26 ± 0.09 and 1.25 ± 0.06 for straight line, COD and simulated team sport running circuit, respectively. To assess the influence of sample rate, data for each trial was collected and analysed at 1 and 5 Hz.

Electronic timing gates (Smart Speed, Fusion Sport, Queensland, Australia) were used to obtain a criterion sprint time for a known distance (accurate to 0.01 s). The GPS estimated distance for the time taken on each course as measured by the timing gates was determined with Logan Plus v4.2.3 software (Catapult Innovations, Scoresby, Australia) for each trial. The start time for each trial was determined by the first increase above zero on the velocity trace (Peterson, et al., 2009). The time from timing lights was used to indicate the end of the movement for each known distance.

3.2.2 Straight-line running

Subjects commenced from a stationary position and completed two trials of each self selected speed of walking, jogging, striding and sprinting. Timing gates were set up at the 0, 10, 20, 40 m points measured subject time over these distances.

3.2.3 Change of Direction

Subjects walked, jogged, strode and sprinted through two different courses (Figure 3.1) of known distance (40 m) and angle of COD (90°). Players commenced from a stationary position and followed a painted course marked on the ground. At each COD, poles were used to ensure players tracked the correct pathway as close to the known distance as possible.

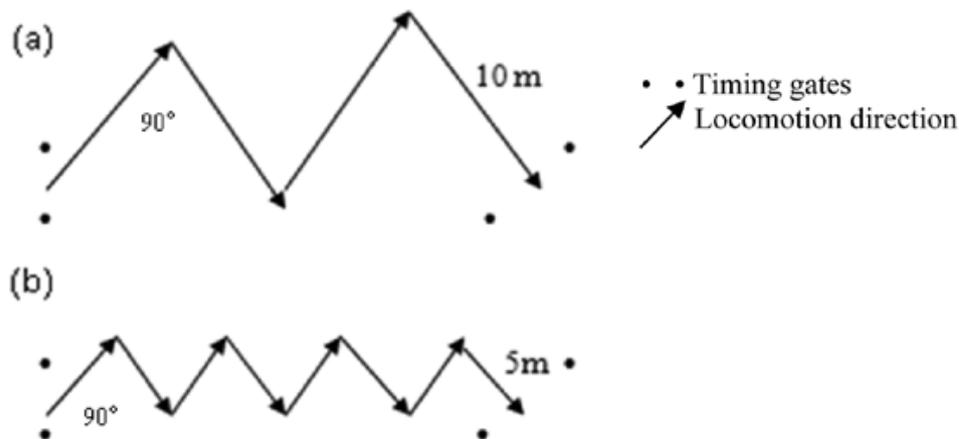


Figure 3.1: Change of direction (COD) course: (a) Gradual 10 m COD. 4×10 m straights with $3 \times 90^\circ$ COD (b) Tight 5 m COD. 8×5 m straights with $7 \times 90^\circ$ COD.

3.2.4 Simulated team sport running circuit

A sample of players ($n=10$) completed five trials of a marked team sport running circuit (140 m) modified from Bishop et al (2001) (Figure 7). The circuit included, two maximal sprints, a zigzag COD, three periods of walking, three periods of jogging, one striding effort and a deceleration to a complete stop. Measurement of the circuit was made with a calibrated measuring tape and goniometer for COD sections. The participants were instructed to start from a stationary position and follow a marked course on the grassed playing field, completing each circuit within one minute. At the COD section, poles and painted lines were used to ensure players

tracked the correct pathway as close to the known distance as possible. Each player performed a familiarisation trial prior to the beginning of the test period and was verbally instructed as to which motion was required for each section of the circuit.

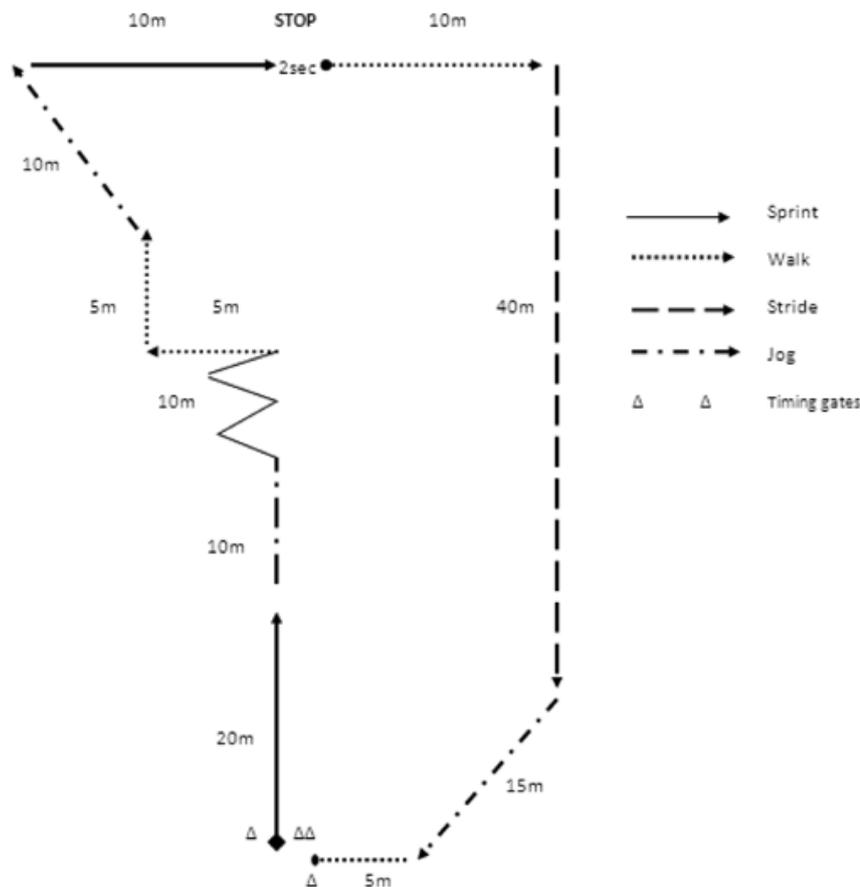


Figure 3.2: Modified team sport circuit (Bishop et al, 2001).

3.2.5 Statistical Analyses

Validity was assessed using the Standard Error of the Estimate (SEE). The SEE was calculated as the SD ($\pm 90\%$ CI) of the % difference between the known distance and the GPS recorded distance for each trial at both 1 Hz and 5 Hz. The percentage difference ($\pm 90\%$ CI) between the reference distance and GPS distance was also calculated to indicate bias (Peterson, et al., 2009).

The reliability of measures in each locomotor pattern for the 40 m straight line, COD and simulated team sport running circuit sampled at both 1 Hz and 5 Hz was

estimated using the $TE \pm 90\%$ CI expressed in absolute and as a percentage (CV). The smallest worthwhile change (SWC), defined as the smallest change of practical importance was calculated as $0.2 \times$ the between subject SD (Pyne, 2003). As a result, variables were considered capable of detecting the SWC if the TE was \leq SWC (Pyne, 2003). Once TE was established, it was divided into criterion categories, being rated as good (CV<5%), moderate (CV 5–10%) or poor (CV>10%), based on previous recommendations (Duthie, et al., 2003b).

3.3 Results

3.3.1 Validity

The accuracy of the GPS, for measuring distance during straight line movements at different speeds, at 1 and 5 Hz is presented in Table 3-1. As the speed of locomotion increased over a given distance, validity decreased. Larger errors were associated with jogging, striding and sprinting over 10 m (Table 3-1). The validity improved as the distance increased for all locomotion speeds at both 1 and 5 Hz (Table 3-1). With the exception of walking at 1 Hz in the tight course, validity decreased as the locomotion speed increased in both the gradual and tight COD (Table 3-2).

Additionally, the higher sample rate improved the measurement accuracy of both the gradual and tight COD trials resulting in error less than 11.7%. The validity of the TD during the simulated team sport running circuit at 1 and 5 Hz was $3.6 \pm 0.6\%$ and $3.8 \pm 0.6\%$ respectively.

Table 3-1: Standard error of the estimate of GPS monitoring of straight line running at different locomotion's and distances. Standard deviation (\pm 90% CI) of the % difference between the known distance and the GPS recorded distance for each trial at both 1 Hz and 5 Hz (n=20).

	10 m		20 m		40 m		20 - 40 m	
	1 Hz	5 Hz						
Walk	23.8 \pm 5.9	21.3 \pm 5.8	17.4 \pm 3.7	16.6 \pm 3.5	9.6 \pm 2.0	9.8 \pm 2.0	15.0 \pm 3.2	11.9 \pm 2.5
Jog	25.7 \pm 5.5	23.2 \pm 4.9	18.3 \pm 3.9	15.3 \pm 3.2	11.5 \pm 2.3	10.7 \pm 2.3	17.5 \pm 3.7	12.5 \pm 5.6
Stride	31.1 \pm 6.6	27.4 \pm 6.6	20.9 \pm 4.4	16.8 \pm 3.4	11.3 \pm 2.4	11.5 \pm 2.4	13.9 \pm 2.9	9.0 \pm 1.9
Sprint	32.4 \pm 6.9	30.9 \pm 5.8	22.3 \pm 4.7	17.0 \pm 3.6	12.2 \pm 2.4	11.9 \pm 2.5	18.5 \pm 3.9	12.9 \pm 2.7

Table 3-2: Standard error of the estimate of GPS monitoring of two change of direction courses at different locomotion speeds. Standard Deviation (\pm 90% CI) of the % difference between the known distance and the GPS recorded distance for each trial at both 1 and 5 Hz (n=20).

	Gradual COD		Tight COD	
	1 Hz	5 Hz	1 Hz	5 Hz
Walk	9.1 \pm 2.4	8.9 \pm 2.3	12.6 \pm 3.3	9.9 \pm 3.1
Jog	10.2 \pm 2.7	9.7 \pm 2.8	9.0 \pm 2.3	10.6 \pm 2.8
Stride	11.5 \pm 3.0	11.0 \pm 3.1	10.4 \pm 2.7	10.8 \pm 2.8
Sprint	12.7 \pm 3.0	11.7 \pm 3.0	12.5 \pm 3.3	11.5 \pm 3.0

3.3.2 Bias

The GPS substantially underestimated the criterion distance when striding and sprinting over short distances (10 and 20 m) at both 1 and 5 Hz (Table 3-3). As the distance increased, the magnitude of the error decreased when jogging, striding and sprinting (Table 3-3). These GPS underestimated the criterion distance during the tight COD trial at all locomotion speeds (Table 3-4). A higher sampling rate decreased the error from the criterion distance in both the tight and gradual COD regardless of locomotion speed. The GPS underestimated the TD of the simulated team sport running circuit by $5.7 \pm 0.6\%$ and $3.7 \pm 0.6\%$ for 1 and 5 Hz respectively.

3.3.3 Reliability

Reliability improved for all locomotor activities moving in a straight line when sampled at the higher rate and over longer distances (Table 3-5). Regardless of locomotion or distance, GPS was incapable of detecting the SWC for straight line locomotion ($TE > SWC$, Table 3-5). The CV for measures over the shorter distances (i.e. 10 m and 20 m) were poor ($CV > 10\%$) regardless of locomotor activity, speed or sampling rate (Table 3-5). The higher sample rate and slower movement speed improved all reliability measures regardless of distance (Table 3-6). The CV measured at 5 Hz for the 20-40 m split were similar, regardless of locomotion speed with values ranging from 12.1% (walking) to 9.8% (sprinting).

Small differences in the reliability measures between the CVs for the tight COD and gradual COD were evident (Table 3-6). In all cases, the magnitude of the TE was substantially greater than the SWC (Table 3-6). As locomotion speed in the COD increased, reliability measures marginally improved at higher sampling rates (Table 8). The CV for both the tight and gradual COD tasks were similar to the 40 m straight

Table 3-3: Percent bias ($\pm 90\%$ confidence interval) of GPS distance from the reference distance (n=20).

	10 m		0-20 m		40 m		20-40 m	
	1 Hz	5 Hz	1 Hz	5 Hz	1 Hz	5 Hz	1 Hz	5 Hz
Walk	2.2 ± 5.9	4.5 ± 5.8	2.3 ± 3.7	5.5 ± 3.5	4.3 ± 2.0	5.3 ± 2.1	0.4 ± 3.2	2.3 ± 2.5
Jog	-10.3 ± 5.5	7.1 ± 4.9	-9.6 ± 3.9	3.2 ± 3.2	0.5 ± 2.4	2.4 ± 2.3	5.7 ± 3.7	4.5 ± 2.6
Stride	-30.8 ± 6.6	-15.0 ± 6.6	-16.9 ± 4.4	-11.8 ± 3.4	-2.9 ± 2.4	-2.2 ± 2.4	9.1 ± 2.9	4.6 ± 1.9
Sprint	-37.1 ± 6.9	-26.0 ± 5.8	-30.9 ± 4.7	-18.6 ± 3.6	-10.1 ± 2.4	-6.2 ± 2.5	1.9 ± 3.9	0.7 ± 2.7

Table 3-4: Percent bias of GPS monitoring of two change of direction (COD) courses for different locomotion speeds. Mean difference of GPS distance from criterion distance expressed as a percentage $\pm 90\%$ confidence intervals (n=20)

	Gradual COD		Tight COD	
	1 Hz	5 Hz	1 Hz	5 Hz
Walk	-2.0 ± 2.4	-0.6 ± 2.3	-9.2 ± 3.3	-5.2 ± 3.1
Jog	-6.1 ± 2.7	-2.3 ± 2.8	-13.4 ± 2.3	-7.1 ± 2.8
Stride	-12.4 ± 3.0	-7.8 ± 3.1	-15.4 ± 2.7	-10.9 ± 2.8
Sprint	-17.4 ± 3.0	-12.9 ± 3.0	-22.2 ± 3.3	-15.8 ± 3.0

Table 3-5: Reliability of GPS in straight line running at different speeds, distances and sample rates (n=20). TE = Typical Error with 90% confidence interval; CV (%) = Coefficient of Variation; SWC = smallest worthwhile change.

	Walk			Jog			Stride			Sprint		
	TE (m)	CV (%)	SWC (m)	TE (m)	CV (%)	SWC (m)	TE (m)	CV (%)	SWC (m)	TE (m)	CV (%)	SWC (m)
1-Hz												
10 m	2.4 (2.0-3.1)	30.8	0.5	2.4 (2.0-3.1)	34.7	0.5	2.8 (2.3-3.6)	58.8	0.6	3.1 (2.6-4.0)	77.2	0.6
20 m	3.1 (2.6-4.0)	20.4	0.7	2.9 (2.4-3.8)	20.9	0.7	4.4 (3.6-5.6)	33.3	0.8	4.3 (3.6-5.5)	44.9	0.9
40 m	2.8 (2.3-3.6)	7.0	0.7	3.5 (2.9-4.5)	9.4	0.9	3.8 (3.1-4.8)	10.5	0.9	3.9 (3.2-5.0)	11.5	0.9
20-40 m	3.2 (2.6-4.0)	17.5	0.6	3.7 (3.1-4.8)	21.0	0.7	2.8 (2.3-3.6)	14.0	0.6	2.4 (2.0-3.1)	14.0	0.7
5-Hz												
10 m	2.6 (2.1-3.3)	23.3	0.5	2.2 (1.8-2.8)	22.8	0.5	2.7 (2.2-3.4)	33.4	0.6	2.6 (2.1-3.3)	39.5	0.6
20 m	3.40 (2.8-4.4)	21.2	0.6	2.6 (2.1-3.3)	15.6	0.6	2.9 (2.4-3.7)	17.5	0.6	3.2 (2.7-4.2)	23.0	0.7
40 m	2.7 (2.2-3.4)	6.6	0.7	3.6 (2.9-4.6)	9.1	0.8	3.5 (2.9-4.5)	9.1	0.8	3.5 (2.9-4.5)	9.2	0.8
20-40 m	2.4 (2.0-3.0)	12.1	0.5	2.3 (1.9-3.0)	12.3	0.5	1.6 (1.3-2.0)	8.0	0.4	1.7 (1.4-2.2)	9.8	0.5

Table 3-6: Reliability of GPS in two change of direction (COD) courses at different sampling rates (n=20). TE = Typical Error with 90% confidence interval; CV (%) = Coefficient of Variation; SWC = smallest worthwhile change.

	Walk			Jog			Stride			Sprint		
	TE (m)	CV (%)	SWC (m)	TE (m)	CV (%)	SWC (m)	TE (m)	CV (%)	SWC (m)	TE (m)	CV (%)	SWC (m)
Gradual COD												
1 Hz	4.3 (3.4-5.9)	11.6	0.7	3.3 (2.6-4.5)	9.0	0.8	4.0 (3.2-5.5)	12.2	0.9	3.3 (2.6-4.5)	10.7	0.9
5 Hz	4.3 (3.4-5.9)	11.5	0.7	3.7 (2.9-5.0)	10.0	0.9	3.45 (2.7-4.7)	9.9	1.0	2.6 (2.1-3.6)	7.9	0.9
Tight COD												
1 Hz	5.3 (4.2-7.3)	17.5	0.9	2.8 (2.3-3.9)	8.6	0.7	3.5 (2.8-4.8)	10.8	0.8	3.3 (2.6-4.5)	12.0	1.0
5 Hz	5.0 (4.0-6.9)	15.2	0.9	3.0 (2.4-4.1)	8.6	0.8	3.1 (2.5-4.3)	9.7	0.9	2.6 (2.1-3.6)	9.2	0.9

line values in jogging, striding and sprinting. However, CV values for COD walking were larger than straight line walking.

The simulated team sport circuit showed good reliability with a CV of 3.6% for each sample rate. However, the TE for 1 Hz: 4.6 m (4.1-5.3 m 90% CI) and 5 Hz: 4.7 m (4.2-5.4 m 90% CI) was again greater than the SWC (1 Hz = 1.0 and 5 Hz = 1.1 m).

3.4 Discussion

The first major finding of this study was that GPS grossly underestimated the criterion distance during sprinting over short distances. This error was evident regardless of sampling rate, although the higher sampling rate improved validity irrespective of distance and locomotion in the straight line, COD and simulated running circuit trials. The reliability of GPS improved as distance travelled increased but decreased as speed increased. In agreement with previous research (Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009; Peterson, et al., 2009) the GPS devices have acceptable reliability and validity for assessing TD during longer duration training drills and games. However, the current results show that these devices cannot be used to measure brief, high-intensity sprints, or slow and fast accelerations over distances of less than 20 m, regardless of sampling rate. The present findings question the efficacy of using GPS technology to quantify high speed movements and accelerations over short distances in team sports. The poor accuracy of these devices for assessing brief accelerations and short sprints may be due to the low number of position measures taken during brief efforts <3 s. However, changes in velocity also seem to influence the accuracy of the measure. The present results show that the 20-40 m distance measures (i.e. post-acceleration) are more accurate than the 0-20 m (i.e. acceleration) phase of the 40 m sprint/stride. This is likely to be associated with the smaller variations in velocity in the final 20 m of these efforts.

Interestingly, there were lower bias values in the 20-40 m phase during sprinting and walking compared to jogging and striding. The higher bias values when jogging and striding might be due to players moving non-constant velocities during this part of the test. However, it is suggested that future studies need to determine the influence of changes in velocity on measurement error with GPS devices.

The measurement accuracy of GPS decreased during high-intensity COD movements regardless of sample rate. The tight COD demonstrated lower validity than the gradual COD, and this may be due to the increased number of speed changes in the tight COD course. Nonetheless, at slow speeds, the GPS units appear to provide a valid measure of distance for gradual COD activities.

The degree of reliability varied as a function of distance and intensity. In straight line trials, the largest CV values occurred during striding and sprinting over shorter distances. This is supported by the finding that reliability improved after the acceleration phase of the 40 m strides and sprints. The poor reliability for these shorter distances may demonstrate the inability of GPS to identify periods of rapid variations in speed. These rapid accelerations over short distances are critical in team sports such as AF, soccer, rugby union and hockey, with typical sprint ranges between 10-20 m (Dawson, et al., 2004b; Duthie, et al., 2006; Impellizzeri, et al., 2008; Rampinini, Bishop, et al., 2007; Sirotic, et al., 2009; Spencer, et al., 2004). Given the larger CV during short, high-intensity efforts, the use of GPS to assess running efforts is inappropriate, especially if data is sampled at 1 Hz.

There was little difference in the reliability of GPS measures between the gradual and tight COD course. Due to the regular changes in direction, acceleration was slower in the agility courses than the straight line course. This most likely explains the improved reliability with the COD courses compared to the straight line movements

of similar speeds. Higher sampling frequencies also improved the reliability during high speed measures when sprinting through the COD courses. This suggests that using GPS at a higher sampling rate is more suitable for use in team sports where changes of direction are prevalent. It is possible that some of the error maybe due to differences between the actual and intended pathway (Coutts & Duffield, 2010). However, in this study error related to deviations from the intended pathway were minimised with the use of poles placed at each COD and painted lines to ensure minimal movement from the set course.

The simulated team sport circuit is more complex, consisting of a combination of locomotion speeds over straight line and COD movements but over a longer distance. The present results show that the validity and CV were similar to what has been reported for 1 Hz GPS (Coutts & Duffield, 2010). The TD measured for longer team sport bouts therefore has acceptable accuracy and reliability. Similar to straight line running, longer durations and/or distances, as well as sampling rate improves the measuring precision of these GPS devices.

Collectively, the present results show that the GPS devices used in this study have an acceptable level of validity and reliability for recording movement patterns at lower speeds and for higher sampling rates over longer efforts. The inability of these GPS units to accurately assess movement during rapid variations in speed over short distances, which are critical in team sports (Dawson, et al., 2004b; Duthie, et al., 2006; Impellizzeri, et al., 2008; Rampinini, Bishop, et al., 2007; Sirotic, et al., 2009; Spencer, et al., 2004), questions the usefulness of these devices for assessing small segments of training or games. In this study, the higher sampling rate improved validity regardless of distance and speed of movement during straight line, COD and the simulated team sport running circuit. However, the poor reliability measures, in

relation to the SWC, suggest that the GPS provides information that currently is unable to identify small changes of practical importance. In all cases, magnitude of the typical error was substantially greater than the SWC.

3.4.1 Practical Applications

GPS micro-technology, such as GPS, is currently utilised in team sports to quantify movement demands in both training and competition. This information can then be utilised to modify the type, duration and intensity of training, improving the specificity of these sessions. In agreement with previous research (Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009; Peterson, et al., 2009), the reliability and validity of GPS to estimate longer distances appears to be acceptable (i.e. <10%) for game and training purposes. However, currently available GPS systems maybe limited for the assessment of brief, high speed straight line running, accelerations or efforts involving a change of direction. These results also show that an increased sample rate improves the reliability and validity of GPS devices. Further development of GPS technology is required before practitioners can be confident about the suitability of GPS for the quantification of short, high intensity intermittent running movement patterns common in team sports. In particular, care needs to be taken when interpreting data on single sprints or small changes in direction and velocity. The degree of error may reduce the ability to report distance covered in narrow speed zones. At present, practitioners may be limited to using variables such as TD obtained for full matches or periods of play.

CHAPTER 4. VARIABILITY OF GPS UNITS FOR MEASURING DISTANCE IN TEAM SPORT MOVEMENTS

4.1 Introduction

Global positioning system (GPS) technology is commonly used for the quantification of movement demands in team sports (Roberts, et al., 2006). Several studies have investigated the reliability and validity of GPS devices for measuring movements and velocities in different sporting activities (Coutts & Duffield, 2010; Duffield, et al., 2009; MacLeod, et al., 2009). However, few have examined the between-unit variation with 5 Hz GPS. Quantification of between-unit measurement variation allows more accurate comparisons between players or bouts of activity. The aim of this study was to examine the differences between distance measures of two GPS units of the same model worn by the same player while performing movements common to team sports.

4.2 Methods

Twenty elite AF players (mean (\pm SD) age, stature and body mass: 24 \pm 4 y, 188 \pm 7 cm, 87 \pm 9 kg, respectively) completed the straight line, change of direction (COD) and team sport specific circuit trials. Eight elite male hockey players (mean (\pm SD) age, stature and body mass: 22 \pm 4 y, 178 \pm 8 cm and 78 \pm 9 kg, respectively) participated in the match play. This study conformed to the National Health and Medical Research Council's Statement on Human Experimentation. All athletes gave informed consent following full disclosure of procedures.

4.2.1 Experimental design

The differences in distance measures obtained from two GPS units worn by the same subject were assessed during two trials each of straight line locomotion at four speeds and two COD courses (Figure 3.1). The antennas of each unit were exposed to allow a clear satellite reception. Trials were completed on a grassed AF field, clear of large buildings to enhance satellite reception.

Between unit variability for high speed running distance (HSR; running speed $> 4.17 \text{ m}\cdot\text{sec}^{-1}$) and TD were made using a team sport running circuit (Figure 3.2) and during match play. Data from eight field players was collected during three AHL matches during the 2009 season ($n=24$). Each game was played in the afternoon at the same venue. In each trial subjects wore two 5 Hz GPS units (MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia) in a custom made harness with the units located on the right and left scapula, approximately 25 cm apart.

The mean \pm SD number of satellites during data collection for the straight line, COD, simulated team sport running circuit and during match play were 8.2 ± 0.6 , 8.3 ± 0.4 and 8.2 ± 0.6 , respectively. The mean HDOP during data collection was 1.5 ± 0.28 , 1.26 ± 0.09 and 1.25 ± 0.06 for straight line, COD and simulated team sport running circuit, respectively. The number of satellites and HDOP (mean \pm SD) during match play data collection for the three AHL games were 8.5 ± 0.5 and 1.2 ± 0.3 ; 7.8 ± 0.4 and 1.1 ± 0.1 ; and, 8.4 ± 0.6 and 1.1 ± 0.1 respectively.

4.2.2 Statistical Analyses

The percentage difference $\pm 90\%$ confidence interval (CI) was used to determine differences between units. This was calculated using the following formulae: $(\text{Unit B}/\text{Unit A}) \times 100/1$. TD and HSR were chosen as variables during the team sport circuit

and match play as a result of the results of Chapter 3 (Coutts & Duffield, 2010).

4.3 Results

Table 4-1 summarizes the between-unit differences for straight line running and COD courses at four different speeds. Differences ($\pm 90\%$ CI) ranged from $9.9 \pm 4.7\%$ to $11.9 \pm 19.5\%$ for straight line movements and from $9.5 \pm 7.2\%$ to $10.7 \pm 7.9\%$ in the COD courses. Similar results (Table 4-2) were exhibited for TD and HSR distance in the simulated team sport circuit and match play.

Table 4-1: Percent difference ($\pm 90\%$ CI) of GPS monitoring between two units in straight line movements and two change of direction (COD) courses for different locomotion speeds.

	Straight line						Change of Direction					
	0-10 m	SWC	0-20 m	SWC	0-40 m	SWC	20-40 m	SWC	Tight	SWC	Gradual	SWC
Walk	10.7 \pm 7.5	6.3	11.1 \pm 4.0	9.3	10.1 \pm 3.9	2.6	9.9 \pm 4.7	3.1	10.8 \pm 7.6	4.2	10.4 \pm 5.7	3.1
Jog	10.9 \pm 7.8	5.2	11.1 \pm 9.3	6.2	10.2 \pm 3.8	2.6	10.3 \pm 4.9	3.3	9.5 \pm 7.2	2.3	10.4 \pm 5.2	2.8
Stride	11.1 \pm 20.8	9.8	10.3 \pm 8.5	5.7	10.2 \pm 4.5	3.0	10.4 \pm 3.9	2.6	10.6 \pm 7.8	3.0	9.7 \pm 4.7	2.5
Sprint	11.9 \pm 19.5	11.0	10.3 \pm 8.1	5.4	10.7 \pm 6.3	3.4	10.5 \pm 5.2	3.4	10.7 \pm 7.9	2.4	10.0 \pm 3.8	2.1

Table 4-2: Percent difference ($\pm 90\%$ CI) of GPS monitoring between two units during a team sport circuit and match play. TD and high intensity running distance (HIR; running speed > 4.17 m.sec⁻¹) are represented.

	Circuit	SWC (m)	Match Play	SWC (m)
Total	11.1 \pm 4.2	1.5	10.3 \pm 6.2	1.9
HIR	11.6 \pm 9.3	3.2	10.3 \pm 15.6	3.1

4.4 Discussion

The present findings show a considerable degree of variation in distance measured from two GPS units worn by the same player completing the same movement task. Additionally, the variation between the two GPS units was similar regardless of the movement pattern.

Whilst previous studies have examined the between-unit variability during cricket (Peterson, et al., 2009) and tennis (Duffield, et al., 2009), only one study has reported this error during field-based team sport specific movements (Coutts & Duffield, 2010). In that study 1 Hz GPS units, were used rather than the 5 Hz units used here. In the present study, the magnitude of the between-unit difference for the team sport circuit was $11.1 \pm 4.2\%$ which is greater than that previously reported (coefficient of variation: 3.5–6.6%) (Coutts & Duffield, 2010). The differences in the between-unit variability reported in these studies maybe due to the different software and hardware used to collect and treat the data. The present results showed that the level of between-unit variation was consistent ($\sim 10\%$) regardless of distance (TD and HSR distance), movement speed and change of direction. These findings have important practical implications as when this between-unit difference is coupled with test-retest

error of GPS (Coutts & Duffield, 2010; Duffield, et al., 2009; Peterson, et al., 2009), the ability to detect small differences between players may be limited. Therefore, to minimise this source of measurement error, it is recommended that the same unit be used for individual players during all exercise sessions. It is also recommended that the between-unit measurement error should be considered if making comparisons between players.

4.4.1 Practical Applications

Analysis of external loads (i.e. total and HSR distance travelled) provides valuable information regarding the physiological and performance requirements of team sport athletes. It is common that sport scientists and coaches use distance measures from matches or training drills to assess work demands and compare performance of team sport athletes. These findings show that careful consideration should be given to the between-unit variability when interpreting results, particularly when comparing distance measures from players using different GPS units. Further work is required to reduce the between-unit variability before comparisons between players can be reliably performed.

CHAPTER 5. INTERNATIONAL FIELD HOCKEY

PLAYERS PERFORM MORE HIGH INTENSITY

RUNNING THAN NATIONAL LEVEL

COUNTERPARTS

5.1.1 Introduction

Hockey is a team sport played by both men and women, with major international tournaments including the Champions Trophy (CT) and the Olympic games. The Australian Hockey League (AHL) is the highest standard of domestic competition in Australia and provides a pathway to international representation. The extent to which the activity profiles in the AHL prepare players to make a successful transition to international competition is not known.

Time–motion analysis provides valuable information regarding the activity profile of players within a team sport (Bangsbo, et al., 1991; Krstrup, et al., 2005; Rampinini, Coutts, et al., 2007), fatigue patterns during matches (Aughey, 2010; Mohr, Krstrup, et al., 2003; Sirotic, et al., 2011) and/or the activity of different levels of competition (Brewer, et al., 2010; Mohr, et al., 2008; Sirotic, et al., 2009). However, in comparison to other team sports, there have been relatively few attempts to determine the activity profile of high level hockey (Gabbett, 2010; Lothian & Farrally, 1994; MacLeod, et al., 2007; Spencer, et al., 2004). Manual video-based time–motion analysis demonstrated that international male hockey players spend most of a match exercising at lower speeds (i.e. standing, walking, jogging), with a small proportion of time (~5.6%) spent at higher speeds (striding and sprinting) and an occasional bout of repeated sprint exercise (Spencer, et al., 2004). Additionally, elite hockey players increase the time spent standing and reduce the time spent jogging from game 1 to

game 3 in an international hockey tournament, indicative of fatigue (Spencer et al., 2005). However, whilst these studies provide useful information on some of the physical requirements of international hockey, no studies have investigated the activity demands of national level competition or compared these to the top level international competition. Further, it is possible the game demands have changed in the 5-6 years since these studies were completed.

As with soccer, hockey categorises players into three distinct positional groups (strikers, midfielders and defenders). Currently no studies have described the specific physical requirements of positional groups within male international or national level field hockey. Understanding the activity profile necessary for success in hockey players according to their positional role during competitive matches (i.e. distance covered and intensity) is necessary to develop sport-specific training protocols. Additionally, the amount of HSR is an important discriminator between elite and sub-elite team sport athletes (Mohr, Krustup, et al., 2003). To date however, no studies have investigated differences in HSR between playing positions, competition levels or during each half in male hockey.

Therefore, the purpose of this study was to examine several aspects of elite hockey running performance. The three specific aims of this study were to determine: 1) the activity profile of national and international hockey competitions, specifically the influence of competition level on HSR; 2) if playing position within a level of competition influences the activity profile; and 3) if the movement characteristics are different between each half of a match.

5.2.1 Experimental Approach to the Problem

The activity profile of national and international level tournaments were examined using GPS technology. Specifically, the level of competition, playing position and

differences existing between the first and second half were investigated. Players were separated into three distinct positional groups (strikers, midfielders and defenders) for positional comparison. An understanding of the positional requirements during tournament play is important for monitoring performance and effectively planning player preparation programs.

5.2.2 Subjects

Sixteen national level hockey players (mean (\pm SD) age, stature and body mass: 22 \pm 4 y, 178 \pm 8 cm and 78 \pm 9 kg, respectively) were assessed while competing in the 2008 AHL. To evaluate international competition, sixteen male hockey players (mean (\pm SD) age, stature and body mass: 27 \pm 4 y, 179 \pm 5 cm and 77 \pm 5 kg, respectively) from the Australian men's hockey team were analysed while competing in the 2009 CT. Only one player competed in both tournaments. Goalkeepers were excluded from this study. This study conformed to the National Health and Medical Research Council's Statement on Human Experimentation. All athletes gave informed consent following full disclosure of procedures.

Endurance performance was measured using the multi-stage fitness test (MSFT), whereby subjects run back and forth on a 20 m course and touch the 20 m line; at the same time a sound signal is emitted from a pre-recorded tape (Ramsbottom, Brewer, & Williams, 1988). The intraclass correlation coefficient (ICC) for test-retest reliability and typical error of measurement (TEM) for the MSFT were 0.93 and 3.5%, respectively (Leger & Lambert, 1982).

5.2.3 Study Design and Procedures

Time-motion analyses were conducted during the national level AHL (six round matches followed by a semi-final and final) and the international level CT (five round matches and a final). During each match 16 players each wore a GPS unit

(MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia) in a custom pocket in the player uniform, located between the scapulae. The antennas of each unit were exposed to allow a clear satellite reception. The number of satellites during data collection for the AHL and CT competition were 8.5 ± 0.7 and 8.3 ± 0.6 , respectively. The mean HDOP, during data collection was 1.50 ± 0.26 and 1.25 ± 0.16 for, AHL and CT competition, respectively. A sample rate of 5 Hz was used for data collection. To limit error, each player wore the same unit for the duration of the competition. The following parameters were assessed for both national (AHL) and international level competitions (CT): TD, also expressed in meters covered per minute ($\text{m}\cdot\text{min}^{-1}$), HSR (running speed $>4.17 \text{ m}\cdot\text{s}^{-1}$) distance, and lower speed running (LSR; $0.10\text{-}4.17 \text{ m}\cdot\text{s}^{-1}$). These measures have demonstrated acceptable levels of reliability for assessing team sport activity demands using GPS (Coutts & Duffield, 2010).

The distances from each field position, not the individual players, were used to describe the positional activity profile (Spencer, et al., 2004). For example, when several players played in one position, the activity profile was recreated by combining data from each substitute playing in that position. The match data was then divided into activity profile for each half of each match in both competitions.

5.2.4 Statistical Analyses

Descriptive data for both competitions is presented as mean \pm SD. All other variables were log transformed to reduce bias due to non-uniformity of error and analyzed using the ES statistic with 90% CI and percent difference to determine the magnitude of effects using a custom spreadsheet (Hopkins, 2003). Mean differences in MSFT performance between competition levels and activity demands (TD, $\text{m}\cdot\text{min}^{-1}$, HSR, LSR) between positions, competition levels and halves, were assessed using a customized spreadsheet (Hopkins, 2003). Differences were classified as substantial

when there was a $\geq 75\%$ likelihood of the effect being equal to or greater than 0.2, and classified as small 0.2-0.6; moderate 0.6-1.2; large 1.2-2.0; and very large 2.0-4.0 (Cohen, 1988). Effects with less certainty were classified as trivial and where the $\pm 90\%$ CI of the ES crossed the boundaries of ES -0.2 and 0.2, the effect was reported as unclear. This statistical approach was utilized to identify meaningful differences whilst accounting for the precision of measurement through confidence intervals.

5.3 Results

Players competing in international competition had a 10.1% greater MSFT performance than those competing at the national level (2859 ± 223 vs. 2568 ± 194 m, ES=1.35). The TD travelled independent of positional groups throughout the 70-mins of play was 9776 ± 720 m and 8589 ± 623 m for CT and AHL matches, respectively. International players performed 42.0% more HSR (2294 ± 433 vs. 1652 ± 416 m; ES=1.45) and 7.6% more LSR (7441 ± 511 vs. 6905 ± 447 m, ES=1.45) than national players. During CT, midfielders had greater HSR distance, but similar LSR distance compared to strikers (Table 5-1). Defenders performed substantially less HSR than strikers (Table 5-1). Moreover, the HSR distance differed markedly between the three positions, with defenders covering the least HSR (1728 ± 201 m).

Within the AHL, there were no differences between strikers and midfielders for TD or $\text{m}\cdot\text{min}^{-1}$. However, the strikers completed more HSR (striker: 1896 ± 368 m; midfield 1778 ± 387 m) but there was little variation in LSR distances. Similar to the CT, the AHL defenders covered less distance in all variables in comparison to the strikers and midfielders, (Table 5-2). Strikers and midfielders had greater HSR during AHL than defenders (Table 5-2). In contrast to CT, AHL midfielders covered more HSR than strikers ($10.1 \pm 7.4\%$). In general, CT had greater movement demands than AHL (Table 5-2). However, the greatest difference between competition levels was

observed in HSR with AHL strikers, midfielders and defenders, performing less HSR than players competing in the same positions in CT.

The TD covered decreased in the second halves across all positions in both the CT (6.1 to 7.5%) and the AHL (2.4 to 4.7%, Table 5-3). In CT, the strikers also demonstrated a 6% reduction in LSA in the second half. In contrast the strikers in AHL demonstrated moderate changes in time-motion variables. Midfielders during both levels of competition showed decreases in distances across all variables from the first to second half. Similarly, the defenders in both the CT and the AHL showed decreases in TD, $\text{m}\cdot\text{min}^{-1}$ and LSA but maintained the ability to perform HSR between the first and second halves.

5.4 Discussion

The main finding of this study was that international players completed more HSR across all positions than players at an elite national level. In both competitions, midfielders and strikers performed more HSR than defenders and the activity demands of players decreased in the second half.

The present study demonstrated that international players covered a greater TD and HSR distance than the national level competition. Our hockey results agree with some (Andersson, et al., 2010; Mohr, Ellingsgaard, Andersson, Bangsbo, & Krustup, 2003; Mohr, et al., 2008) but not all previous studies (Bradley, et al., 2009) that have reported greater TD in higher level soccer competition. Elite AF also has higher TD and number of high intensity efforts than sub-elite competition (Brewer, et al., 2010). However, care must be taken in comparing data between these sports as each have different rules (i.e. field size, match duration, player substitution and rotation) and also different match analysis methods have been used (e.g. GPS, semi-automated computerized systems and manual video-based analysis). Nonetheless, it seems that

international hockey has greater physical demands than the AHL. These findings should be taken into account when planning to use AHL to prepare players for future international competition. In support of recent research (Andersson, et al., 2010; Mohr, et al., 2008) reporting differences in HSR profiles between international and elite domestic soccer players, we also found that international field hockey competition has greater HSR demands than national level competition. There are several possible explanations for the differences in HSR between competitions. The most likely explanation in this study is the greater endurance capacity of the international players when compared to AHL players.

Furthermore, as the aerobic fitness of soccer players increased, match running performance also improved (Helgerud, et al., 2001; Impellizzeri et al., 2006). Indeed, a 10% increase in $\dot{V}O_{2\max}$ resulted in a 20% increase in match running distance in young elite players in one study (Helgerud, et al., 2001). Similarly, a 7% increase in $\dot{V}O_{2\max}$ resulted in a 6% increase in TD and 18% increase in high intensity activity during soccer match play of elite juniors (Impellizzeri, et al., 2006). Interestingly, the magnitude of change in aerobic fitness reported in these previous training studies is similar to the difference between the international and national players' aerobic capacity in this study.

Table 5-1: Differences in TD, meters per minute, lower and high speed distances for different playing positions during international and national level matches.

International	Striker vs Midfielder			Striker vs Defender			Defender vs Midfielder		
	%Diff	ES	Qualitative Descriptor	%Diff	ES	Qualitative Descriptor	%Diff	ES	Qualitative Descriptor
TD (m)	2.3 ± 3.8	0.3	triv - mod +ve	-4.1 ± 5.0	-0.5	mod - triv -ve	5.9 ± 3.7	0.8	small - large +ve
m·min⁻¹	3.3 ± 3.0	0.5	triv - mod +ve	-5.5 ± 4.5	-0.8	large - triv -ve	8.1 ± 3.6	1.1	mod - large +ve
LSR (m)	0.8 ± 2.9	-0.2	unclear	-3.2 ± 4.2	-0.4	mod - triv -ve	4.4 ± 3.0	0.6	triv - mod +ve
HSR (m)	10.1 ± 7.4	0.8	small - large +ve	-26.6 ± 8.2	-2.4	v. large - large -ve	49.9 ± 6.2	3.4	v. large - v. large +ve
National									
TD (m)	-0.6 ± 3.4	-0.9	unclear	-8.1 ± 3.6	-1.2	large - mod -ve	8.4 ± 2.6	1.4	mod - large +ve
m·min⁻¹	-1.3 ± 2.8	-0.2	unclear	-9.4 ± 2.6	-1.9	v. large - large -ve	9.3 ± 2.8	1.5	mod - large +ve
LSR (m)	-1.8 ± 3.6	-0.2	unclear	1.3 ± 3.4	0.2	unclear	-2.4 ± 3.0	-0.4	mod - triv -ve
HSR (m)	-6.8 ± 9.3	-0.4	mod - triv -ve	-36.1 ± 11.1	-2.1	v. large - large -ve	51.5 ± 12.1	1.8	large - v. large +ve

TD = TD; m·min⁻¹= meters per minute; LSR= Lower speed running;
 HSR= High speed running; % Diff = Percentage difference; ES= Effect size

Table 5-2: Differences in the physical requirements of positions between international and national level competition.

	Striker vs Striker			Midfielder vs Midfielder			Defender vs Defender		
	%Diff	ES	Qualitative Descriptor	%Diff	ES	Qualitative Descriptor	%Diff	ES	Qualitative Descriptor
TD (m)	-10.0 ± 5.0	-1.3	large - mod -ve	-12.1 ± 2.7	-2.1	v. large - large -ve	-13.8 ± 3.7	-2.2	v. large - large -ve
m·min⁻¹	-8.0 ± 3.6	-1.4	large - mod -ve	-11.1 ± 2.8	-1.9	v.large - large -ve	-11.9 ± 3.8	-1.9	v.large - large -ve
LSR (m)	-7.1 ± 3.8	-0.9	large - small -ve	-4.3 ± 2.8	-0.7	mod - small -ve	-10.9 ± 3.1	-1.9	v.large - large -ve
HSR (m)	-19.9 ± 8.8	-1.5	large - mod -ve	-32.1 ± 7.9	-2.4	v. large - large -ve	-30.3 ± 10.7	-1.9	v. large - large -ve

TD = TD; m·min⁻¹= meters per minute; LSR= Lower speed running;
 HSR= High speed running; % Diff = Percentage difference; ES= Effect size

Table 5-3: Table 13: TD, meters per minute, low and high speed distances comparisons during first and second half during international and national level matches.

International	Striker			Midfield			Defender		
	%Diff	ES	Qualitative Descriptor	%Diff	ES	Qualitative Descriptor	%Diff	ES	Qualitative Descriptor
TD (m)	-6.1 ± 7.0	-0.6	large-trivial -ve	-7.5 ± 4.1	-0.8	large-small -ve	-6.9 ± 5.6	-0.7	large-trivial -ve
m·min⁻¹	-3.3 ± 5.9	-0.4	unclear	-5.9 ± 4.2	-0.6	mod -small -ve	-4.6 ± 5.5	-0.5	mod - triv -ve
LSR (m)	-6.0 ± 6.6	-0.7	large-triv -ve	-6.7 ± 4.2	-0.7	mod -small -ve	-6.9 ± 5.7	-0.7	large-trivial -ve
HSR (m)	-6.8 ± 11.2	-0.5	unclear	-8.7 ± 6.8	-0.6	mod - triv -ve	-4.9 ± 9.8	-0.3	unclear
National									
TD (m)	-4.3 ± 3.5	-0.6	mod - triv -ve	-4.7 ± 4.9	-0.5	mod - triv -ve	-2.4 ± 3.4	-0.7	mod - triv -ve
m·min⁻¹	-3.2 ± 4.1	-0.4	mod - triv -ve	-4.8 ± 2.9	-0.8	large-small -ve	-2.8 ± 3.0	-0.5	mod - triv -ve
LSR (m)	-4.2 ± 4.5	-0.5	mod - triv -ve	-2.3 ± 4.0	-0.3	mod - triv -ve	-3.2 ± 3.0	-0.5	mod - triv -ve
HSR (m)	-8.6 ± 11.9	-0.4	mod - triv -ve	-8.1 ± 12.2	-0.4	mod - triv -ve	-1.0 ± 13.7	-0.3	unclear

TD = TD; m·min⁻¹= meters per minute; LSA= Low speed running;
 HSR= High speed running; % Diff = Percentage difference; ES= Effect size

In addition to physical fitness, other factors may explain the differences in the activity demands between the different competition levels. For example, differences in tactics, technical abilities, or the quality of the opposition could affect the movement demands in hockey. Several studies from professional soccer have shown these to be factors that affect the amount of HSR performed (Bradley, et al., 2009; Rampinini, et al., 2008; Rampinini, et al., 2009). The activity profiles could have been further influenced by motivational factors, such as the competitive importance placed on the game or the coaches use of the continuous substitutions rule throughout the match (Brewer, et al., 2010; Di Salvo, et al., 2009; MacLeod, et al., 2007; Mohr, Krstrup, et al., 2003). Many factors influence the differences in HSR between competitions. These should be taken into account when interpreting differences between positional demands in each competition level.

The present study confirmed that there were positional differences in activity profiles in both the CT and AHL. In the AHL, both the strikers and midfielders covered greater distance than defenders. In contrast, in women's AHL, midfielders and defenders covered the greater TDs than strikers (Gabbett, 2010). This difference may be due to the variations in the tactical requirements of specific positions and playing styles of teams. In CT, there were smaller differences in the TD between these playing positions. It is possible that these positional differences are due to the greater physical capacity or tactical strategies employed by the defenders at this level. Further research that investigates the relationship between technical/tactical skills and physical performance is required to elucidate these positional differences.

Different positional requirements were also observed for HSR in both competitions. Specifically, midfielders and strikers covered more HSR than defenders regardless of

competition level. This observation is in accordance with female AHL competition where midfielders covered more distance in HSR than strikers and defenders (Gabbett, 2010). Moreover, it was reported from one international hockey match that midfielders and strikers also had a higher sprint frequency than defenders (Spencer, et al., 2004). However, direct comparison with these previous studies is difficult due to the different match analysis methods used. The present information may assist the physical preparation of talented national level players, enabling them to make a successful transition to international match play.

In the current study, the positional activity profile decreased in the second half for both competitions. These findings agree with soccer research that demonstrated a reduction in TD covered in the second half compared with the first (Bangsbo, et al., 1991; Mohr, Ellingsgaard, et al., 2003). Others have shown decreased positional and movement demands during the second half of elite (Coutts, et al., 2010) and sub-elite AF matches (Brewer, et al., 2010). However, unlike the current study, no differences were found between the elite and sub-elite AF leagues (Brewer, et al., 2010). Additionally, the amount of HSR was significantly reduced in hockey (MacLeod, et al., 2007), soccer (Krustrup & Bangsbo, 2001; Mohr, Ellingsgaard, et al., 2003) and rugby league (Sirotic, et al., 2009) in the second half of matches. In comparison, the current study showed only small changes in HSR for midfielders (CT and AHL) and strikers (AHL) from the first to second halves, whilst, defenders maintained the amount of HSR during the match in both competitions.

The use of distances from each field position, not the individual players, to describe the positional demands may have protected anticipated declines in HSR from the first to second halves. Also, the smaller decrease in HSR in the present study may be related to the unlimited substitution rule as well as positional and tactical

requirements of defenders employed during both competitions. It is likely that the coaches manage player rotations in hockey to maintain the exercise intensity of the team. Future studies should examine the relationship between player rotation and activity demands in hockey.

In summary, the present study demonstrated that international competition substantially increases the positional movement of hockey athletes, with greater HSR at the international level. Additionally, positional differences with midfielders and strikers performing more HSR than defenders were observed. Finally, results indicated that regardless of playing level, players had reduced running and were unable to maintain the demands in the second half of a match. However, further research is required to confirm optimal strategies for preparing hockey players for the demands of international competition.

5.5 Practical Applications

These results can be used by coaches to develop specific tactical and rotational strategies which attempt to maintain the level of HSR throughout a match. Differences in HSR and aerobic capacity between levels highlight one area of improvement required by national level players. Whilst the activity profile of CT competition suggests a need for greater aerobic capacity development in international players, it is not clear from the current study whether the fitness levels of the players in examined here is due to the demands of international training and competition or was in fact present initially and acted as a discriminator for selection. It is possible that both natural selection and the training process have played a role. Players at the national level may require additional conditioning to achieve the higher aerobic capacity required if aspiring to international representation. The relatively large difference in HSR between the two levels shows the importance of being able to perform greater

amounts of HSR and to recover from these actions throughout the game. Thus the training of elite hockey players should focus on improving their ability to perform intense exercise and to recover rapidly from periods of high-intensity running. Finally, emphasis should be placed in the individualization of conditioning programs to address the specific demands of the different playing positions. Specific game related training drills may be used to address this need.

CHAPTER 6. GPS ANALYSIS OF INTERNATIONAL FIELD HOCKEY TOURNAMENT

6.1 Introduction

Hockey is an international sport played at many standards, ranging from amateur to elite level. The most important international competitions are the CT and the Olympic games. The CT consists of the top six ranked countries playing a round-robin style tournament, within a period of nine days. This schedule may involve intense periods where teams are required to play up to three matches in four days. With limited time to recover before the next match and an increased importance of match outcomes as the tournament progresses, the ability to maintain exercise intensity across a tournament could be important as it is possible players will experience accumulated fatigue.

International male hockey players spend most of a match exercising at low intensity (i.e. standing, walking, jogging), with a small proportion of time (~5.6%) spent at higher intensities (striding and sprinting) and an occasional bout of repeated sprint exercise (Lythe & Kilding, 2011; Spencer, et al., 2004). Several studies have shown a decrement in physical performance during soccer matches (Mohr, Krstrup, et al., 2003; Mohr, et al., 2005; Rampinini, Coutts, et al., 2007). In particular, some studies have shown that HSR and sprinting decrease between the first and second half. This decline in physical activity has been linked to match related fatigue (Bangsbo, et al., 2006; Mohr, Krstrup, et al., 2003; Mohr, et al., 2005). Similar findings have been observed in elite female hockey players with a decline in high intensity exercise in the second half of matches (MacLeod, et al., 2007). However, other studies from elite men's hockey have shown that the distance covered at HSR did not decrease as the

halves progressed (Lythe & Kilding, 2011; Spencer, et al., 2004). Differences in the results may be due to the data collection method used in these time-motion analysis studies (i.e. GPS vs. Video-based). Additionally, these time-motion analysis methods may not have been sensitive enough to detect HSR. The use of subjective techniques (MacLeod, et al., 2007; Spencer, et al., 2004) and more recently, data collection using 1 Hz GPS units (Lythe & Kilding, 2011) to describe player activity may not be sensitive enough to accurately categorise high intensity running distances. Several studies have shown that HSR is important to performance in team sports (Di Salvo, et al., 2009; Mohr, Krustup, et al., 2003; Rampinini, Coutts, et al., 2007). Indeed, in soccer HSR differentiates between the tactical roles of players (Di Salvo, et al., 2007) as well as being related to the overall success of a team (Rampinini, Coutts, et al., 2007). However, the extent to which playing position influences high speed running performance in elite hockey across a tournament is currently unknown (Chapter 5).

Only one study has examined changes in activity profiles over a tournament scenario in elite hockey players using video-based time-motion analysis. During the tournament investigated, players increased the time spent standing and reduced the time spent jogging from match 1 to match 3, indicative of fatigue. In that study, residual fatigue was evident in subsequent matches when players competed in three hockey matches within a four-day time period. However, during major international tournaments, more than three matches are played. For example, the CT consists of six matches played over a period of nine days. Thus the fatigue experienced by players competing in the CT may be even greater than previously reported (Spencer, et al., 2005), although this is yet to be investigated.

Information on the activity profile of players in a single match may provide valuable information on positional profiles in hockey. However a detailed analysis throughout

a tournament could provide a greater insight into these requirements over the duration of such competitions. Previous studies examining activity profiles in a tournament have compared subsequent matches to the first match played within a tournament (Montgomery, et al., 2008; Rowsell, et al., 2007). Whilst this approach provides a comparison with a theoretically 'fatigue-free' baseline (i.e. match 1), results may be heavily influenced by tactics, opposition, environmental and other factors related to the first match. This is especially the case in quasi-experimental studies that have analysed activity profiles of teams participating in international competitions. Therefore, this method of analysis may be limited. An analysis method that may ameliorate some of the limitations of this approach is to compare activity profiles of players in each match within a tournament to the typical or average match requirements of that team participating within the tournament. Although each method of comparison has limitations, performing both levels of analysis may potentially provide a more complete understanding of the changes in exercise intensity within an international tournament.

Therefore the purpose of this study was to investigate the influence of multiple matches on exercise intensity during a world class hockey tournament. The specific aims of this study were to determine: (1) if the mean match intensity changed throughout a tournament, specifically HSR; and (2) if playing position influences movement output across the tournament.

6.2 Methods

Sixteen male field hockey players (mean (\pm SD) age, stature and body mass, estimated $\dot{V}O_{2\max}$: 27 \pm 4 y, 179 \pm 5 cm, 77 \pm 5 kg and 64.2 \pm 3.1 ml.kg⁻¹min⁻¹, respectively) from the Australian field hockey team were investigated while competing in the 2009 CT, held in Melbourne, Australia. Goalkeepers were excluded from this study. This study

conformed to the National Health and Medical Research Council's Statement on Human Experimentation. All athletes gave informed consent following full disclosure of procedures.

6.2.1 Experimental design

Time-motion analyses were conducted during the international level CT which consisted of five round matches and a final. The matches were played in a stable ambient temperature (i.e., temperature ranged between 22 °C and 26 °C). The six matches were played over nine days, with a rest day separating matches two and three, three and four, and four and five. Each match consisted of two 35 minute halves and was played under FIH rules which allow for the use of unlimited substitutions. During each match 15 players (N=15) each wore a GPS unit (MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia) in a custom pocket in the player uniform, located between the scapula. The antennas of each unit were exposed to allow a clear satellite reception. The number of satellites and the mean HDOP during data collection was 8.3 ± 0.6 and 1.25 ± 0.2 , respectively. A sample rate of 5 Hz was used for data collection. To limit error, each player wore the same unit for the duration of the competition (Coutts & Duffield, 2010).

The distances from each field position, not the individual players, were used to describe the positional activity profile (Lythe & Kilding, 2011; Spencer, et al., 2004). For example, when several players played in one position, the activity profiles were recreated by combining data from each substitute playing in that position. The rotational strategy was predetermined and the timing of each substitution recorded during the match. The match data was then divided into activity profiles for three distinct positional groups; strikers, midfielders and defenders.

The following parameters were assessed during the matches: TD, HSR (running speed $>4.17 \text{ m}\cdot\text{s}^{-1}$) distance and LSR ($0.10\text{-}4.17 \text{ m}\cdot\text{s}^{-1}$). These measures are more reliable for assessing team sport activity patterns than using narrow speed bands (especially at higher speeds) when using GPS (Chapter 3).

Data from each position across the tournament was averaged to calculate the tournament average (TA). This information was divided into positional groups for the above parameters. Each of the round matches and final was then compared to the TA to determine changes in exercise intensity.

6.2.2 Statistical Analyses

Descriptive data is presented as mean \pm SD. All other variables were log transformed to reduce bias due to non-uniformity of error and analyzed using the ES statistic with 90% CI and percent difference to determine the magnitude of effects using a custom spreadsheet (Hopkins, 2003). Mean differences in movement demands (TD, HSR, LSA) between positions and matches, were assessed using a customized spreadsheet (Hopkins, 2003). Likely differences between means of less than 75% were considered to not be practically important (Cormack, Newton, & McGuigan, 2008). The likelihood of a $> 75\%$ difference in means was accepted as representing a practically meaningful difference. Differences $> 95\%$ and $>99\%$ were classified as very likely and almost certainly, respectively (Hopkins, 2003).

6.3 Results

Table 6-1 illustrates the match score against each of the opponents during the CT tournament. The mean (\pm SD) number of substitutions per match was 65 ± 2 with the same substitution strategy used across each positional group in each match. Individual match running performance as well as tournament average for TD, LSA and HSR is shown in Table 6-2.

Table 6-1: Round, opponent and result for Australian men's field hockey team in the Champions Trophy 2009

Round	1	2	3	4	5	6 (Final)
Opponent	Korea	Holland	England	Germany	Spain	Germany
Result	4-0	7-2	2-1	1-3	10-3	5-3

Table 6-2: Mean match running performance (meters) during an international field hockey tournament

STRIKER							
OPPONENT	Korea	Holland	England	Germany	Spain	Final	TA
TD (m)	10787 ± 211	9791 ± 40	8956 ± 343	10530 ± 773	9211 ± 288	9638 ± 253	5506 ± 4984
LSA (m)	8013 ± 80	7354 ± 2	6944 ± 166	7951 ± 232	6975 ± 52	7192 ± 132	4087 ± 3826
HSR (m)	2706 ± 57	2382 ± 16	1975 ± 89	2497 ± 202	2160 ± 140	1418 ± 77	1240 ± 1138
MIDFIELD							
OPPONENT	Korea	Holland	England	Germany	Spain	Final	TA
TD (m)	10336 ± 208	10342 ± 332	10185 ± 195	10310 ± 297	9900 ± 180	9883 ± 329	5652 ± 5182
LSA (m)	7642 ± 67	6889 ± 47	7387 ± 31	7677 ± 133	7223 ± 11	7357 ± 35	4042 ± 3820
HSR (m)	2787 ± 65	2536 ± 120	2597 ± 169	2545 ± 25	2399 ± 88	2459 ± 10	1435 ± 1289
DEFENDER							
OPPONENT	Korea	Holland	England	Germany	Spain	Final	TA
TD (m)	9514 ± 21	9433 ± 474	9871 ± 47	10251 ± 30	8638 ± 516	9010 ± 314	5255 ± 4843
LSA (m)	7600 ± 135	7706 ± 370	7936 ± 30	8310 ± 170	7200 ± 126	7363 ± 194	4268 ± 3938
HSR (m)	1887 ± 83	1675 ± 13	1837 ± 18	1868 ± 128	1418 ± 120	1716 ± 98	978 ± 877

TD= TD; LSA = Low speed activity distance; HSR= High speed running distance; TA= Tournament Average (mean± SD)

6.2.3 Comparison to Match 1

Differences in TD, LSA and HSR distance for different playing positions when compared to the match 1 are shown in Table 6-3. The overall physical output (TD, LSA, and HSR) of the strikers was lower in matches 3 and 5 when compared to match 1. The strikers completed less LSA in all matches, except for match 4 a loss against Germany. The HSR decreased in matches 3, 5, 6 however, no variation was found in matches 2 and 4.

Compared to match 1, variations in TD covered by the midfielders were only demonstrated in matches 5 and 6 with less distance covered in these matches. The greatest variation was observed in HSR distance. In all matches, when compared back to match 1, less HSR distance was performed. However, the amount of HSR did not decrease as the tournament progressed.

With the exception of match 4 (a loss to Germany), there was relatively little variation in the movement characteristics of the defenders during the tournament. In match 4, the defenders had higher TD and LSR distance. In matches with a definitive winning score line (greater than 2 goals), defenders performed less HSR.

All positions showed the lowest physical output in match 5 where the team won by a large margin (10-2 vs. Spain). Only the defenders LSR did not conform to this pattern with no clear difference observed.

6.2.4 Comparison to Tournament Average (TA)

Comparisons between individual matches and the TA characteristics for strikers, midfielders and defenders are shown in Table 6-4. There were no practically important differences between the variables in TD for strikers, except between match 1 and 4. Within these matches, strikers covered a greater distance than the TA. Also, the strikers LSA distance decreased in match 3, but increased in match 4 which coincided with a defeat against Germany.

Midfielders and defenders showed far more variation in each match when compared to the TA. Midfielders covered less distance in match 5 and 6. Match 1 and 6 provided the greatest variation in HSR, with midfielders performing more HSR in match 1 but less in match 6. Increases in LSR were evident in match 1 and 3; however less distance was covered in match 2 when compared to the TA.

Defenders showed the largest variations in distance in each movement category of all positions. All three variables were higher in matches 3 and 4 when compared to the TA. More HSR was completed in matches 1, 3 and 4 when compared to the TA. Interestingly, match 5, where the team won by the largest margin (10-3), defenders decreased in all variables. However, in the other match with a large winning score line (match 2: 7-2) no clear difference was observed.

6.3 Discussion

This is the first study to investigate the activity profile of elite field hockey players during the CT. Results indicate that this elite team was able to maintain exercise intensity when playing six matches in a period of nine days. These results are in contrast to previous investigations of tournament play in field hockey. Only one study has examined fatigue over a tournament scenario in elite hockey players (Spencer, et al., 2005). In that study, players increased the time spent standing and reduced the time spent jogging from match 1 to match 3, suggestive of fatigue. In contrast, when assessing LSR across all positions in the current study this was not evident. Only strikers followed a similar pattern. This was only apparent when each match was compared to the first match. No distinct pattern was observed when comparing back to the TA. However, direct comparison with these previous studies is difficult due to the different match analysis methods used (e.g. GPS and manual video-based analysis). Further, it is possible that activity profiles have changed in the 5-6 years since the earlier study was completed.

Table 6-3: Differences in TD, lower and high speed distances for different playing positions when compared to Match 1 of an international hockey tournament

STRIKER	TD			LSA			HSR		
	%Diff	Qual	ES	%Diff	Qual	ES	%Diff	Qual	ES
M1 v M2	10.1 ± 33.9	unclear	0.3 ± 0.8	8.9 ± 39.3	+ve likely, probable	0.6 ± 2.4	14.1 ± 108	unclear	0.4 ± 2.1
M1 v M3	20.6 ± 58.2	+ve likely, probable	1.4 ± 3.4	15.5 ± 68.2	+ve likely, probable	0.9 ± 3.2	36.9 ± 36.6	+ve likely, probable	1.2 ± 1.2
M1 v M4	2.4 ± 38.1	unclear	0.2 ± 2.6	0.7 ± 36.3	unclear	0.0 ± 1.2	8.5 ± 63.6	unclear	0.6 ± 3.4
M1 v M5	17.1 ± 46.9	+ve likely, probable	1.5 ± 3.6	14.8 ± 43.8	+ve likely, probable	1.2 ± 3.3	25.5 ± 72.4	+ve likely, probable	1.3 ± 3.1
M1 v M6	11.8 ± 33.0	unclear	0.2 ± 0.4	11.3 ± 34.5	unclear	0.0 ± 0.0	12.7 ± 37.3	+ve likely, probable	0.6 ± 1.6
MIDFIELD									
M1 v M2	0.1 ± 7.6	unclear	0.1 ± 1.1	11.4 ± 11.6	+ve likely, probable	1.1 ± 1.1	11.4 ± 20.7	+ve likely, probable	0.6 ± 1.1
M1 v M3	1.4 ± 4.4	unclear	0.4 ± 1.1	3.4 ± 4.7	+ve likely, probable	0.8 ± 1.1	7.3 ± 8.9	+ve likely, probable	0.9 ± 1.1
M1 v M4	0.2 ± 5.0	unclear	0.1 ± 1.1	-0.5 ± 4.7	unclear	-0.1 ± 1.1	10.2 ± 15.5	+ve likely, probable	0.7 ± 1.1
M1 v M5	4.4 ± 4.7	+ve likely, probable	1.0 ± 1.1	5.9 ± 4.7	+ve very likely	1.3 ± 1.1	7.4 ± 9.2	+ve likely, probable	0.9 ± 1.1
M1 v M6	4.6 ± 4.9	+ve likely, probable	1.0 ± 1.1	3.9 ± 6.1	+ve likely, probable	0.7 ± 1.1	13.2 ± 8.0	+ve very likely	1.8 ± 1.1
DEFENDER									
M1 v M2	0.6 ± 15.4	unclear	-0.1 ± 1.4	-1.7 ± 23.8	unclear	-0.1 ± 1.7	12.9 ± 13.9	+ve likely, probable	1.6 ± 1.7
M1 v M3	-3.4 ± 17.4	unclear	-0.4 ± 1.4	-4.6 ± 21.3	unclear	-0.3 ± 1.4	2.8 ± 9.2	unclear	0.5 ± 1.4
M1 v M4	-7.5 ± 17.1	-ve likely, probable	-0.7 ± 1.4	-8.9 ± 21.2	-ve likely, probable	-0.7 ± 1.4	1.0 ± 7.5	unclear	0.2 ± 1.5
M1 v M5	9.9 ± 18.1	+ve likely, probable	0.9 ± 1.6	5.1 ± 21.6	unclear	0.4 ± 1.5	33.3 ± 15.2	+ve very likely	3.3 ± 1.6
M1 v M6	5.6 ± 19.3	unclear	0.5 ± 1.5	3.1 ± 22.4	unclear	0.2 ± 1.5	10.9 ± 31.6	unclear	0.5 ± 1.4

M1=Match 1; M2= Match 2; M3= Match 3; M4= Match 4; M5= Match 5; M6= Match 6; %Diff= Percentage Difference; Qual= Qualitative Outcome; ES= Effect Size; TD= TD; LSR = Low speed activity distance; HSR= High speed running distance

Table 6-4: Differences in TD, lower and high speed distances for different playing positions when compared to the tournament average (TA) during international hockey

STRIKER	TD			LSA			HSR		
	%Diff	Qual	ES	%Diff	Qual	ES	%Diff	Qual	ES
M1 v TA	-8.6 ± 35.0	-ve likely, probable	-0.5 ± 1.5	-7.1 ± 34.9	unclear	-0.1 ± 0.4	-13.4 ± 47.5	unclear	-1.3 ± 3.5
M2 v TA	0.6 ± 12.6	unclear	0.2 ± 3.2	1.3 ± 16.8	unclear	0.1 ± 1.2	-1.1 ± 103.9	unclear	-0.1 ± 1.7
M3 v TA	10.2 ± 45.6	unclear	0.3 ± 1.0	7.5 ± 53.7	+ve likely, probable	0.0 ± 0.2	18.6 ± 30.1	+ve likely, probable	1.1 ± 1.6
M4 v TA	-6.4 ± 19.9	-ve likely, probable	-1.1 ± 3.1	-6.3 ± 10.6	-ve likely, probable	-1.6 ± 2.5	-6.0 ± 58.9	unclear	-0.4 ± 3.0
M5 v TA	7.1 ± 32.0	unclear	0.4 ± 1.7	6.8 ± 24.0	unclear	0.21 ± 0.7	8.7 ± 68.0	unclear	0.4 ± 2.7
M6 v TA	2.2 ± 11.4	unclear	0.5 ± 2.2	3.5 ± 4.7	unclear	0.2 ± 0.2	-2.3 ± 31.0	unclear	-0.2 ± 2.0
MIDFIELD	%Diff	Qual	ES	%Diff	Qual	ES	%Diff	Qual	ES
M1 v TA	-1.1 ± 4.4	unclear	-0.3 ± 1.1	-3.6 ± 4.8	-ve likely, probable	-0.9 ± 1.1	-6.4 ± 10.3	-ve likely, probable	-7.2 ± 1.07
M2 v TA	-1.0 ± 7.6	unclear	-0.2 ± 1.1	7.4 ± 11.8	+ve likely, probable	0.71 ± 1.1	4.3 ± 21.6	unclear	0.2 ± 1.1
M3 v TA	0.3 ± 2.4	unclear	0.1 ± 1.1	-0.3 ± 3.7	unclear	-0.1 ± 1.1	0.4 ± 10.4	unclear	0.1 ± 1.08
M4 v TA	-0.9 ± 4.0	unclear	-0.3 ± 1.1	-4.1 ± 3.6	-ve likely, probable	-1.3 ± 1.1	-11.1 ± 16.0	unclear	0.2 ± 1.09
M5 v TA	3.2 ± 3.5	+ve likely, probable	1.0 ± 1.1	1.9 ± 3.7	unclear	0.57 ± 1.1	0.5 ± 10.6	unclear	0.1 ± 1.08
M6 v TA	3.4 ± 3.8	+ve likely, probable	1.0 ± 1.1	0.2 ± 5.5	unclear	0.0 ± 1.1	6.0 ± 9.9	+ve likely, probable	0.7 ± 1.08
DEFENDER	%Diff	Qual	ES	%Diff	Qual	ES	%Diff	Qual	ES
M1 v TA	0.5 ± 18.5	unclear	-0.5 ± 1.6	2.4 ± 22.3	unclear	0.18 ± 1.6	-8.0 ± 6.0	-ve very likely	-2.2 ± 1.5
M2 v TA	1.2 ± 8.7	unclear	0.2 ± 1.5	0.6 ± 9.8	unclear	0.1 ± 1.5	-8.7 ± 13.8	unclear	0.4 ± 1.7
M3 v TA	-3.4 ± 7.3	-ve likely, probable	-0.8 ± 1.7	-2.4 ± 7.2	-ve likely, probable	-0.6 ± 1.6	-5.3 ± 9.1	-ve likely, probable	-0.9 ± 1.4
M4 v TA	-7.0 ± 6.7	-ve likely, probable	-1.6 ± 1.4	-6.8 ± 6.9	-ve likely, probable	-1.6 ± 1.4	-7.0 ± 7.3	-ve likely, probable	-1.5 ± 1.5
M5 v TA	10.4 ± 7.0	+ve very likely	2.3 ± 1.5	7.6 ± 6.5	+ve very likely	1.71 ± 1.5	22.7 ± 15.1	+ve very likely	2.4 ± 1.6
M6 v TA	6.1 ± 17.9	unclear	0.6 ± 1.7	5.5 ± 19.2	unclear	0.5 ± 1.6	2.1 ± 31.4	unclear	-0.2 ± 2.0

M1=Match 1; M2= Match 2; M3= Match 3; M4= Match 4; M5= Match 5; M6= Match 6; TA= Tournament Average; %Diff= Percentage Difference; Qual= Qualitative Outcome; ES= Effect Size; TD= TD; LSA = Low speed activity distance; HSR= High speed running distance

In general, research in soccer has investigated fatigue over the course of a match or different phases of a season (Di Salvo, et al., 2007; Krustup, Mohr, Steensberg, et al., 2006; Mohr, Krustup, et al., 2003; Rampinini, et al., 2009). A recent study examined the effects of three matches in five days in professional soccer, suggested that the activity profiles were not influenced by the short recovery between matches (Odetoyinbo, et al., 2009). Similar results were observed when comparing the same top class soccer players over two consecutive matches (Rey, et al., 2010) suggesting that activity profiles were not influenced by the short recovery periods between matches. Collectively, these findings support the current results, suggesting that short periods of recovery do not necessarily affect activity profile of elite level hockey players.

One of the most significant rule changes in hockey has been to allow unlimited interchange of players during matches. This change may have markedly altered the tactical and apparent physiological requirements of the match (Spencer, et al., 2005). Unfortunately, the number of substitutions has not been described in previous hockey research. Similar to other team sports (Basketball, Ice hockey, AF), coaches in elite hockey use a high number of interchanges in an attempt to maintain the exercise intensity of the team. This tactic allows attacking and defensive pressure to be applied to the opposition throughout a match (Charlesworth, 2001). In the current study, a high number of substitutions were used to rotate players throughout each match and the same substitution strategy was used for each match. This tactical approach may have permitted the maintenance of positional intensity by allowing players time to recover on the bench. This interchange strategy may have influenced the ability of players to cope with the requirements of the tournament, given the short recovery periods between matches. However, this strategy relies on an even distribution of

talent (technical skill efficiency and tactical knowledge) throughout the team and may not suit teams with a lack of depth. In this study, the technical skill efficiency was not analysed or controlled for. Therefore, future studies should examine the importance of these abilities within different rotational strategies in team sports such as hockey.

In addition to significant rule changes, recent studies have reported higher fitness levels in modern day elite hockey players (Lythe & Kilding, 2011). Indeed, research from soccer has demonstrated in both referees and players that increases in fitness translate to enhanced physical outputs during matches (Helgerud, et al., 2001; Krustup, Mohr, & Bangsbo, 2002). Players who can sustain a high work-rate throughout a match gain an advantage over equally skilled players, whose energy can approach depletion towards the end of a match or after a series of high intensity efforts, resulting in reduced performance (Reilly, Williams, Nevill, & Franks, 2000). The elite Australian hockey players had similarly high aerobic capacities to their New Zealand counterparts (Lythe & Kilding, 2011), but higher than previously reported for elite players (Spencer, et al., 2004). The higher fitness of these elite players, coupled with a high rotational strategy during each match, may partly explain the ability to maintain high exercise intensity during the tournament.

Situational variables including match location, match status (i.e. whether the team was winning, losing or drawing) (Lago, Casais, Dominguez, & Sampaio, 2010), and the quality of the opposition (strong or weak) are important factors for soccer performance. In a recent study of elite Spanish soccer players investigating the effect of score-line on performance, players performed less high-intensity activity when winning than when they were losing. In agreement, the midfielders and defenders in this study performed less HSR compared to match 1, in matches with a large positive score line. This was evident when comparing matches back to the first match of the

tournament. However, when comparisons were made to the TA, only defenders reduced the amount of HSR when the team was winning. In the most significant victory, comparing back to the TA results suggested that the score-line did not influence the amount of HSR performed for strikers and midfielders. Conversely, the opposite was true for defenders. In the victory with the greatest margin, (i.e. 10-3 victory against Spain), defenders decreased the amount of HSR by $22.7 \pm 15.1\%$ when compared to the TA. This may have been due to the lack of defensive play required during the match with the ball likely spending the majority of time in the attacking half of the field.

Soccer players also performed less low-intensity activity when losing than when winning (Lago, et al., 2010). Interestingly, in the only loss of the tournament in this study (match 4 vs. Germany), when compared back to the TA, players LSA distance across the three positions increased. However, only the defenders increased the amount of LSA compared to the first match of the tournament. Given that winning is a comfortable status for a team (Bloomfield, Polman, & O'Donoghue, 2005), it is possible that opposition players assumed a ball contention strategy, keeping the match slower. This is typical of European field hockey teams when in a winning position, playing the ball around defensive personnel to maintain possession denying opposition use of the ball. Defenders also increased HSR (when compared to TA) during this match and the close 2-1 victory against England. This may be explained by the defensive players being under greater sustained periods of pressure with the ball in the defensive half of the field for a greater period of time. Additionally, the requirement to cover attacking leads from defenders might lead to an increase in the amount of HSR.

Two styles of analysis were completed in this investigation, often providing different results. By comparing matches back to the first match of a tournament, the assumption made is that this match is free of fatigue and not influenced by contextual factors. However, when compared to the TA, no distinct trends emerged. This may suggest that both methods have limitations and that these limitations need to be considered when interpreting results in tournament based time-motion analysis studies. By performing both methods of analysis, however, a more complete understanding of the tournament may be revealed.

6.3.1 Practical Applications

This information can be used to assist in the design physical preparation programs as well as guide the formation of tactical strategies when preparing for elite international hockey players for competition in a tournament format. These findings suggest that short periods of recovery between consecutive matches do not necessarily affect activity profile of elite level hockey players. However, the high levels of fitness as well as the technical ability of the elite level players in this study may have contributed to these results. Caution is required if attempting to adopt this strategy in teams with lower fitness or skill levels. Although each method of comparison used in this study has limitations, performing two levels of analyses provides a greater understanding of the activity profiles for team sports competing in tournaments.

6.3.2 Conclusion

In summary, the activity profiles of players from an elite hockey team competing in an international tournament were analysed. Results indicate that this elite team was able to maintain exercise intensity when playing six matches in a period of nine days. These results are in contrast to previous investigations of tournament play in field hockey. The high number of interchanges used by elite hockey coaches in this study

may have contributed to maintenance of activity profiles throughout the tournament. This tactic allowed attacking and defensive pressure to be applied to the opposition not only throughout a match, but throughout the duration of the nine day tournament. The higher fitness of these elite players, coupled with a high rotational strategy during each match, may also explain the ability to maintain high exercise intensity during the tournament. A potential limitation of this study was the relatively low number of matches and players examined. Therefore, the patterns observed might only be specific to this particular team. Accordingly, care should be taken when generalising these findings to other hockey teams or sports

CHAPTER 7. GENERAL DISCUSSION

7.1 Overview

This thesis has presented four studies that attempt to extend the current understanding of the application of GPS for quantifying the activity profile of hockey athletes. Initially, a study was conducted to determine the validity and reliability of a 5 Hz GPS system. Following this, the magnitude of between-unit variation was examined to assess the ability of these units to be used for making comparisons between players. Two studies were then conducted to describe the activity profile of positional groups within elite hockey using the variables identified as being the most valid and reliable. Study three investigated the impact of the level of competition and positional requirements on the activity profile of elite level hockey players. Study four described the activity profile of three distinct positional groups at the elite level across an international level hockey tournament. Specifically, this study assessed positional differences, activity profile modifications from first to second half and compared the activity profile of all matches to the first match and the tournament average. In the final section of this thesis, key findings from the present work are highlighted and discussed in light of related research, and especially recent manuscripts that have been published subsequent to the studies presented in this thesis. Avenues for future research as well as recommendations arising from the present results are also considered.

7.2 Advancements in GPS technology

7.2.1 The effect of GPS sample rate on reliability and validity

Prior to this thesis, few studies had investigated the reliability and validity of GPS technology for the assessment of team sport movements (Barbero Álvarez, et al.,

2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009; Peterson, et al., 2009). Additionally, most studies had assessed the validity and reliability of these GPS devices with distance and positional data recorded at only 1 Hz (Barbero Álvarez, et al., 2010; Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009), with only one utilising 5 Hz data (Peterson, et al., 2009). Chapter 3 of this thesis determined the validity and reliability of GPS for the assessment of team sport athletes' specific movements. In agreement with previous research (Coutts & Duffield, 2010; Edgecomb & Norton, 2006; MacLeod, et al., 2009; Peterson, et al., 2009), GPS devices have acceptable reliability and validity for assessing TD during longer duration training drills and games. Team sports however, require a mixture of movements, completed at a variety of intensities, incorporating many, and often unpredictable changes of direction. The use of GPS to determine these types of movement is, at present, limited. The results of Chapter 3 and 4 suggest that GPS under-estimates the criterion distance during short distance sprinting, which is prevalent in team sport (Dawson, et al., 2004b; Duthie, et al., 2006; Spencer, et al., 2004). This error was evident regardless of GPS sample rate. However, a higher sample rate improved validity irrespective of distance and locomotion in the straight line, COD and simulated running circuit trials.

A recent study using a different criterion measure as well as a more recent GPS device than used in this thesis, points to improved accuracy (Varley, Fairweather, & Aughey, 2012). In that investigation, 5 and 10 Hz GPS units were compared to a laser (sampling at a rate of 50 Hz) to assess their suitability for measuring instantaneous velocity during the acceleration, deceleration, and constant velocity phases of straight-line running. Findings determined that 10 Hz devices provided an acceptable level of accuracy and reliability for determining instantaneous velocity for all phases of

straight-line running. Furthermore, the higher sampling rate had greatly improved reliability during the constant velocity and acceleration phase and deceleration phase when compared with 5 Hz units. Interestingly, the accuracy of GPS in measuring changes in velocity during deceleration was poor, even with a higher sampling rate overestimations of up to 19.3% existed. The reason for this finding is unclear and warrants investigations given that decelerations can be frequent and important movements in team sport.

As the 10 Hz devices were only released in the past two years, limited research exists regarding their use in the sporting environment (Castellano, Casamichana, Calleja-González, San Román, & Ostojic, 2011; Pyne, Petersen, Higham, & Cramer, 2010; Varley, et al., 2012). Initial comparison between 5 and 10 Hz units were performed over a straight line course of 10, 20, 30 and 40 m. When compared to sprint efforts over the same distances, the 10 Hz unit is markedly more accurate (SEE= 10-m, $13.9 \pm 5.1\%$; 20-m, $8.8 \pm 3.2\%$; 30-m, $6.2 \pm 2.3\%$; and 40-m, $5.0 \pm 1.8\%$). Also, as distance travelled increased, the reliability of the 10 Hz devices improved (TE \pm 90% CI; 10 m = $11.7 \pm 3.6\%$; 20 m = $6.9 \pm 2.1\%$; 40 m = $3.8 \pm 1.1\%$). The efforts in both studies were maximal sprints performed in a straight line. It would be of interest to determine the validity and reliability for other velocities (i.e. walking, jogging and striding) as well as team sport specific movements involving COD. Although given the reliability of sprinting, it may be that these lower velocity movements follow the trend of 5 and 1 Hz models with lower speeds exhibiting greater levels of reliability. The higher number of samples per second of 10 Hz units may increase the accuracy of these devices to assess brief accelerations involved in COD activities. Future research investigating the effectiveness of 10 Hz devices to accurately determine high intensity movements involving COD is necessary.

7.2.2 Criterion measures used in GPS validity studies

The validity of a test or new measurement system has typically been determined by comparisons to a criterion measure or “gold standard” procedure. The first difficulty encountered when assessing GPS validity is determining the gold standard in measurement for comparison. There have been three methods used in the literature investigating the validity of GPS for use in sport: timing gates, laser and VICON analysis.

The most widely used method is to measure a course with a trundle wheel or tape measure and setting timing gates at the start and finish of the course to obtain a time for a known distance. The detail of this method has previously been discussed (Chapter 3). The current studies have attempted to limit the amount of error within the criterion measure. The ability of a trundle wheel or tape measure to accurately measure the known distance is one such example. In an attempt to limit this error, calibrated trundle wheels and tape measures have been utilised. Further, during trials involving sport specific circuits, poles and painted lines were used to ensure players tracked the correct pathway as close to the known distance as possible. Accurately determining the starting point for movement in the GPS software is extremely difficult and finally there is some inherent error in the ability of timing gates to accurately measure time over the course (0.01 s) (Aughey, 2011a).

When assessing changes in velocity, one study used laser technology to measure changes in velocity during rapid actions such as accelerations. Compared with timing gates, which can only determine average velocity based on a limited number of samples, laser devices sample at 50 Hz (Varley, et al., 2012). This should increase the sensitivity of the criterion measure to a greater extent than timing gates. However, this

method can only be used to assess straight line running and may be limited in its ability to assess COD movements which are prevalent in team sports.

In an investigation of tennis movements, a high resolution motion analysis device, the VICON motion analysis system, was used to determine criterion movement distance and speed data during tennis drills. Three-dimensional (3D) positional reflective markers were attached to a harness of one of the participant's GPS devices and recorded by a 22 camera VICON motion analysis system (Oxford Metrics, UK) operating at 100 Hz. The accuracy of the VICON system was calibrated to less than 1 pixel for each camera, representing an error of 0.0008% (Duffield, et al., 2009). This method increased the accuracy of the gold standard criterion measure, overcoming the errors associated with timing gates (Duffield, et al., 2009). However, the technical practicalities of this method, associated cost and set up time limited its use as a comparative method, in this study.

7.2.3 Effect of sample rate on measuring acceleration and COD using GPS.

Speed and acceleration are important qualities in field sports (Aughey, 2010; Aughey, 2011b), with running speed over short distances fundamental to success (Baker & Nance, 1999; Sayers, 2000). In hockey, players accelerate over short distances and sprint to create space, chase opponents, and to penetrate the opposition's defence. The majority of these movements also involve changes in direction as well as rapid decelerations. The ability to quantify these rapid acceleration-deceleration phases would enable sports practitioners to gain better insight into the associated physical cost of these movements. Newer GPS models with higher sample rates may provide an acceptable tool for the measurement of constant velocity, acceleration, and deceleration during straight-line running and have sufficient sensitivity for detecting

changes in performance in team sport. However, researchers may be limited to simply reporting the occurrence of decelerations, as opposed to quantifying the distance and duration.

7.3 Comparison of Activity profile

7.3.1 Comparing player performances using GPS

The capacity to compare player performance and activity profiles during competition or training is of great interest to coaches and support staff. With the level of between-unit variation for 5 Hz units ~10% (Chapter 4), regardless of distance (TD and HSR), movement speed and change of direction, it is recommended the same unit is used for individual players during all exercise sessions. It is also recommended that the between-unit measurement error should be considered if making comparisons between players. Sampling at 10 Hz, enables these evaluations to take place with greater certainty, and without the requirement of the same unit on the same player. Recently, the inter-device reliability of 10 Hz units was determined with small variations between devices evident. Authors reported a CV of 1.3% and 0.7% in sprints of 15 m and 30 m, respectively (Castellano, et al., 2011) concluding that it is not always necessary to monitor players with the same device. This enables comparisons to be made between players with a greater level of confidence and precision.

Differences in methodology make comparison to other research difficult. In other studies of inter-unit reliability multiple units have been worn by either the same subject or a number of subjects (Coutts & Duffield, 2010; Peterson, et al., 2009). However in that study, researchers compared differences between the performances of nine participants who each wore a single unit (Castellano, et al., 2011). This method makes comparison of the difference between units for the same performance difficult.

7.3.2 Comparison between sports

The extensive use of GPS to assess activity profiles in team sports allows interesting comparisons to be made. Sports such as AF (Aughey, 2010; Aughey, 2011b; Brewer, et al., 2010; Gray & Jenkins, 2010; Wisbey, Montgomery, & Pyne, 2007), rugby (Cunniffe, et al., 2009), cricket (Peterson, Pyne, Portas, & Dawson, 2011), soccer (Hill-Haas, Coutts, Rowsell, & Dawson, 2008) and hockey (Gabbett, 2010; Lythe & Kilding, 2011) regularly use GPS to investigate both competition and training loads on players. Comparisons between sports can be made using distance when expressed per minute of match time ($\text{m}\cdot\text{min}^{-1}$). Figure 7.1 provides a summary of approximate $\text{m}\cdot\text{min}^{-1}$ derived from GPS data from a variety of team sports.

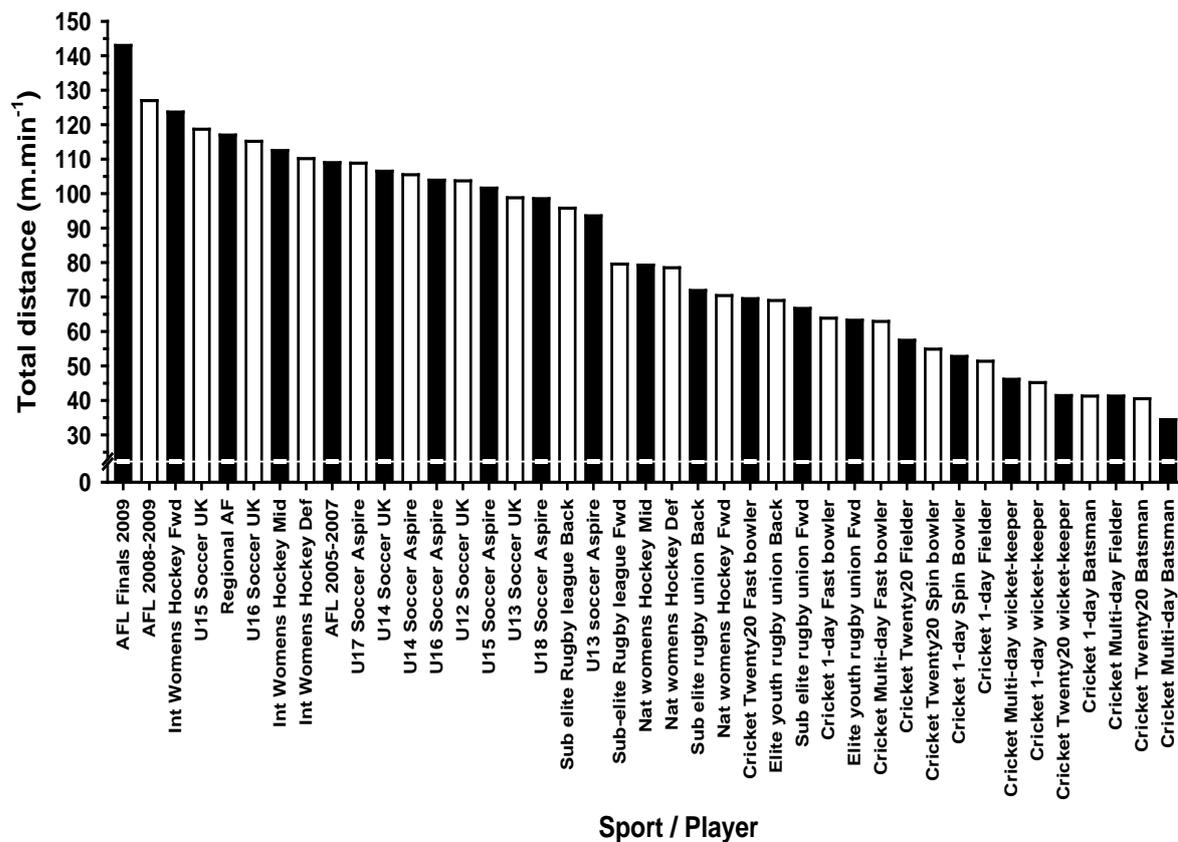


Figure 7.1: Summary of team sport $\text{m}\cdot\text{min}^{-1}$ as derived by GPS data (Reproduced from Aughey, 2011).

In comparison to other sports, international hockey players cover a high distance per minute (Figure 7.1). Only AF players competing in finals exhibited higher $\text{m}\cdot\text{min}^{-1}$ values. This discrepancy is likely due to the larger playing field in AF and the distance demands this places on players. Unfortunately, no information exists which allows for comparison to male elite level soccer using GPS technology. It has been reported that elite level soccer players cover distances of $11,393 \pm 1,016$ m, when measured using other computer based technologies (Di Salvo, et al., 2007). When converted to distance covered per minute of match time (90 min), these players cover similar distances ($115.3 - 137.9 \text{ m}\cdot\text{min}^{-1}$) to elite level hockey players.

Table 7-1: TD covered in elite and sub-elite hockey competition

	CT	AHL
TD (m)	9776 ± 720	8589 ± 623
$\text{m}\cdot\text{min}^{-1}$	137 ± 9	122 ± 9
LSR (m)	7441 ± 511	6905 ± 447
HSR (m)	2294 ± 433	1652 ± 416
HSR $\text{m}\cdot\text{min}^{-1}$	32 ± 6	25 ± 8

CT= Champions Trophy; AHL = Australian Hockey League; TD = Total Distance; $\text{m}\cdot\text{min}^{-1}$ = Meters per minute; LSR= Low speed running; HSR= High speed running; HSR $\text{m}\cdot\text{min}^{-1}$ = High speed running meters per minute

Thus the relationship between high-velocity running and match performance can be summarised as follows; i) the ability to perform a greater amount of HSR can discriminate between elite and sub-elite standards of play (Mohr, Krstrup, et al., 2003) ii) within a competition the more successful teams will perform less high-velocity running than less successful teams (Di Salvo, et al., 2009; Rampinini, et al., 2009), iii) against better opposition a given team is likely to perform a greater amount of high-velocity running (Rampinini, Coutts, et al., 2007).

7.3.3 Rule changes in hockey

Despite rule changes allowing unlimited interchange which have markedly altered tactics in elite level hockey, the number of interchanges that occur has not been reported. A greater number of short rest periods throughout a half of hockey, may allow players to sustain higher intensity movements and reduce the effect of fatigue on performance. Coaches and support staff are continually searching for the ideal rotation strategy to maximise and maintain the intensity of the team, while still allowing for the structural and tactical nuances to consistently be applied. This strategy is usually applied with a specific number of minutes allocated to each positional group. For example, in the study completed in Chapter 6, players in each positional group had a set number of minutes on and off the field. Whether this was the most effective use of playing time or resting time is unknown and may depend on the fitness of each individual player. The results of the matches, as well as the maintenance of HSR across the tournament, suggest the rotation strategy implemented for this team, in this tournament, was effective. The high level of aerobic fitness of the playing squad ($64.2 \pm 3.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), which is comparable to other international level hockey players (Lythe & Kilding, 2011), may be one contributing factor to the success of the team. Furthermore, this strategy of continual rotation would only be effective and indeed was effective, if the playing group was of a consistently high skill level. Rotating players of lesser ability or talent at this level would negate this concept.

7.4 Key findings / Practical applications

In summary, this thesis has attempted to increase the understanding of the match profile and activity demands of elite hockey players. This was achieved by conducting research which investigated the accuracy of GPS technology to assess activity profiles

in team sport. The reliable and valid variables derived from this research were then used to further understand differences between two groups of hockey players varying in playing ability and positional roles. The results may assist sports scientists, coaches and conditioning specialists to optimise the performance of elite hockey players.

The following section outlines the key findings and practical applications resulting from each of the four chapters.

7.4.1 Study 1: The validity and reliability of GPS units for measuring distance in team sport specific running patterns.

Key findings:

1. The 1 and 5 Hz GPS units underestimated the criterion distance during sprinting over short distances.
2. The reliability of 1 and 5 Hz GPS improved as distance travelled increased but decreased as speed increased.
3. The 1 and 5 Hz GPS devices have acceptable reliability and validity for assessing TD during longer duration training drills and games.

Practical Applications:

1. One and 5 Hz GPS devices cannot currently be used to measure brief, high-intensity sprints over distances of less than 20 m or accelerations / decelerations, regardless of sampling rate.
2. It is recommended wide velocity bands be used to report distance covered in specific speed zones.

7.4.2 Study 2: Variability of GPS units for measuring distance in team sport movements

Key findings:

1. There is a considerable degree of variation ($9.9 \pm 4.7\%$ to $11.9 \pm 19.5\%$ for straight line running movements and from $9.5 \pm 7.2\%$ to $10.7 \pm 7.9\%$ in the COD) in distance measured from two GPS units worn by the same player completing the same movement task.
2. The variation between the two GPS units was similar regardless of the movement pattern.

Practical Applications:

1. Between-unit difference should be used in conjunction with test-retest error of GPS when assessing athlete performance.
2. To minimise the source of measurement error, it is recommended that the same unit be used for individual players during all exercise sessions.

7.4.3 Study 3: International field hockey players perform more high intensity running than national level counterparts

Key Findings:

1. International players completed a greater TD and HSR distance across all positions than players at an elite national level.
2. In both competitions, midfielders and strikers performed more HSR than defenders.

3. The positional activity profile decreased in the second half for both competitions

Practical Applications:

1. Players at the national level may require additional conditioning to achieve the higher aerobic capacity required if aspiring to international representation.
2. The training of elite field hockey players should focus on improving their ability to perform intense exercise and to recover rapidly from periods of high-intensity running.
3. Emphasis should be placed on the individualization of conditioning programs to address the specific demands of the different playing positions and underlying physiological limitations.

7.4.4 Study 4: GPS analysis of international field hockey tournament

Key Findings:

1. This elite team was able to maintain exercise intensity when playing six games in a period of nine days.
2. Performing two methods of analysis, firstly against a tournament average and secondly, against the first match of a tournament, provides a more complete understanding of the activity profiles during tournament play.

Practical Applications:

1. This information can be used to guide player physical preparation and tactical strategies when preparing for international competition.
2. Caution is required if attempting to adopt a strategy that involves a high number of substitutions in teams with lower fitness or skill levels.

CHAPTER 8. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 Limitations

8.1.1 GPS

Coupled with the previously discussed development of a “gold standard” criterion measure, accurately determining the starting point for a movement is difficult to establish in the GPS software. The start time was determined by the first increase above zero on the velocity trace and then, using each associated sprint time (from timing gates), the associated distance was determined. Therefore, the validation of GPS to date has methodological limitations that although they can be controlled for, still must be taken into account when interpreting results.

Global positioning systems have rapidly advanced in the past 10 years. During this time, software and hardware has become more sophisticated, with an increased sample rate one such advancement. At the time of these studies the highest available sample rate was 5 Hz. Currently, at least one manufacturer has made available units sampling at 10 Hz. This increase in sample rate has already been proven to enhance the validity and reliability of straight line movements and may yet demonstrate the ability to detect brief high intensity acceleration phases involving COD that are associated with team sports.

8.1.2 Time-motion analysis in hockey

Using high level athletes as a research cohort during competition provides a unique opportunity to understand elite performance. The data obtained reflects current trends that are directly applicable to athletes at the same or aspiring to compete at similar levels. However, the ability to control variables and create a stable research

environment is reduced. Injuries to players during matches, unexpected score lines and the influence of team tactics, opposition strategies and umpires' decisions on results are all intrinsic qualities of sporting competition that can confound the results. Time-motion analysis studies do have a number of potential limitations, mostly relating to the validity and reliability of measurement. In order to lessen these concerns and to address the issue of representation, an increase in games sampled and analysed may need to be carried out. Since variability between matches may be inherent to invasion style team sports, it might be that a larger number of matches is needed to check when the average values stabilise in order for a true work-rate profile to be established (Drust, Atkinson, & Reilly, 2007).

There are inherent difficulties in investigating both physical and technical outputs during a team sport and it is acknowledged that the present thesis was conducted using just eight AHL and six CT matches, albeit against different opposition. This number of matches limits the statistical power of the findings and recommendations but does provide a unique insight into the potential effects of an elite level tournament on activity profiles. As well as the limited number of games, the different opposition may also have provided limitations to research design. Typically, most elite level hockey is played in tournament situations with clusters of 6-8 matches over a short time period. While this potentially affects the control of the research, the advantage is that data is collected in 'real' environments giving insights into elite competition rather than under contrived practice match settings. The information analysed also came from only one team, therefore the activity profiles and results observed might be a reflection of this particular team and difficult to extrapolate to other teams.

The use of distance from each position, rather than the distance covered by individual players, to describe the positional activity profile may have protected anticipated

declines in TD and HSR when the first and second halves of matches were compared. Also, the smaller decrease in HSR in the present study may be related to the unlimited substitution rule as well as positional and tactical requirements employed during both competitions. It is likely that the coaches manage player rotations in field hockey to maintain the exercise intensity of the team. Future studies should examine the relationship between player rotation and activity profile in field hockey.

Recent soccer research has also shown that activity profiles in the same league are influenced by team success, with the less successful team players often having higher intensities of effort, possibly because they are forced to chase more to try to win back the ball (Di Salvo, et al., 2009; Mohr, Krstrup, et al., 2003). Within a game, other factors such as aerobic capacity, motivation, chance of winning and match tactics (of both teams) can clearly affect the activity profile of players (Rampinini, Coutts, et al., 2007; Rampinini, et al., 2009; Rampinini, Sassi, Sassi, & Impellizzeri, 2004). These are all limitations of time-motion analysis and are difficult to control for. Similar to soccer, each playing position in hockey has different tactical requirements in relation to ball movement throughout a match (Rampinini, Coutts, et al., 2007). Unfortunately, information regarding match statistics and ball involvements was not able to be collected during the two tournaments. In a study of elite soccer, forwards and midfielders completed similar amounts of VHIR. However, it was the forwards who covered a significantly greater portion of this distance with the ball when compared to other positions (Castagna, et al., 2006; Rampinini, Coutts, et al., 2007). This information could have implications for the design of position specific small sided games and skill based conditioning training drills.

Difficulties exist when comparing recent findings and data with reported results from the literature. Different technologies, methods and categorisations for the assessment of activity profiles indicate these comparisons are potential limitations.

8.2 Future Research

8.2.1 The use of GPS in team sport analysis

The application of GPS to future research is likely to focus on two distinct areas. Firstly, the further increases in sample rate and secondly, the integration of GPS data with statistical and strategic information.

With 10 Hz units entering the commercial market, the need to establish the reliability, validity and variability for sport specific team sport movements exists. This should occur prior to their use in sporting situations. Determining the variables that these units can measure accurately will enable practitioners to confidently report and assess training and match variables. The increased sample rate may enable a greater number of areas to be investigated with confidence. Most notably, number of sprints or efforts at different velocities, distance covered when sprinting and the number of repeated sprint efforts performed is of great interest to coaches and sport scientists. Some of these are already incorporated into the assessment of training and competition in professional sport. However, the accuracy and precision of these measures using current 1 and 5 Hz units is questionable. The use a 10 Hz sample rate may enable this to be performed with future investigations focusing on these issues.

The creation of guidelines for velocity bands using 1, 5 and now 10 Hz units would enable continuity in reporting as well as consistent methodology for ease of comparison between studies, athletes and sports. The recommendations from this study regarding wide velocity bands could be used as a starting point for future investigations. With the advent of 10 Hz units, those using this new technology, once

validated, may have the potential to use narrower bands and increase the detail in reporting of these zones. Conversely, when sampling at 1 or 5 Hz sample rates, velocity band width may be limited to two zones: HSR and LSR. Increases in sample rate may enable these to be expanded to five zones, similar to those used in other video-based time-motion analysis studies.

Assessing activity levels and running intensities of players using real time GPS software may provide coaches and support staff with information to assist in the appropriate times to interchange players (Aughey & Falloon, 2010). Pre-determined ranges of HSR or HSR $\text{m}\cdot\text{min}^{-1}$ could be individually established prior to competitions and coupled with the “coaches’ eye” (the coaches ability to make strategic or tactical changes based on experience or intuition) could provide a more complete picture on when players are decreasing their ability to produce high intensity efforts. These levels could be established as a result of individual speed data collected as part of routine fitness testing batteries. High velocity running ranges could be determined from 0-40 m sprint times and used as thresholds for individual players during matches. For example, players with lower maximal velocities as determined using this sprint data may then have lower HSR ranges. While these may be time consuming to determine for an entire squad, it may individualise the HSR distance thresholds used. Other researchers have suggested using a player’s individual high intensity threshold based on speed at the second ventilatory threshold ($\text{VT}_{2\text{speed}}$) to determine HSR distance (Abt & Lovell, 2009). When this method was compared to the HSR distance from a computerised match analysis system, HSR distance was substantially underestimated (Abt & Lovell, 2009).

Zones representing different sports or even sex specific zones could be determined which better represent the HSR requirements of sports. Recent work in this area has

proposed standard definitions (velocity ranges) that could be determined by an objective analysis of time-motion data identifying the average velocity distribution (Dwyer & Gabbett, 2012). A curve fitting process has then been suggested to determine the typical locomotor categories. Based on the findings of these analyses, recommendations about sport-specific velocity ranges to be used in future time-motion studies of field sport athletes could then be made (Dwyer & Gabbett, 2012). This method may allow a more accurate comparison between players competing in the same sport. For example, the HSR zone suggested in that study for women's hockey is lower than that of men's soccer and hockey. If the same categories are used, HSR in women's team sports may be underestimated (Dwyer & Gabbett, 2012).

Differences in match-to-match HSR could also be attributed to the influence of different opponents with factors such as playing styles, fitness and tactics being the likely cause of this variance (Rampinini, Coutts, et al., 2007). These characteristics must be taken into consideration when using HSR to discriminate between matches and players performance.

As previously mentioned, the incorporation of tactical and skill information with GPS would provide a greater and more comprehensive analysis of team sport. This information could enhance the understanding of position specific requirements not only from a movement standpoint, but also from a game involvement perspective. This information would further enhance the ability of coaches and conditioning specialists to devise positional and strategic training drills which involve appropriate velocities, intensities and distances, as well as ball involvements and tactical movement patterns.

8.2.2 Future studies in hockey

With the introduction of GPS technology, sport scientists and support staff are able to gain specific information on the distances covered in low and high intensity activities achieved by players during training and competition. Coaches are increasingly trying to match the demands of competition in the training environment, from both a physical and technical aspect. This series of studies provides the information regarding the physical demands of competition at the elite level. The missing component is the analysis of the training environment. A greater understanding of training allows for the tailoring of training to adapt players to the activity profiles required in competition. This has been completed in women's hockey where the discrepancy between competition requirements and training stimulus was found (Gabbett, 2010). Specifically, female AHL players spent more time in low intensity activities, but less time in moderate and high intensity activities in training than in competition (Gabbett, 2010). This type of analysis has yet to be completed in elite male hockey.

Recent rule changes may have markedly altered the tactical and apparent physiological requirements of the match. The use a high number of interchanges by coaches is an attempt to maintain the exercise intensity of the team. This tactic allows attacking and defensive pressure to be applied to the opposition throughout a match. Developing a team and in turn, a more individualised substitution system, appropriately matched to the capacity of the available players, could increase performance statistics and consequently the likelihood of success. Fitness and physiological parameters could be partnered with GPS information, specifically the amounts of HSR in predetermined periods of play or rotations, to investigate the optimal amount of time each player can sustain high intensity movements. Coupled

with this, is the amount of recovery time each player requires between these periods of intense activity to maintain performance levels.

It has been suggested that physical performance in elite soccer may be influenced by match contextual factors. Activity profiles can be affected by the level of opponent as well as differences in tactics and styles of play adopted by opposition teams (Rampinini, Coutts, et al., 2007). Investigation of the effect of the opponent on the reference team has been completed in soccer, but never in elite hockey. Internationally, different nations and regions of hockey are renowned for their different styles of play and the influence of these on Australian teams would be of interest to coaching and sport science staff. Furthermore, the physical cost of tactics employed by coaches would be valuable information for preparation and conditioning staff, enabling them to ready players for the demands of specific strategies. Full ground presses, where intense levels of pressure are applied all over the field, zone defences, man-to-man marking and half ground presses are specific defensive strategies employed by hockey coaches. The cost of these strategies and determining the length of time these tactics can be employed before the amount of sustained pressure (HSR distance) diminishes would be invaluable information for coaching staff. Practice matches with the reference team playing a consistent style and the opposition team changing their tactics would enable this type of analysis to be completed. Comparisons could be made between GPS data of specific periods of play where different tactics or styles of play are employed.

Rule changes in hockey have dramatically transformed the game over the years. The most recent change to the rules came in 2010 when the FIH Hockey Rules Board introduced a significant change into the procedures for taking a free hit, centre pass or side-line hit. A “self-pass” was introduced, which enables the player taking the free

hit to play the ball themselves and effectively “play on” (FIH Rules of hockey, 2010). This rule makes the game more continuous with fewer breaks in play. Players and coaches alike already recognize that this rule change has had an effect in the game, but empirical evidence confirming this has not been presented. Comparisons between GPS match data collected before and after the introduction of this rule could identify if this is in fact the case.

As there has been only a relatively small amount of published literature on elite hockey, it is likely that there is still much to learn and significant benefit to be gained from the investigation of activity profiles, positional requirements and competition analysis.

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APPENDIX 1: INFORMATION FOR PARTICIPANTS

8.2.3 *Study 1 & 2*

1. *The validity and reliability of GPS units for measuring distance in team sport specific running patterns*
2. *Variability of GPS units for measuring distance in team sport movements*

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH



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You are invited to participate

You are invited to participate in a research project entitled:

The validity and reliability of GPS units for measuring distance in team sport specific running patterns

This project will be conducted within the School of Exercise Science Victoria University by Dr Robert Aughey and Ms Denise Jennings. This study will form part of a PhD study conducted by Ms Denise Jennings.

Project explanation

Analysis of team sport players during competition provides valuable information regarding the physiological requirements of matches and activity profiles of players. This information can subsequently be used to enhance the specificity of training programs to better prepare athletes for the rigors of competition. There have been numerous attempts to determine the physical demands of team sports during competition. ^{1,2,3,4}

Whilst the use of video-based time-motion analysis (TMA) has been well documented, ^{1,2,3,4} there is little published data examining the use of Global Positioning Systems (GPS) for game and player analysis. ⁵ Video-based TMA, has a number of limitations. Specifically, the validity and reliability of data collection and the time consuming nature of analysis ⁶. GPS technology has the potential to provide a more comprehensive, accurate and automated examination of player movements in invasion style team sports (e.g. hockey, rugby, rugby league, soccer and Australian Rules football). Few studies however, have investigated the reliability and validity of GPS technology for assessment of team sport qualities.

At present conventional GPS devices sample at a rate of 1 hertz (Hz). Time-motion analysis in a number of team sports has revealed that the majority of sprints are less than 2 seconds in duration or performed over a distance of less than 20 m ^{7,8}. In light of this, sampling at a rate of 1 Hz may be insufficient to detect short high speed movements typical in team sports. With the development of new technology, a higher sampling rate of 5 Hz is available. This sampling rate may increase the number of high intensity sprints detected, providing a more accurate picture of the physiological characteristics required in team sports.

An initial briefing session will provide an overview of the project and, if you agree to take part, require completion of a consent form.

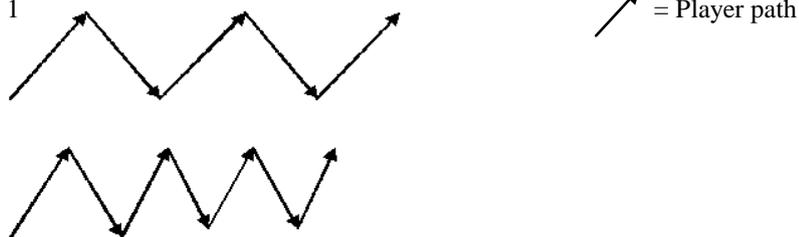
What will I be asked to do?

You will be asked wear 2 GPS units while moving through a series of movement patterns outlined below. You will perform two trials of each of the following courses at the following speeds; walk, jog, stride, sprint.

The following movement patterns will be assessed:

- (1) Straight line course with light gates set up at 0, 10 m, 20 m, 40 m.
- (2) Change of direction (figure 1)
 - a. Gradual
 - b. Tight

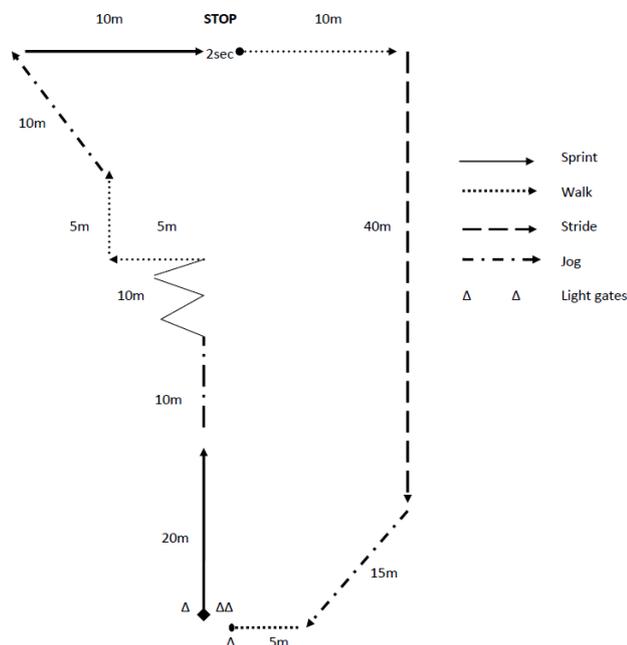
Figure 1



- (3) Sport specific circuit (figure 2)

Players will complete five trials of a team sport circuit involving changes of direction, sprinting, acceleration and deceleration efforts. This will be performed to determine inter unit reliability during sports specific movements over a greater distance.

Figure 2



How will the information I give be used?

Information collected will be downloaded and analysed to assess the following variables:

- TD travelled 1 Hz
- TD travelled 5 Hz

This information will subsequently be used to assess the reliability, validity and variability of the GPS units to measure distances commonly seen in team sports.

What are the potential risks of participating in this project?

There are no physical risks for participants involved with this study. A thorough warm up will be performed prior to data collection of each movement pattern.

How will this project be conducted?

The project will be performed prior to training at the Essendon Football Club training ground. Data will be collected from the GPS units and following this analysis, results will be presented back to the group during an information session. The results from this study may have implications to the information collected from the GPS units during matches throughout the season.

Who is conducting the study?

This study is being conducted by Victoria University.

For further information regarding this study, please contact the Principal Investigator, Dr Rob Aughey on, 9919 5551 or email: Robert.aughey@vu.edu.au or Denise Jennings at the Essendon Football Club, Physical Preparation Department on, 92300220 or email: djennings@essendonfc.com.au .

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.

8.2.4 Study 3 & 4

3. *International field hockey players perform more high intensity running than national level counterparts,*
4. *GPS analysis of international field hockey tournament*

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH



You are invited to participate

You are invited to participate in a research project entitled:

A GPS analysis of physical demands in domestic and international field hockey

This project will be conducted within the School of Exercise Science Victoria University by Dr Robert Aughey and Ms Denise Jennings. This study will form part of a PhD study conducted by Ms Denise Jennings.

Project explanation

Analysis of team sport players during competition provides valuable information regarding the physiological requirements of matches and activity profiles of players. This information can subsequently be used to enhance the specificity of training programs to better prepare athletes for the rigors of competition. There have been numerous attempts to determine the physical demands of team sports during competition.

Until recently, it has been difficult to quantify player movement demands as it has required manual analysis with only one player being analysed at a time. However, with recent technological developments there are now many systems that can analyse movement patterns of many players in team sports simultaneously, including manual and computer-assisted video-based time-motion analysis systems, triangulation of miniature electronic transmitters and global positioning system (GPS) devices. These advances have led to the widespread use of these technologies in many sports. Specifically, GPS technology is used by many sports to quantify movement demands during training and competition.

In field hockey, there are few studies that have utilised this technology for analysis of competition demands at the elite level. To date no studies have investigated or compared the physiological demands of elite men's national level competition or elite international

competitions. This information may be useful for coaches and conditioning staff in designing appropriate training drills for specific role requirements of individual players and assist in the progression of players from sub-elite to elite levels of competition.

An initial briefing session will provide an overview of the project and, if you agree to take part, require completion of a consent form.

What will I be asked to do?

You will be asked for permission to analyse the GPS files collected during the 2008 Australian Hockey League (AHL) tournament to identify the physical and positional demands of this competition.

How will the information I give be used?

Information collected will be downloaded and analysed to assess the following variables:

- TD travelled
- Meters covered per minute of play
- High intensity running distance
- High intensity running meters per minute of play

This information will subsequently be used to enhance the specificity of training programs to better prepare athletes for the rigors of international competition

What are the potential risks of participating in this project?

There are no physical risks for participants involved with this study, as we are analysing data already collected by sport science staff associated with the team.

How will this project be conducted?

The project will require analysis and data mining of GPS files already collected. Following this analysis, results will be presented back to the group during an information session. The results from this study may have implications to the design of your physical preparation program for future tournaments.

Who is conducting the study?

This study is being conducted by Victoria University.

For further information regarding this study, please contact the Principal Investigator, Dr Rob Aughey on, 9919 5551 or email: Robert.aughey@vu.edu.au or Denise Jennings at the Essendon Football Club, Physical Preparation Department on, 92300220 or email: djennings@essendonfc.com.au .

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.

APPENDIX 2: INFORMED CONSENT FORM

8.2.5 *Study 1 & 2*

1. *The validity and reliability of GPS units for measuring distance in team sport specific running patterns*

2. *Variability of GPS units for measuring distance in team sport movements*

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH



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INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study into the validity and reliability of GPS units for measuring distance in team sport specific running.

The aims of this study are to assess the reliability and validity at both 1 Hz and 5 Hz of the MinimaxX GPS device for the assessment of different movement patterns and distances common to team sport play.

This information will be useful for coaches and conditioning staff in improving the accuracy of the information used to describe performance during training and team sport competition.

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:

The validity and reliability of GPS units for measuring distance in team sport specific running patterns

being conducted at Victoria University by: Dr Rob Aughey

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 Denise Jennings and that I freely consent to participation involving the below mentioned procedures:

- GPS data collection during 3 different movement patterns
- Analysis of GPS data collected during sampling session

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, ph. 03 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

*[*please note: Where the participant/s are aged under 18, separate parental consent is required; where the participant/s are unable to answer for themselves due to mental illness or disability, parental or guardian consent may be required.]*

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH



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INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study into the analysis of physical demands in domestic and international field hockey.

The aims of this study are:

- (1) To determine the physical demands and positional differences in national level and international field hockey competition
- (2) To compare the physical demands of national level and international field hockey, and
- (3) To examine high intensity running demands during different competition levels (domestic and international) for players in various playing positions.

This information will be useful for coaches and conditioning staff in designing appropriate training drills for specific role requirements of individual players and assist in the progression of players from sub-elite to elite levels of competition.

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:

The GPS analysis of physical demands in domestic and international field hockey

being conducted at Victoria University by: Dr Rob Aughey

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 Denise Jennings and that I freely consent to participation involving the below mentioned procedures:

- Analysis of GPS data collected during the 2008 AHL tournament
- Analysis of GPS data collected during the 2009 Champions Trophy tournament

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, ph. 03 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

*[*please note: Where the participant/s are aged under 18, separate parental consent is required; where the participant/s are unable to answer for themselves due to mental illness or disability, parental or guardian consent may be required.]*