THE MEASUREMENT AND ANALYSIS OF THE
PHYSICAL PERFORMANCE OF SOCCER PLAYERS

A thesis submitted in fulfilment of the requirements for
the degree Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Troy Rohan Flanagan

July 2010
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Abbreviations

3D: three dimensional
C: Celsius
cm.s\(^{-1}\): centimetres per second
cm: centimetre
D1: Division one
D2: Division two
D3: Division three
D4: Division four
deg.s\(^{-1}\): degrees per second
dw: dry weight
FIFA: federation internationale de football association
g: gram
g: acceleration due to gravity
GPS: global positioning system
Hz: Hertz
kcal.min\(^{-1}\).kg\(^{-1}\): kilocalories per minute per kilogram
kj: kilojoule
kj.min\(^{-1}\): kilojoules per minute
km: kilometres
km.hr\(^{-1}\): kilometres per hour
L.min\(^{-1}\): litres per minute
m: metres
m.s\(^{-1}\): metres per second
MAIN: magnetic and inertial navigation system
MB: megabyte
min: minutes
MJ: megajoule
ml.min\(^{-1}\).kg\(^{-1}\): millilitres per minute per kilogram
mmol.L\(^{-1}\): millimoles per litre
NiMH: nickel metal hydride
\(n\): subject numbers
oz: ounces
\(P\): p value
PC: personal computer
PL: Professional League
rad.s⁻¹: radians per second
s: second
SPA: Soccer Performance Analysis
% TE: Percent typical error of measurement
USA: United States of America
VO₂max: maximum oxygen uptake
Summary

The purpose of this thesis was to identify a solution to the problem previously identified by sport scientists and coaches working with elite professional soccer teams: it is difficult to measure and analyse the physical performance of soccer players during match play (Bangsbo & Mohr, 2005; Burgess et al., 2006; Krstrup et al., 2006). This thesis comprised of chapters that sequentially identified the problem, examined how to analyse the on-field physical performance, determined how to comprehensively measure the on-field movements, successfully validated a possible solution and trialled a new locomotion tracking prototype.

The review of literature in Chapter 1 primarily focused on reviewing the data and the measurement techniques that have been employed by investigators to quantify the physical performance of soccer players. This review facilitated the identification of the problem and revealed the inadequacy of current measurement techniques to quantify the physical performance of soccer players. There has been very little data published by investigators on soccer player performance beyond describing only general movements made by players during a match. Short term, ballistic and sport specific movements have rarely been measured due to the technical limitations of the measurement techniques adopted by investigators. Consequently, the problem that current technology was either too invasive or was not sensitive enough to remotely track all types of movements made by players was identified and translated into a clear problem definition.

The requirements for solving this problem were detailed in Chapters 2 and 3. Chapter 2 focused on identifying the requirements for interpreting the on-field performance of soccer players. More specifically, this section identified what information was needed to effectively analyse and interpret the physical performance of soccer players. This information was used to describe the required measures and how these different variables can be used to evaluate if
a player's performance was successful. Chapter 3 examined the requirements for comprehensively measuring the movements of a soccer player during a match. The critical measurements that must be made by a new tracking system were identified. The design requirements were prioritised and a hardware technology solution was selected from a range of possible options.

From the analysis in Chapter 3, it was identified that no technology solution was readily available to coaches and sport scientists that met the design requirements and could also measure the entire range of complex and sport specific movements made by players in any playing environment. Chapter 4, therefore, focused on determining the reliability and validity of magnetic and inertial motion tracking technology; its ability to detect ballistic and subtle sports specific actions; and its ability to be modified to meet the design requirements for elite sport so that it can operate in a professional soccer match environment. For initial proof of concept, a somewhat invasive magnetic and inertial motion tracking system, Shadowbox™ (Shadowbox, Park City, USA), previously designed for tracking skis and snowboards, was used in a series of validity studies. When attached to the ankle, the Shadowbox™ tracking system was proven to have high validity against a criterion method, the Vicon MX™ motion tracking system (Vicon Motion systems Ltd, Oxford, UK), during a series of soccer specific actions ($R^2=0.93$ for kicking a ball, $R^2=0.92$ for one-touch pass of a ball, $R^2=0.95$ for slide tackle) and also against the Optojump™ gait analysis system (Microgate, Bolzano, Italy) during walking ($R^2=0.99$) and running ($R^2=0.99$) experiments. Validating the technology using these movements was important, since the majority of movements made by soccer players are either soccer specific actions or movement (gait) around the field (Bangsbo, 1995). In addition, the problem of examining the data collected by magnetic and inertial motion tracking technology to distinguish different movements was also addressed. Two similar movements, jumping and heading the ball, were selected to determine if there were
infact differences between the ankle biomechanics of the two actions. The magnetic and inertial motion tracking technology was able to detect the biomechanical differences between the two actions when the sensor was attached to the ankle. Despite the actions being performed in random order over two trials, the trajectory, displacement and speed of the ankle was reproducible and differentiated the actions. Curve fitting equations for the average 3D trajectory of the ankle during jumping and heading were developed. These can be used to detect jumps or headers from random movement data during a match. This experiment validated the magnetic and inertial navigation motion analysis system's ability to detect and discriminate between different soccer specific actions from movement data.

Since this motion tracking technology solution was proven to be a valid and reliable solution for motion tracking of soccer players, a new miniature and inertial navigation (MAIN) motion tracking system was developed to meet more of the design requirements, compared to the larger, unusable commercially available sensors and those previously used by other investigators to measure sports biomechanics (Brodie et al., 2008). The MAIN motion tracking system was 80% smaller and had 86% less mass compared to the Shadowbox™ system. It was miniaturised to a point where it is significantly less invasive than any other system and was small enough to potentially be built into a shoe or shin pad in future applications. In addition to size, other high priority design requirements were also met, including high sensor precision, operates independently from a computer, extended battery life, structurally robust to handle impact and an on-board memory capacity to last an entire match. Results from the experiments on the MAIN motion tracking system showed it to have high precision with an average typical error of measurement (TEM) of 0.88% error between steps during a walking trial. These results proved that modifying the magnetic and inertial sensors to meet the identified design requirements for operation in the professional soccer match environment did not significantly impact the precision of the technology.
In summary, this thesis systematically identified and solved a series of challenging problems. This thesis was the first of its kind to prove that the magnetic and inertial navigation motion tracking technology: (1) can perform valid measures of soccer specific movements, including one-touch pass of a ball, slide tackle, kicking (drive) a ball, jumping and heading a ball, (2) can perform valid measures of gait, including walking and running, (3) can discriminate kinematic differences between short-term, ballistic soccer specific actions including jumping and heading a ball, (4) can be modified to meet the unique design requirements for operation in the elite soccer match environment without compromising the sensor precision and (5) is the first viable solution of its kind suitable for measuring the physical performance of soccer players.
CHAPTER 1

Problem Definition and Identification of Need
1.1 On-field performance of elite soccer players

The performance of a soccer player during a match can be divided into three components: the technical or skill performance, the tactical performance and the physical performance. The technical components primarily consist of the quality of skills executed during a match by a player. The tactical component refers to the overall strategy and style of play executed to defeat opponents and the opposing team. The physical performance incorporates all of the discrete movements and efforts made by a player during a match.

Modern professional coaches and sport scientists are currently attempting to quantify the performance of soccer players with the aim of determining how the game was won or lost, who played well and what were the players' strengths and weaknesses (Healey, 2009). The primary goal of this analysis is to work out ways to enhance the athletic performance of the individual players and the collective team.

Professional soccer teams now have access to significant statistical analysis on the technical and tactical performance, either through the media or proprietary software that can collect and analyse player data in real time during a match (Turner, 2007). However, there is a notable absence of real time data on the physical performance of players. The recent introduction of Satellite Global Positioning System (GPS) technology in the Australian Professional Soccer League during matches has started to solve this issue (Merrick, 2006). However, this technology is limited in solving all types of movements made by a player during a match due to its slow sample rate and inability to work inside indoor stadiums. Coaches are, therefore, unable to objectively evaluate the entire physical performance of soccer players on the field and rely on published data in sport science journals to estimate the physical workloads of players in each position during a match.
This chapter, therefore, focuses on reviewing the current level of understanding of the on-field performance of soccer players. In addition, this review also evaluates the factors that affect the on-field physical performance that need to be considered when analysing performance and how the on-field movements of players have been measured by investigators to date and the limitations of these techniques.

1.1.1 Player physical performance during soccer match play

1.1.1.1 Physical activity during soccer match play

Investigations into the activity profile of elite first division soccer players have shown that they have approximately 1000-1400 changes in playing activities during a match (Reilly & Thomas, 1976; Bangsbo, 1994) occurring approximately every 4-5 seconds (Rienzi et al., 2000). Notational analysis studies on the activity patterns of professional soccer players have recorded players moving at speeds varying from walking to slow-moderate jogging, running and intermittent maximal sprint efforts throughout the two 45 minute (min) halves of a match (Saltin, 1973; Knowles & Brooke, 1974; Whitehead, 1975; Reilly & Thomas, 1976; Withers et al., 1982; Rienzi et al., 2000; Burgess et al., 2006). The recorded average frequency between sprint or high intensity efforts by professional soccer players during a match have ranged between 40 to 90 seconds (Reilly & Thomas, 1976; Mayhew & Wenger, 1985; Bangsbo et al., 1991). In addition, sport specific actions of soccer players during a match include jumping, tackling an opponent, heading the ball, receiving the ball, dribbling the ball, passing, throw ins and kicking at goal (Luhtanen, 1994). The mode of running is not purely in a straight line during match play. For example, Withers et al. (1982) found Australian Professional National League soccer players performed approximately 50 high speed changes in direction during a match. Therefore, the activity profile of a soccer player can be characterised as repeated, high intensity, multidirectional sprint and match specific efforts,
interspersed with varying bouts of low to moderate intensity activity for the duration of the game.

The distances travelled by soccer players during a match have been investigated on a number of players from different nationalities and playing levels and have been summarised in Table 1-1. An early investigation by Saltin (1973) determined the distances travelled by Swedish division one professional soccer players using video analysis. Players with normal pre-game intramuscular glycogen levels travelled a total distance of 12 km during a match. Whitehead (1975) also found English division one professional soccer players to run an average of 11.7 km during a match. Only four players were evaluated in this study. However, studies by Reilly and Thomas, (1976) and Knowles and Brooke (1974) on significantly greater number of subjects and matches found English professional division one players to travel only 8.6 km and 4.8 km respectively. Possible reasons for this discrepancy could be the manual nature of the techniques used in these studies to estimate distances from video and the observational nature of the methods used. A later study by Kan et al. (2004) also found Japanese and United Arab Emirates players to travel approximately 6.5-6.9 km during a match. The number of subjects and matches recorded could also influence these results, since only 1-4 matches were studied in those investigations with unusually lower results for distances travelled. A more comprehensive study by Withers et al. (1982) on 20 Australian professional division one soccer players during 20 matches found similar findings to Whitehead (1975), with players travelling a total distance of 11.5 km. A similar study of comparable subject numbers and matches by Ekblom (1986) found Swedish professional soccer players of various divisions to travel a total distance of 9.6 – 10.6 km during a match. German professional division two players were also found to travel 9.8 km during a match in the same study. Bangsbo et al. (1991) investigated 14 Danish male professional soccer
Table 1-1. Previously recorded on-field locomotion patterns and distances travelled (metres) of soccer players during soccer match play

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality of Players</th>
<th>Playing Level</th>
<th>subject # /gender</th>
<th>Match (#)</th>
<th>Distance travelled (metres)</th>
<th>Sprints (#)</th>
<th>Distance/ Sprint (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Saltin (1973)</td>
<td>Sweden</td>
<td>Professional D1</td>
<td>5</td>
<td>1</td>
<td>12,000 6,100 5,900 3,240</td>
<td>2,880</td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>Whitehead (1975)</td>
<td>England</td>
<td>Professional D1-2</td>
<td>4 male</td>
<td></td>
<td>11,700 2,025 1,748</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1976</td>
<td>Reilly &amp; Thomas (1976)</td>
<td>England</td>
<td>Professional D1</td>
<td>40 male</td>
<td>51</td>
<td>8,680* 2,150 3,187 1,810</td>
<td>974 15 65</td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>Withers et al. (1982)</td>
<td>Australia</td>
<td>Professional D1</td>
<td>20 male</td>
<td>20</td>
<td>11,527 3,026 5,139 1,506</td>
<td>666</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>Ekblom (1986)</td>
<td>Sweden</td>
<td>Professional D1-4</td>
<td>44 male</td>
<td>24</td>
<td>9,600-10,600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>Van Gool et al. (1988)</td>
<td>Belgium</td>
<td>Collegiate</td>
<td>7 male</td>
<td></td>
<td>10,200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>Bangsbo et al. (1991)</td>
<td>Denmark</td>
<td>Professional D1-2</td>
<td>14 male</td>
<td>34</td>
<td>10,800</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Ogushi et al. (1993)</td>
<td>Japan</td>
<td>Collegiate</td>
<td>2</td>
<td>1</td>
<td>10,809</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>Miyagi et al. (1999)</td>
<td>Japan</td>
<td>Professional D1</td>
<td>1 male</td>
<td>6</td>
<td>10,460 5,315 5,141</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>Rienzi et al. (2000)</td>
<td>England</td>
<td>Professional D1</td>
<td>6 male</td>
<td>1</td>
<td>10,104 3,068 6,111 887</td>
<td>268</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Krustrup et al. (2006)</td>
<td>Denmark</td>
<td>Professional D4</td>
<td>7</td>
<td>3</td>
<td>9,750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Burgess et al. (2006)</td>
<td>Australia</td>
<td>Professional D1</td>
<td>45 male</td>
<td>45</td>
<td>10,100 5,275 4,825 3,400</td>
<td>3,800 1,800 1,000</td>
<td>58 17</td>
</tr>
</tbody>
</table>

D1 = Division One, D2 = Division Two, D4 = Division Four, PL = Professional League, National = National Team. *not a full game of data (extrapolated data)
players over 34 matches and found players to travel 10.8 km. Similar findings during this period were also found by Ohashi et al. (1988) who found four Japanese National Team players to travel and average of 10.3 km during a match. In the late 1990’s and early 2000’s, researchers began to reinvestigate the distances travelled, since the technology became more automated and sophisticated (Miyagi et al., 1999; Rienzi et al., 2000). Investigations by Miyagi et al. (1999) found one Japanese professional first division player to run an average total distance of 10.5 km over six matches, while Rienzi et al. (2000) found six English professional division one players to run an average total distance of 10.1 km during a match and 17 South American National team players to run an average of 8.6 km during nine matches. Interestingly, a recent comprehensive study by Burgess et al. (2006) on 45 Australian First Division professional soccer players over a playing season also found players to travel 10.1 km using a new video and computer software-based tracking system. It is difficult to attribute the variations observed in total distances travelled by players solely to possible estimation or methodological errors. There are a number of factors which may affect the total distances travelled by players including various tactical and match environment conditions (Kirkendall, 1985; Drust et al., 1998; Reilly, 2003). Interestingly, distances travelled during a match for second division (Whitehead, 1975; Ekblom, 1986; Bangsbo et al., 1991) and collegiate level (Van Gool et al., 1988; Ogushi et al., 1993) players of approximately 10-11 km are not greatly different from those studies on first division players. However, elite male junior level soccer players have been shown to run only 6.6 km during match play (Ohashi et al., 2002).

The research conducted on the distances travelled by soccer players has shown substantial variations in distances walked, jogged, run and sprinted during match play. In particular, distances travelled by professional first division players ranged from 2.0 – 3.4 km for
walking, 1.7 – 6.1 km for jogging, 0.9 – 2.6 km for running and 0.5 – 2.8 km for sprinting (Saltin, 1973; Knowles & Brooke, 1974; Whitehead, 1975; Reilly & Thomas, 1976; Withers et al., 1982; Rienzi et al., 2000; Burgess et al., 2006). From these studies it appears that as the locomotion speed gets progressively faster, the degree of variation in distances travelled increases. The average distance walked for studies listed in Table 1-1 is 2880 ± 556 m, jogging is 3686 ± 1639 m, running is 1589 ± 645 m and sprinting is 1165 ± 992 m, equating to a 19%, 44%, 40% and 85% variation respectively from the means. This also indicates that the detection of locomotion using the methods adopted by researchers in these studies may be more erroneous as the speed of locomotion increases. Bouts of high speed running and sprinting during match play are often less than two seconds (Bangsbo et al., 1991; Burgess et al., 2006). These movements are more difficult to detect using manual and observation-based methods for detecting speed and distances travelled. As a result, a more precise system for detecting distances travelled at high running speeds needs to be developed to establish if the observed variation in running and sprinting distances is due to methodological errors or is due to different match environment conditions.

The intermittent nature of activities during soccer match play has been investigated by several researchers. In particular, Table 1-2 summarises the research that has focused on the role of different locomotion or activity types in both time and distance as an overall contribution to locomotion during match play. Results from studies on the percentage of match time players are spending at high intensities or sprinting ranges from 0.5-11.3% of the total time or 3-24% of the total distance travelled during the match. These data suggest that sprinting makes up a relatively small component of the match. However, sprinting during a soccer match is often associated with gaining possession, evading and chasing players at critical moments of the match. Sprints performed by players during Danish first division matches were found by
Table 1-2. Percent contribution of time and distance of various locomotion modes and incidence of high intensity efforts recorded during soccer match play.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality of Players</th>
<th>Playing Level</th>
<th>subject /gender</th>
<th>Matches (#)</th>
<th>Stand (%)</th>
<th>Walk (%)</th>
<th>Jog (%)</th>
<th>Run (%)</th>
<th>High Intens. Average time between High intensity/sprints</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>% Contribution of time during matches</td>
</tr>
<tr>
<td>1982</td>
<td>Withers et al. (1982)</td>
<td>Australia</td>
<td>Professional D1</td>
<td>20 male</td>
<td>20</td>
<td>-</td>
<td>26%</td>
<td>45%</td>
<td>13%</td>
<td>5.8%</td>
</tr>
<tr>
<td>1985</td>
<td>Mayhew &amp; Wenger (1985)</td>
<td>USA</td>
<td>Professional D1</td>
<td>3 male</td>
<td>4</td>
<td>2%</td>
<td>46%</td>
<td>38%</td>
<td>-</td>
<td>11.3% 39 s</td>
</tr>
<tr>
<td>1991</td>
<td>Bangsbo et al. (1991)</td>
<td>Denmark</td>
<td>Professional D1-2</td>
<td>14 male</td>
<td>34</td>
<td>17%</td>
<td>40%</td>
<td>35%</td>
<td>7%</td>
<td>0.7% 70 s</td>
</tr>
<tr>
<td>1992</td>
<td>Bangsbo (1992)</td>
<td>Denmark</td>
<td>Professional D1</td>
<td>9 male</td>
<td>34</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6%</td>
<td>2.5/0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Professional D2</td>
<td>5 male</td>
<td>34</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4%</td>
<td>1.6/0.5%</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Contribution of distance during matches</td>
</tr>
<tr>
<td>1973</td>
<td>Saltin (1973)</td>
<td>Sweden</td>
<td>Professional D1</td>
<td>5 male</td>
<td>9</td>
<td>-</td>
<td>27%</td>
<td>49%</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>1974</td>
<td>Knowles &amp; Brooke (1974)</td>
<td>England</td>
<td>Professional D1</td>
<td>40 male</td>
<td>4</td>
<td>-</td>
<td>35%</td>
<td>54%</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>1976</td>
<td>Reilly &amp; Thomas (1976)</td>
<td>England</td>
<td>Professional D1</td>
<td>40 male</td>
<td>51</td>
<td>-</td>
<td>25%</td>
<td>38%</td>
<td>21%</td>
<td>11% 90 s</td>
</tr>
<tr>
<td>2000</td>
<td>Rienzi et al. (2000)</td>
<td>South America</td>
<td>Professional D1</td>
<td>6 male</td>
<td>1</td>
<td>-</td>
<td>30%</td>
<td>60%</td>
<td>9%</td>
<td>3%</td>
</tr>
<tr>
<td>2005</td>
<td>Bangsbo &amp; Mohr (2005)</td>
<td>Italy</td>
<td>Professional D1</td>
<td>28 male</td>
<td>1</td>
<td>-</td>
<td>38%</td>
<td>48%</td>
<td>11%</td>
<td>4%</td>
</tr>
<tr>
<td>2006</td>
<td>Burgess et al. (2006)</td>
<td>Australia</td>
<td>Professional D1</td>
<td>45 male</td>
<td>45</td>
<td>-</td>
<td>34%</td>
<td>38%</td>
<td>18%</td>
<td>10% 96 s</td>
</tr>
</tbody>
</table>

D1 = Division One, D2 = Division Two, D3 = Division Three, PL = Professional League, National = National Team. High Intens. = high intensity.
Bangsbo (1994) to last an average of only 2 seconds or approximately 17 metres. In this study, the average total number of sprints was 19. Similar results were found by Reilly and Thomas (1976), where English professional soccer players completed an average of 15 maximal sprints during a game. A recent study by Burgess et al. (2006) on Australian professional first division players found that players completed 58 sprint efforts of less than 2 seconds duration, which is almost three times the number previously recorded during first division soccer matches. This may be partly due to differences in methodologies and technologies used to detect sprints and subtle differences in the definitions of sprinting activities between various investigators. A milestone study by Bangsbo and Mohr (2005) was recently conducted to detect player position and running speed on the playing field using a sophisticated multiple camera and software-based system (AMISCO, Sport Universal, Italy). Players \((n=28)\) performed 36 sprints greater than 21 km.hr\(^{-1}\) having an average and peak distance of 18 ± 1 m and 38 ± 4 m. Due to the high sample rate of the measurement system used, this study was more likely to detect short term, ballistic movements. Consequently, the increased number of sprints was significantly higher than the earlier investigations and seems to be in line, but not as numerous as those found by Burgess et al. (2006). Nonetheless, the number of sprints detected and reported during first division match play has increased in recent years in studies that are using more sophisticated software and camera-based systems.

The average running speed of Australian male professional soccer players in a study by Burgess et al. (2006) was found to be 6.7 km.hr\(^{-1}\). Other studies on professional soccer players have reported speeds of 5.7 km.hr\(^{-1}\) for South American players, 5.8 km.hr\(^{-1}\) for English players and 7.6 km.hr\(^{-1}\) for Asian players (Yamanaka et al., 1988). Bangsbo and Mohr (2005) recently examined the fluctuations in high-intensity exercise and running speeds of Italian male professional soccer players during a game. The average speed of the recorded sprints during the match was 23.0 km.hr\(^{-1}\), while the peak speed obtained in the sprints was 26
In addition, the peak velocity reached in a single sprint was $31.9 \pm 0.8 \text{ km.hr}^{-1}$. Peak sprint speed during the initial 15 minutes of the match was $30.1 \text{ km.hr}^{-1}$.

The ratio between the time spent at high speed running, low speed running and standing or walking for entire matches has been investigated by Bangsbo (1994) to be $1:4.3:7.1$ for Danish professional players. Similarly, ratios between high speed running and jogging, walking and standing for male soccer players were found to be $1:4.5:5.2:2.2$ and $1:3.4:4.1:0.2$ by Bangsbo et al. (1991) and Mayhew and Wenger (1985), respectively. The duration of the high intensity effort can also have an effect on the intermittent nature of the game. For example, Bangsbo and Mohr (2005) found that sprints over more than 30 m demanded markedly longer recovery time than the average sprints of between 10-15 m. The average recovery time between sprints was $195 \pm 26$ s. Players who performed sprints longer than 30 m had an increased recovery time by 47%, compared to regular sprints during the match. These results, however, are only guide for the activity ratio, since the running patterns can vary significantly from player to player during a match.

At present, only one study has investigated the acceleration of male professional soccer players (Erdmann, 1993). Data from this study suggested that elite male soccer players accelerate up to 4 m.s$^{-1}$. Additional research using technology that can make multiple measures of acceleration rates of players per second is needed to further investigate the acceleration and deceleration movements of soccer players during match play.

Other actions made by soccer players during match play include tackles, headers, jumps, shooting for goal, passing the ball, trapping the ball, throwing the ball into play, intercepting passes and dribbling the ball. On average, elite soccer players execute 10.9-14.0 tackles (Withers et al., 1982; Ekblom, 1986), 30 dribbles of the ball for an average of 2.9 s, 8.9-9.9
headers (Rico & Bangsbo, 1992), 15.5 jumps, 33 passes (Burgess et al., 2006) and 5.3
instances where players get up from the ground per game (Reilly & Thomas, 1976).

In summary, studies on the activities undertaken by soccer players have shown match play to
involve frequent high intensity sprints and ballistic match specific activities of varying
frequency and duration, interspersed with bouts of low to moderate intensity movement.
However, the match activity data collected from various studies has shown significant
variation, particularly in high speed activities. This may be attributed to a combination of
factors, including a difference in physical demands on players in different leagues and
differences in recording and estimation methods of locomotion in these studies, particularly of
high speed running. As a result, a comprehensive investigation of locomotion activities still
needs to be conducted using a measurement system that can precisely detect short term,
ballistic high speed movements made by players during a match.

1.1.1.2 Physiological demands during soccer match play

Researchers have often attempted to quantify the degree of physiological stress placed on
soccer players during different modes of locomotion. This is an important step in the
performance analysis process to determine the intensity of exercise, economy of movement
and the degree of physiological fatigue during a match.

Estimates of energy expenditure can be derived using the data collected on the locomotion
patterns of soccer players during match play. Using the average speeds and known body mass
of players, Shephard (1992) used prediction equations to derive values between 2728-3698 kj
for top level players. Another method used by investigators was to estimate oxygen
consumption and energy expenditure from heart rates recorded during match play, based on
the linear relationship between heart rate and corresponding oxygen consumption rates in the
laboratory (Bangsbo, 1994; Esposito et al., 2004). Investigations into the average heart rates recorded during soccer matches have reported average heart rate ranges from 160 – 180 beats per minute (Seliger, 1968a; Seliger, 1968b; Raven et al., 1976; Withers et al., 1977; Van Gool et al., 1983; Bangsbo & Mizuno, 1988; Nowacki et al., 1988; Rohde & Espersen, 1988; White et al., 1988; Reilly, 1990; Ogushi et al., 1993; Smith et al., 1993; Bangsbo, 1994; Krustrup et al., 2004; Bangsbo et al., 2006). These studies have shown heart rates of male soccer players to average approximately 170 beats per minute for the duration of the game. Based on heart rate, estimates of the average intensity of match play by male soccer players have been reported at approximately 70-75% of their maximal oxygen intake (Reilly & Thomas, 1979; Rohde & Espersen, 1988; Van Gool et al., 1988), equating to an approximate energy expenditure of 72.8 kJ.min\(^{-1}\) or 6.55 MJ for a 90 minute match (Shephard, 1992). However, this method is somewhat limited in its ability to predict energy expenditure due to the equations’ biases towards steady aerobic exercise as opposed to the intermittent and short term activities of soccer match play. This method underestimates energy expenditure, since research has shown that running backwards or sideways increases energy costs by 20-40% as the speed is increased from 5-9 km.hr\(^{-1}\) (Reilly & Bowen, 1984). In addition, possessing and controlling the ball during match play increases the stride rate and decreases stride length and subsequently increases energy costs of running (Reilly & Ball, 1984; Reilly, 1994a; Reilly, 1994b). Investigations using the direct measurement of oxygen consumption during match play has shown energy expenditures rates of 50 kJ.min\(^{-1}\) or 2.5 MJ per game in low level competitions (Durnin et al., 1997). Another study reported a range of 22-44 kJ.min\(^{-1}\) in male students during soccer match play (Covell et al., 1965). However, investigations on top class soccer matches have found players to expend approximately 0.18 kcal.min\(^{-1}\).kg\(^{-1}\) or 5 MJ per game (Seliger, 1968a). The energy expenditure has been shown to be decreased in lower playing levels, since a study on Japanese college soccer players using the same Douglas bag technique for measuring oxygen consumption showed similar heart rates, but 30-50% lower
oxygen consumption than professional players (Ogushi et al., 1993). Data from studies that have used Douglas bags to measure oxygen consumption are questionable, since the collection method of expired air is somewhat invasive and would restrict the high speed movement activity of players during match play. In addition, the study by Seliger (1968) on energy expenditure during a match only collected 10 minutes worth of match data.

Investigations into the oxygen consumption rates measured directly during match play by outfield players have averaged 3.18 L.min\(^{-1}\) (Seliger, 1968a) and 3.55 L.min\(^{-1}\) (Seliger, 1968b). Estimated oxygen consumption rates using linear regression equations from heart rates achieved during match play have shown that the average oxygen uptake during match play is approximately 70 – 75 % VO\(_{2\max}\) (Reilly & Thomas, 1979; Rohde & Espersen, 1988; Van Gool et al., 1988). Consequently, further investigation into the aerobic fitness levels of elite professional soccer players have been found to be very high (Ekblom, 1986; Apor, 1988; Nowacki et al., 1988; Wisløff et al., 1998). VO\(_{2\max}\) scores of elite professional soccer players have regularly been observed above 65 ml.min\(^{-1}\).kg\(^{-1}\) in laboratory-based tests.

Due to the high intensity nature of activities during match play, anaerobic energy production via non-oxidative metabolic pathways is high at certain times. The rates of creatine phosphate utilisation and glycolysis are high during moments of intense anaerobic turnover, such as sprinting with relatively short rest periods. Intramuscular creatine phosphate levels in Danish Fourth Division soccer players have been sampled during match play and were significantly depleted from 88 mmol.kg\(^{-1}\) dry weight (dw) at rest to 76 mmol.kg\(^{-1}\) dw in the first half and 67 mmol.kg\(^{-1}\) dw after an intense period in the second half (Krustrup et al., 2006). Muscle lactate after intense periods in the first and second halves was on average 15.9 and 16.9 mmol.kg\(^{-1}\) dw, compared to resting levels of 4.2 mmol.kg\(^{-1}\) dw. Interestingly, blood lactate levels have been recorded between 3 – 10 mmol.L\(^{-1}\) for first division players (Ekblom,
However, the relationship between the observed blood and muscle lactate levels in soccer players during match play appears to be poor (Krstrup et al., 2006). Muscle pH was 6.96 and 7.07 after the first and second halves respectively. Muscle glycogen depletion decreased significantly from $449 \pm 23$ to $255 \pm 22$ mmol.kg$^{-1}$ dw during the game, with $47 \pm 7$% of the fibres being completely or almost empty of glycogen at the completion of the match. These results indicate the anaerobic metabolic system plays a significant role in delivering energy and fuelling performance during soccer match play.

In summary, the research conducted on the physiological demands of soccer match play have generally shown a match to involve high levels of energy expenditure and significant contributions from the aerobic and anaerobic metabolic systems of the body. Much of this data is varied and inconclusive, possibly due to the varying measurement methodologies, different skill and fitness levels of players and the positional and tactical roles executed in these matches. Analysis of performance during match play should, therefore, consider not only the movement patterns, but also the match environment, the physiological cost, economy of movement and fatigue levels of players during match play.

1.1.2 Tactical and technical performance during soccer match play

Although successful performance in soccer match play requires superior levels of physical fitness to sustain a high work rate during matches, it is the technical and tactical skill level that usually separates successful soccer players and team performance during first division match play (Sforza et al., 1997).

From the 1960’s until present, much of the research into the performance of professional soccer players has focused on the technical and tactical performance and is summarised in Appendix 1. While the ability of investigators to detect the on-field physical performance has
been limited by technology, the measurement of technical and tactical aspects of soccer
players has been somewhat easier for investigators due to technology advances. Research
into the technical and tactical aspects of elite soccer match play have used technologies that
include hand collected statistics (Reep & Benjamin, 1968; Ali, 1988; Bate, 1988; Harris &
Reilly, 1988; Olsen, 1988; Pollard, 1988; Gerisch & Reichelt, 1993; Jinshan et al., 1993;
Lanham, 1993; Garganta et al., 1997; Abt et al., 2002; Ensum et al., 2005; Hughes &
Churchill, 2005; Hughes & Jones, 2005; Lanham, 2005; Taylor et al., 2005), computerised
notational analysis systems with customised keyboards (Church & Hughes, 1987; Pollard,
1988), touch pads (Hughes et al., 1988; Dufour, 1993; Partridge et al., 1993; Yamanaka et al.,
1993; Luhtanen et al., 1997; Yamanaka et al., 1997) and statistical computer software
packages (Bishovets et al., 1993; Lanham, 1993; Grehaigne et al., 2002; Lawlor, 2004).

Studies on the technical and tactical determinants of successful goal scoring in international
matches have shown correlated match events to goals scored (Reep & Benjamin, 1968; Bate,
1988; Hughes et al., 1988; Olsen, 1988; Jinshan et al., 1993; Garganta et al., 1997). Olsen
(1988) found the average number of touches by the scoring player before scoring a goal to be
1.0, the average space around the player was 1.0 m, the average number of touches of the ball
by the player who passes the ball to the scorer was 4.0 and the average number of passes in
the scoring movement was less than 3.0 by teams during the 52 matches of 1986 World Cup.
These factors which lead to successful performance have also been confirmed by Garganta et
al. (1997), Bate (1988) and Reep and Benjamin (1968) who showed the number of passes in a
successful scoring movement to be less than 3 to 4 passes. Interestingly, Jinshan et al. (1993)
investigated the 52 matches from the 1990 World Cup and showed the contribution of pattern
of play prior to scoring a goal was 4.3% by crossing the ball from midfield, 27.8% dribbling
and crossing the ball, 18.3% from penetrating the central area of the field and 32.2% from set
plays during a match. Consequently, these studies indicate that there are tactical situations which predispose teams to scoring goals.

Studies which have looked at a comparison of tactical characteristics of successful versus unsuccessful soccer teams during international matches have shown various tactical characteristics of successful teams (Harris & Reilly, 1988; Hughes et al., 1988; Olsen, 1988; Garganta et al., 1997; Luhtanen et al., 1997; Hughes & Churchill, 2005). Hughes et al. (1988) investigated four matches from the 1986 World Cup finals and showed successful teams had more kicks and shots at goal inside the penalty area, less fouls, more use and possession of the ball in the midfield area of the pitch and more touches per possession. Olsen (1988) investigated 52 matches of the 1986 World Cup and also found successful teams to have less dribbling into a scoring position on the field, more single touches of the ball before shooting at goal, a high incidence of goals with less than two preceding passes and forward players who kicked goals had more than four metres of space around them in attack. During the 1990 World Cup, Luhtanen (1993) investigated the tactical characteristics of successful teams. This study showed successful teams had more offensive actions, more offensive attacks where the ball was not lost, greater number of passes to the centre of the field, more scoring attempts, shots on goal and greater numbers of goals. Garganta et al. (1997) found successful teams changed the rhythm of the game from fast to slow ball movements, varied their attacking methods and had different direct and indirect styles of play. Harris and Reilly (1988) investigated 24 matches in the English Premier League and found successful teams created more distance between attacking players and defenders when attacking, they used more passes of the ball through the defenders when attacking and outnumbered the opposition in the attacking third of the field. A recent study by Hughes and Churchill (2005) on 30 matches in the 2001 Copa America Cup showed successful teams gained the ball more in the attacking quarter of the field, had shorter and fewer passes whilst
in possession of the ball, had shots at goal from closer range and a wider variety of passes and shots at goal, when compared to unsuccessful teams.

In contrast, studies on the tactical performance of unsuccessful teams have shown losing teams dribbled with the ball more, particularly along the sides of the playing pitch, they played more on the edges of the field, passed the ball wide as they approached the goals and lost possession in the defending area of the pitch more than successful teams. Olsen (1988) also showed the tactical emphasis of unsuccessful teams during the 1986 World Cup to be a man-to-man style of defence, rather than players organising themselves into a zone defence. Hughes and Churchill (2005) more recently found unsuccessful teams in the 2001 Copa America Cup to execute limited types of passes and shots at goals, compared to successful teams.

The previously mentioned investigations on the technical and tactical aspects of soccer match play have shown that teams apply different tactics, team formations and ball movements to win matches. These tactics are likely to impact the movement patterns and the physiological demands of match play. The tactical style of play and skill level of players, therefore, should also be considered when analysing the performance of soccer players during a match.

1.2 The factors affecting the on-field physical performance of elite soccer players

1.2.1 Match conditions

Each soccer match is played against a unique opposition, often with subtle and sometimes significantly different tactical styles of play and is played in different environmental conditions against opponents of varying skill level. Each of these factors are likely to impact the movements made by players on the field. This section, therefore, discusses the different match conditions that should be considered when analysing performance.
1.2.1.1 Player position

Research has focused on either the fitness capacities of players of various playing positions (Thomas & Reilly, 1976; Smaros, 1980; Van Gool et al., 1988; Bangsbo et al., 1991; Bangsbo, 1994; Bangsbo et al., 2004; Dunbar & Treasure, 2004) or the on-field work rate of various playing positions (Reilly & Thomas, 1976; Withers et al., 1982). Due to the limitations of the measurement techniques used during the scientific analysis of match play, the effect of the physical capacities of soccer players of different positions on their on-field physical performance has not been thoroughly investigated.

It has been shown that Danish midfield players have a higher maximal aerobic capacity ($\text{VO}_{2\text{max}}$) than other player positions (Bangsbo et al., 1991; Bangsbo, 1994). $\text{VO}_{2\text{max}}$ has been reported in the past to correlate with distances covered during a match (Thomas & Reilly, 1976; Smaros, 1980; Van Gool et al., 1988). More recently, the difference in $\text{VO}_{2\text{max}}$ and treadmill running performance between midfielders versus forwards and has been shown to be significant (Bangsbo et al., 2004). The higher aerobic capacities observed in midfield players can be partly explained by the natural specialisation by players with better physical capacities towards positions which require additional running.

There is some evidence, however, to support that the performance analysis process should consider the specific fitness levels of each player. While previous research has shown different physical capacities between playing positions, some research has shown the opposite. In a study of 89 English Premier League players, no differences were found in field and laboratory tests for aerobic endurance, anaerobic endurance, agility and speed endurance in players of different positions (Dunbar & Treasure, 2004).
An important question remains: do the varying physiological capacities of players translate into greater work rates on the field? The on-field work rates of different positions have been investigated by researchers (Reilly & Thomas, 1976; Withers et al., 1982). Similarly, these studies have used indirect measures which suffer from questionable reliability and validity. In addition, due to the cumbersome nature of these methods, very few players and matches have been analysed, making it difficult to extrapolate clear relationships from these studies. As a result, there are many contradictory findings on the on-field work rates of soccer players of different positions.

The general trend amongst studies is that midfielders tend to run further distances in comparison to other playing positions (Reilly & Thomas, 1976). This has been explained by midfielders spending more time jogging and low speed running. In contrast, a study on Australian professional soccer players found no difference between the total distances covered by players of different positions (Withers et al., 1982). These contradictory studies have caused confusion over the differences in the on-field physical performance of different positions. In addition, it is unclear if the total distance travelled during a match is valid and a key indicator of successful on-field physical performance. Limitations in match analysis technology has forced researchers to collect only broad measures such as the total distance travelled by players, while important indicators such as acceleration and deceleration around opponents during a match, for example, currently remain extremely difficult to measure and unknown for players of different positions.

Another method that investigators have used to discriminate between player positions has been to record the time players spend at various running intensities during a match. Observations of Danish National Level players found that midfielders spend less time standing than forwards and defenders (Bangsbo et al., 1991). Defenders were also found to
spend more time standing than forwards and midfielders. Midfielders walked and ran at low speeds more than forwards and defenders. In this study, no differences were found in the total time spent at moderate and high intensity running, sprinting or running backwards for any playing position. While this study showed that there was little relationship between player position and high intensity running, the sensitivity or sample rate and the accuracy of the measurement technique used to measure the fast movements made by players limited this author’s ability to discriminate between different player positions. No measures of acceleration or deceleration were recorded in this study.

In summary, while there are some discrepancies in the literature, the majority of research supports that there is a difference between the physiological capacities and work rates of different playing positions. Consequently, playing position is an important factor to consider when analysing the physical performance of a soccer player.

1.2.1.2 Competition Level

When analysing the on-field performance of soccer players during match play, the standard of competition also needs to be taken into account. Studies have shown a difference in the physical capacities and characteristics of players in various leagues around the world (Rienzi et al., 2000; Aziz et al., 2004; Bloomfield et al., 2004a; Bloomfield et al., 2004b; Dunbar & Treasure, 2004; Kan et al., 2004; Philippaerts et al., 2004; Power et al., 2004; Sampaio & Macas, 2004). One study investigated the physical profile of the players across four of the major European Leagues and showed differences in body proportions of international players, players who had represented their country, FIFA world rankings of international players and players who had scored international goals (Bloomfield et al., 2004b). In addition, reduced physical capacities have been reported in lower ranked leagues such as the Asian leagues (Aziz et al., 2004). When comparing between different divisions of specific leagues, there
also appears to be a difference in physical capacity. First team players performed better than
second and lower division players in a range of physical performance tests in both English
(Dunbar & Treasure, 2004; Power et al., 2004) and Portuguese soccer players (Sampaio &
Macas, 2004). Another study found differences in body shape and composition between
different international leagues (Bloomfield et al., 2004a). This suggests that different body
shapes predispose players to be successful in different leagues. In addition, youth players of
age 15-16 years old who reach National level have better physical capacities than players at a
regional level (Philippaerts et al., 2004).

While much research has focused on the physiological capacities of players, the differences in
on-field physical performance of players from different leagues, however, is less clear. Japanese
players playing in lower ranked leagues have been recorded as running less than 7
km in a game (Kan et al., 2004) compared to their European counterparts who run 8-10 km
(Van Gool et al., 1988; Bangsbo et al., 1991; Rienzi et al., 2000). Kan et al. (2004) also
found the average speed of Japanese players to be faster for teams in an international match
versus a domestic Japanese League match. A study by Rienzi et al. (2000) found differences
in work rates on the field between leagues. South American players covered 1.5 km less
distance than English Premier League players. These few studies have often involved only
one-off evaluations of matches, making it difficult to conclusively evaluate the true effect of
playing standard on the on-field physical performance during match play. A number of
matches need to be observed across leagues with a valid and reliable method to quantify on-
field movements. In addition, these studies have indirectly measured the on-field
performance of soccer players using unsophisticated methods and should be viewed with
cautions.

In summary, the literature shows that players in different professional soccer leagues have
different physical capacities, causing them to have different ability to physically perform
during a match. Performance analysis of players should also take the playing standard into consideration, since higher work rates are expected in higher ranked leagues.

1.2.1.3 Environmental conditions

Previous investigations on the effects of environmental conditions on player on-field performance have shown that the work rates of players are affected by environmental conditions (Ekblom, 1986). In particular, Ekblom (1986) investigated the distance that soccer players covered at high intensities during match play at 20 and 30 degrees Celsius (°C). Results showed that the distance covered by players at high intensities was almost halved in hotter conditions. Players travelled a total distance of 900m of high intensity running at 20°C versus 500m at 30°C.

Numerous studies have previously demonstrated that thermal stress reduces exercise capacity in humans (Saltin et al., 1972; MacDougall et al., 1974; Schmidt & Bruck, 1981; Hessemer et al., 1984; Kozlowski et al., 1985; Bruck & Olschewski, 1987; Nielsen et al., 1990; Walsh et al., 1994; Lee & Haymes, 1995; Febbraio et al., 1996; Booth et al., 1997; Galloway & Maughan, 1997; Gonzalez-Alonso et al., 1997). However, research to date on the effects of environmental conditions has resulted in little quantitative data on the effects of varying humidity levels on the physical performance of soccer players. Previous research using controlled laboratory-based experiments on humans, however, has shown humidity to increase the thermal load and decrease subsequent exercise performance (Castle et al., 2006). Further studies are required to help quantify the effects of varying heat and humidity levels on the on-field physical performance during soccer match play.

Another condition that needs to be considered when discussing the influence of environmental conditions on soccer players is the effect of cold ambient temperature on the on-field physical performance. Previous controlled laboratory studies have shown a reduced performance and
adverse physiological effects in trained humans who exercise in cold conditions (Tikuisis et al., 1999; Crowe et al., 2007). To date, no specific research has been published on the effects of cold temperatures on the on-field work rate of soccer players. However, it is likely that cold conditions may reduce the on-field performance of soccer players, since previous laboratory-based research has shown human muscle performance to be reduced as muscle temperature declines (Bergh & Ekblom, 1979).

In addition to temperature and humidity, the physical performance of soccer players is also likely to be affected by playing at varying levels of altitude above sea level. Danish National soccer team players were performance tested in an environmental pressure chamber in conditions that corresponded to 2550 m above sea level (Bangsbo et al., 1988). Players performed an intermittent exercise test and showed a 5% increase in heart rate, 16% increase in blood lactate and 19% increase in ventilation rates compared to values obtained during the same test at sea level.

In summary, with limited technology available to easily measure the locomotion characteristics of soccer players, very few studies have investigated the effects of various environmental conditions on the physical performance of soccer players during match play. More investigations are required to help further understand the nature of the observed differences in on-field work rate and performance capacities of soccer players during matches in varying environmental conditions.

1.2.1.4 Match tactics

When analysing the physical performance of soccer players, the tactics of the game needs to be taken into account. The observed differences in physical demands for different playing positions may be partly explained by the differing tactical roles of each position.
Differences in the on-field physical work rate for each playing position have been well documented, including distances covered (Reilly & Thomas, 1976; Withers et al., 1982; Bangsbo et al., 1991; Bangsbo, 1992), number and frequency of efforts (Reilly & Thomas, 1976; Mayhew & Wenger, 1985; Bangsbo, 1992), running patterns in different areas of the field (Grehaigne, 1988) and mode of locomotion during match play (Saltin, 1973; Knowles & Brooke, 1974; Reilly & Thomas, 1976; Withers et al., 1982; Mayhew & Wenger, 1985; Bangsbo et al., 1991). However, while the locomotion characteristics of players in these investigations have been extensively described, none of these studies have documented the style of play, positional formation or orientation of each player during attacking and defending situations. Therefore, the effect of different styles of play on the location, running patterns and work rates for each playing position is still poorly understood. Different styles of play that have been employed by professional soccer teams include playing with an emphasis on retaining possession, slowing down the speed of the game, delaying attacking moves until opportunities to attack are presented or playing with an emphasis on speed of movement. Although little research has been undertaken on the effects of different styles of play on work rate, these tactics are likely to either level out work rate between players or increase the physiological stress imposed on some players (Reilly et al., 1991). This may also explain the very large variations in distances travelled by elite division one players (6.6 km – 12.0 km) during matches played in different international leagues (Saltin, 1973; Withers et al., 1982; Rienzi et al., 2000; Kan et al., 2004).

In summary, the style of play and the positional roles of players is likely to affect the work rate of players during a match. The tactical emphasis of the game should be considered when evaluating the physical performance of a player.
1.2.2 Player Characteristics

There are various player specific characteristics that affect the on-field performance of soccer players during match play. Various factors contribute to the soccer player’s ability to perform physically on the field, including body composition, gender, aerobic power, anaerobic power, speed, speed-endurance, fatigue, agility, acceleration, strength and training status. The purpose of this section is to review the relationship between each of these characteristics and their effect on the on-field physical performance during matches.

1.2.2.1 Body Composition

The body composition of elite soccer players has been thoroughly investigated across different playing levels, particularly the stature, mass and body fat levels of players (Bangsbo, 1992; Matkovic et al., 1993; Dunbar & Power, 1997; Mercer et al., 1997; Tiryaki et al., 1997; Casajus, 2001; Dowson et al., 2002; Arnason et al., 2004; Bloomfield et al., 2004a; Aziz et al., 2005b; Sampio & Maças, 2005). However to date, no studies have investigated the direct effect of a change in body composition over time on the on-field physical performance such as speed, acceleration, work rate and fatigue levels of a soccer player. This is primarily due to the lack of technology available to measure on-field physical performance. However, differences found in various investigations on the body composition of soccer players across different leagues, divisions and on-field positions, may partly explain the differences in on-field physical performance of players at higher player levels and different playing positions. In order to examine if there does exist a preferred body type for optimal on-field physical performance the results of studies investigating the body composition on elite soccer players from various countries, divisions and playing positions have been compared in Appendix 2.

Results of studies that have quantified the body composition of professional soccer players at different playing levels, including first division (Bangsbo, 1992; Matkovic et al., 1993;
Dunbar & Power, 1997; Mercer et al., 1997; Casajus, 2001; Arnason et al., 2004; Bloomfield et al., 2004a; Aziz et al., 2005a, Brewer, 1991; Aziz et al., 2005b), second division (Brewer & Davis, 1991; Tiryaki et al., 1997; Sampaio & Maçãs, 2005) and third division players (Dunbar & Power, 1997; Tiryaki et al., 1997) as well as players at national team level (Dowson et al., 2002) have shown subtle differences in body size and shape of soccer players across different playing standards.

Players who compete in first division professional soccer in the more successful European-based professional clubs are generally regarded to be of higher standard than many Asian-based leagues, based on previous performances in World Cup soccer. The stature of more successful European-based players are taller, ranging from 177-183 compared to Asian-based players have ranged from 173-174 cm. The narrow range of mean scores recorded on European-based players from successful countries such as England, Portugal, Denmark, Croatia, Spain, Italy and Germany suggests that there is an optimal stature for successful physical performance.

A significant increase in subcutaneous body fat has been shown to decrease performance in sports such as distance running (Cureton et al., 1978; Cureton & Sparling, 1980), cycling (Norton & Olds, 1996) and general exercise (Hansen, 1973). This is primarily due to an increase in energy expenditure required to carry the additional fat mass during exercise. This relationship between higher levels of body fat and decreased physical performance can be indirectly observed when comparing results from professional first division and second division players. Second division players have been found to have higher levels of body fat compared to first division players in the English Football League (Brewer & Davis, 1991). Some significant discrepancies in percent body fat scores do exist between different professional soccer leagues. For example, total body fat percentage scores for first division
players have ranged from 7.6% body fat in Turkish players (Tiryaki et al., 1997) to 12.6-16.2% in English first division players (Dunbar & Power, 1997). This discrepancy may, however, be explained by the majority of studies having relatively low subject numbers (n<20) as well as differences in experimental methods and prediction equations used to derive percent body fat.

The effect of body mass on the physical performance of soccer players is not clear. However, trends in body mass in studies listed in Appendix 2 across different levels suggest that an optimal body mass is preferred for successful performance. These studies show a trend for body mass to be higher in national team players (Dowson et al., 2002) and first division professional soccer players (Bangsbo, 1992; Matkovic et al., 1993; Mercer et al., 1997; Casajus, 2001; Arnason et al., 2004) compared to second (Brewer & Davis, 1991; Tiryaki et al., 1997; Sampaio & Maças, 2005) and third division players (Dunbar & Power, 1997; Tiryaki et al., 1997). This is partly explained by the higher levels of muscle mass needed to execute greater levels of speed and power during a game at international and professional first division levels.

The vast majority of studies on the body composition of elite soccer players have reported overall team averages. However, investigations into the effect of positional differences on body composition have shown slight differences between anthropometrical characteristics. Data collected on elite first division Danish footballers by Bangsbo (1994) showed a significant difference between central defenders versus midfield and forward players. In this study, central defenders had a significantly greater stature and mass compared to full-backs, midfield players and forwards. Similar findings were also recently reported in a comprehensive study on elite first division Icelandic players (n=306) by Arnason et al. (2004), with results showing that defenders have significantly higher scores for stature. This
is partly explained by the positional role of defenders needing to have greater strength, muscularity and size in order to defend off players trying to attack towards goal during match play. Interestingly, no differences were found in per cent body fat levels or body mass index for strikers, midfielders or defenders (Arnason et al., 2004).

In summary, the body compositions of elite soccer players have been well investigated and trends in scores for various physical characteristics across different playing standards have suggested that there is a preferred body type for optimal on-field physical performance. However, the direct effect of an altered or improved body composition on the ability of a player to perform physically on the field is still currently not well understood.

1.2.2.2 Gender

Research into the effect of gender on the on-field physical performance of soccer players has been somewhat contradictory. Investigations into the physical performance of male and female soccer players have been primarily limited to total distances covered by players during a match and the duration and frequency of high intensity efforts, such as sprinting.

In a study by Davis and Brewer (1993), elite female Swedish National players travelled 8.5 km during a match. Much of the data on elite male soccer players has found players to run between 8-12 km (Table 1-1). Another recent study on elite female players found players to run between 9.7-11.3 km, with an overall average total distance of 10.3 km (Krustrup et al., 2005). While there is considerable evidence to support that males generally have superior strength, stamina and speed compared to women (Murphy et al., 1986; Cureton et al., 1988; Brooks et al., 2000), physical performance in the form of total distance travelled during a soccer match does not significantly discriminate the two genders. This may be due to either an improvement in the professionalism and physical attributes of elite international female
soccer players or due to a technical limitation such as a lack of sensitivity in the measurement devices used to accurately measure on-field locomotion of players.

The nature of short term high intensity efforts performed by elite female athletes compared to male athletes is still not well understood. A recent study found elite female players to have a high intensity effort every 4 s, a mean total of 125 high intensity runs of 2.3 seconds in duration (Krustrup et al., 2005). Previous research found elite females players to have a high intensity effort every 7.6 seconds, a mean total of 92 high intensity efforts of 4.0 seconds duration (O'Donoghue et al., 2004). Data on elite males, however, has shown high intensity of 1.5-2.5 seconds duration (Bangsbo, 1992), occurring anywhere between a wide range of every 39 to 195 seconds (Reilly & Thomas, 1976; Mayhew & Wenger, 1985; Bangsbo et al., 1991; Bangsbo & Mohr, 2005; Burgess et al., 2006).

Gender differences have been shown in the physiological capacities of players tested in controlled laboratory conditions. Studies on female soccer players have shown a lower maximal aerobic power or VO$_{2\text{max}}$ than male players. Mean VO$_{2\text{max}}$ scores for elite female players range from 43 ml.min$^{-1}$.kg$^{-1}$ for Turkish female soccer players (Tamer et al., 1997), 49.1 ml.min$^{-1}$.kg$^{-1}$ for New Zealand National team members (Dowson et al., 2002), 52 ml.min$^{-1}$.kg$^{-1}$ for English players (Davis & Brewer, 1993), 54 ml.min$^{-1}$.kg$^{-1}$ for Japanese National players (Kohno et al., 1990) and 53.3 to 57.6 ml.min$^{-1}$.kg$^{-1}$ for Danish National players after a 3 month training intervention (Jensen & Larsson, 1993). While the highest published score for a female player was 63.8 ml.min$^{-1}$.kg$^{-1}$ (Jensen & Larsson, 1993), female scores are generally significantly below males for maximal aerobic capacity. Scores for male players are summarised in Appendix 3 and ranged from 60-70 ml.min$^{-1}$.kg$^{-1}$ for males of various nationalities, leagues and divisions. In addition to aerobic capacity, studies have shown that female soccer players have a lower peak running speed in controlled field testing.
conditions (Polman et al., 2004) compared to male players (Cometti et al., 2001; Little & Williams, 2005b). Furthermore, female players have also been shown to have significantly higher total body fat (~20-22%) (Colquhoun & Chad, 1986; Withers et al., 1987; Jensen & Larsson, 1993) versus men (~10-12%) (Maughan, 1997; Rico-Sanz, 1998; Casajus, 2001; Arnason et al., 2004). Female players also have a lower muscle mass (Colquhoun & Chad, 1986) and less muscular strength than male players (Kohno et al., 1990). Therefore, it is difficult to explain why gender differences in the on-field physical performance have not been found by investigators. This trend supports the theory that the current state of the art in tracking technology is not sensitive enough to discriminate between players of differing standards and genders.

In summary, the effects of gender on the on-field physical performance of soccer players is not well understood and requires considerable investigation. While the physiological characteristics and capacities of male and female players have been shown to be significantly different, current technology has failed to discriminate between males and females for on-field physical work rate and performance. It is possible, therefore, that new measurement technology with the capacity to accurately and sensitively detect all types of movements of players during a match could discriminate the performance differences between the two genders. This would improve the understanding of the relationship between the different physical characteristics observed in the two genders and the physical performance achieved during match play.

1.2.2.3 Aerobic Power

The aerobic power of soccer players needs to be high because a large proportion of energy supplied during soccer match play is contributed by the aerobic energy system (Apor, 1988). In addition, it is widely accepted that the aerobic power of soccer players is well trained in
order to meet the repeated activity demands over the duration of a match (Bangsbo & Mizuno, 1988; Nowacki & Preuhs, 1993; Hoff, 2005; Impellizzeri et al., 2005b; Reilly, 2005).

However, the effect of a change in aerobic power on the work rate and physical performance of players during actual match play has only been investigated by one investigator, Helgerud et al. (2001), who found significant performance benefits, including a 20% improvement in total distance covered during the match.

An indirect evaluation of the effects of aerobic power on physical performance was conducted by Tumilty (1993) who compared the scores of elite male, youth soccer players (n=16) on a soccer match simulation performance test to results from various controlled laboratory and field-based physiological fitness tests. A negative correlation was found between aerobic power, determined from a treadmill VO$_{2\text{max}}$ test, and the decline in sprint performance during the match simulation performance test, indicating that a higher aerobic power is important for sustained physical performance throughout a game. This physical performance test, however, was a simulated match test and was conducted on elite junior soccer players and therefore may not transfer to elite senior professional players. Consequently, additional research is required on senior elite professional soccer players during actual match play to further clarify the effects of a high aerobic power on the ability to repeat high intensity efforts during match play.

Another method of determining the importance of the role of the aerobic power during soccer match play is to examine studies on the laboratory determination of aerobic power across different playing levels to see if players from higher playing divisions have better aerobic power. The aerobic power of professional soccer players has been well researched by measuring the VO$_{2\text{max}}$ on a treadmill in the laboratory (Raven et al., 1976; Apor, 1988; Faina et al., 1988; Nowacki et al., 1988; Bunc et al., 1991). VO$_{2\text{max}}$ scores of soccer players have
also been estimated from aerobic capacity from field-based aerobic capacity tests (Dunbar & Power, 1997; Mercer et al., 1997; Tiryaki et al., 1997). Appendix 3 shows the results of studies on the VO$_{2\text{max}}$ scores for different types of soccer players. Interestingly, the general trend of results from studies investigating the aerobic capacity of soccer players shows VO$_{2\text{max}}$ scores vary considerably amongst different nationalities, playing levels and genders. Studies on national level male soccer players have shown mean VO$_{2\text{max}}$ scores ranging from 58.7 ml.min$^{-1}$.kg$^{-1}$ in the Canadian Olympic soccer team (Rhodes et al., 1986) to 66.4 ml.min$^{-1}$.kg$^{-1}$ in the World Champion German National soccer team (Nowacki et al., 1988). In addition, research on first division professional soccer players has also shown mean VO$_{2\text{max}}$ scores ranging from 51.6 ml.min$^{-1}$.kg$^{-1}$ in Turkish players (Matkovic et al., 1993) to 66 ml.min$^{-1}$.kg$^{-1}$ in Hungarian (Apor, 1988) and English Premier League players (Reilly & Thomas, 1976). Similarly, the results of studies investigating the VO$_{2\text{max}}$ of elite national and first division female soccer players have also shown large variations in aerobic power amongst nationalities and playing levels. Mean VO$_{2\text{max}}$ scores range from 43.15 ml.min$^{-1}$.kg$^{-1}$ in Turkish female soccer players (Tamer et al., 1997), 49.1 ml.min$^{-1}$.kg$^{-1}$ in New Zealand National players (Dowson et al., 2002), to 57.6 ml.min$^{-1}$.kg$^{-1}$ in Danish female first division soccer players (Jensen & Larsson, 1993). In addition, high VO$_{2\text{max}}$ scores, equivalent to those seen in first division male players, have been found in second (Brewer & Davis, 1991) and third division (Dunbar & Power, 1997) professional male soccer players, which indicates that a high aerobic power is not the only determinant of successful on-field soccer performance and does not discriminate between players from different playing divisions.

Possible reasons for this disparity in aerobic power between players of different countries, playing levels and genders could be the variation in subject numbers which ranged from less than ten subjects (Faina et al., 1988; Jensen & Larsson, 1993), through to significant numbers of subjects (Reilly & Thomas, 1976; Jankovic et al., 1993; Matkovic et al., 1993; Bangsbo,
Differences in the test protocols used in determining aerobic power of soccer players also partly explains the reported differences in scores (Metaxas et al., 2005). In addition, field-based fitness test methodologies used by some investigators to estimate VO\textsubscript{2max} scores of elite athletes (Dunbar & Power, 1997; Mercer et al., 1997; Tiryaki et al., 1997; Strudwick et al., 2002) have less validity when administered on different populations in a variety of field-based environmental conditions (Metaxas et al., 2005).

In summary, despite the observed discrepancies in the aerobic power of elite professional soccer players, aerobic capacities of soccer players are generally high and the contribution of energy production from the aerobic energy system during match play is significant. However, there is a significant lack of understanding of the direct effect of a superior aerobic power on the ability to sustain on-field physical performance during actual match play. This limits the ability to evaluate physical performance relative to the player's aerobic capacity and conditioning.

1.2.2.4 Anaerobic power

The on-field physical demands of soccer match play includes repeated short-term, high-intensity bouts of exercise over 90 min, which are partially fuelled by the body’s anaerobic energy system (Ekblom, 1986; Jones & Helms, 1993; Drust et al., 2000; Bangsbo, 2003). As a result, it is desirable for elite soccer players to have high anaerobic power. Anaerobic power refers to the highest rate of anaerobic energy release and anaerobic capacity reflects the maximal anaerobic energy production an individual can obtain in any exercise bout to exhaustion. However, the relationship between a high anaerobic power and the ability to perform repeated high intensity efforts during soccer match play is still poorly understood due to the inability to precisely detect and quantify short term ballistic efforts, fuelled by the anaerobic energy system, during match play.
One indirect method used by investigators to assess the importance of a high anaerobic power for successful soccer physical performance has been to conduct isolated and laboratory-based performance tests on players. Tests on soccer players to determine their anaerobic power have included maximal sprint tests over short distances (Tumilty, 1993; Dunbar & Power, 1997; Mercer et al., 1997; Wilkinson et al., 1997; Balsom et al., 1999; Bangsbo & Michalsik, 2002; Hoff, 2005; Sampaio & Maçãs, 2005), explosive vertical jump tests (Cochrane & Pyke, 1976; Raven et al., 1976; Thomas & Reilly, 1979) and short term maximal cycling tests in the laboratory (Bergh & Ekblom, 1979). In addition, tests of anaerobic capacity have included short term maximal treadmill running tests on fixed gradients to fatigue (Tumilty, 1993). Regardless of the test methods used in these studies, soccer players were found to have well developed levels of anaerobic power, indicating that it is an important physiological determinant of successful performance.

Another method for determining the importance of anaerobic power for successful on-field physical performance was used by Tumilty (1993), where 16 elite youth Australian soccer players were examined for anaerobic capacity and performance decrement during a game simulation test. Interestingly, results showed that players with higher anaerobic power had significant drop off in sprint performance as the match simulation test progressed. This study showed that, along with other factors, successful performance is likely to be partially related to anaerobic power and high levels of anaerobic fitness. More research needs to be conducted on actual match situations to further examine the effects of anaerobic power on not just sprint performance, but all types of high intensity, anaerobic activities during match play.

A further method of determining the relationship between high levels of anaerobic power and successful on-field physical performance is to assess the anaerobic energy demands during match play. The contribution of anaerobic metabolism to the total energy metabolism during
soccer match play has been examined in various studies, mainly through the measurement of blood lactate concentration. Appendix 4 shows the results of studies investigating the blood lactate response of elite soccer players during match play. Mean scores from these studies for blood lactate during match play for elite soccer players ranged from 4 mmol.L\(^{-1}\) to above 10 mmol.L\(^{-1}\). Significant variation in blood lactate responses to match play have been found across different nationalities and playing levels. However, most studies have shown a reduction in blood lactate in the second half of the match. This is possibly related to the observed reduction in distance covered (Withers et al., 1982; Van Gool et al., 1988; Bangsbo, 1992) and the number of high intensity efforts during the second half of soccer matches (Bangsbo, 1994). Therefore, anaerobic energy production during matches may be related to the work rate of soccer players, particularly during the latter stages of the game. Consequently, it may be highly advantageous for elite soccer players to have a high anaerobic power for successful repetition of high intensity efforts for the duration of a match. On the other hand, Roi et al. (2004) investigated the blood lactate levels of Italian first division players \((n=21)\) and found no relationship between blood lactate levels recorded at the completion of matches and playing position or match outcomes.

In summary, it is well established that anaerobic energy production plays an important role in fuelling exercise during soccer match play and the anaerobic capacities of soccer players are well developed. Since the anaerobic capacity of a player is likely to affect the physical work rate and performance during a match it should be established and considered when analysing performance.

1.2.2.5 Speed

Sprinting ability is possibly one of the most important physical requirements necessary for a soccer player to execute during match play, because it is often used at critical time during a
game. For example, high speed running and sprinting is typically used in match situations to avoid or chase an opponent, to intercept a pass or dribble a ball at high speed. Studies investigating the percent contribution of time spent at high running and sprinting speeds during first division soccer matches found a very wide range from 2% to 11% of the total match time (Withers et al., 1982; Mayhew & Wenger, 1985; Bangsbo et al., 1991; Bangsbo, 1992). Various investigations into the contribution of high intensity running and sprinting to the total distance travelled during first division soccer matches ranged widely from 3-11% of the total distance (Knowles & Brooke, 1974; Reilly & Thomas, 1976; Rienzi et al., 2000). In addition, there have been varied results for total distances sprinted during a game, ranging between approximately 250 m to 2880 m (Saltin, 1973; Whitehead, 1975; Reilly & Thomas, 1976; Withers et al., 1982; Rienzi et al., 2000), made up of approximately 20-30 individual sprints (Reilly & Thomas, 1976; Bangsbo, 1992) ranging from 1.5 m to 105 m in length (Kollath & Quade, 1993; Bangsbo, 1994). While results on high speed running have varied, it is generally agreed that capacity of soccer players to produce high speed running during a match is important for successful on-field physical performance.

The importance of maximum speed can be assessed indirectly through examining the speed of soccer players at various levels of competition. Previous investigations on the maximal sprinting speed of soccer players have used isolated field-based sprint tests as opposed to measuring sprint performance during match play. These studies have shown both a difference (Whitehead, 1975; Ekblom, 1986; Brewer & Davis, 1991; Bangsbo, 1992; Kollath & Quade, 1993; Mohr et al., 2003; Sampio & Maçãs, 2005) and no difference (Dunbar & Treasure, 2005; Power et al., 2005) in maximal sprinting ability in field-based sprint tests between soccer players of different playing standards. For example, no differences in maximal sprinting ability were found between English Premier League first team and reserves players (Power et al., 2005) or between different Premier League clubs (Dunbar & Treasure, 2005).
However, research on Portuguese players \((n=146)\) of different levels ranging from junior and regional players through to national level players showed a significant difference in abilities to reproduce maximal sprint efforts in a controlled field-based test (Sampaio & Maçãs, 2005). In addition, German National League players have been shown to have significantly faster sprint performance during 5, 10, 20 and 30 m sprints tests versus top class amateur players (Kollath & Quade, 1993).

Apart from obvious individual differences in maximal sprint capacity between players, another explanation for the variation in recorded number, frequency and duration of sprints and high intensity efforts during a match could be the ability of the player to conserve energy during a game and only perform high intensity and sprint activities when needed. To date, no study has examined the relationship between a player’s ability to conserve energy and the subsequent sprint performance throughout a match. Another possible explanation for the variation in results on sprint performance during soccer match play could be the failure of the tracking methodologies used by investigators to accurately detect all short term, high speed efforts. The more manual methods, such as the recorded voice and hand notation methodologies used by Asami et al (1988) have lower sensitivity to brief ballistic movements and may not have accurately detected the frequency and duration of sprint efforts.

In summary, the sprint performance requirements of soccer players during match play have been shown to be varied. This indicates that a player's inherent sprint ability may be affecting the speed, frequency and duration of sprint efforts during a match.

1.2.2.6 Fatigue

Studies that have only observed match activities, have found the running speed, number of sprints and high intensity runs and the distance covered is lower in the second half than in the
first half of the game (Reilly & Thomas, 1976; Bangsbo, 1992; Bangsbo, 1994; Rebelo et al., 1998; Mohr et al., 2004). Mohr et al. (2003) observed that for both top-class players and professional players of a lower standard, the amount of high intensity running was reduced in the last 15 minutes of a game. Bangsbo and Mohr (2005) also examined the reduction in speed during match play in male professional first division players in the Italian Seria A league using the AMISCO (Sport Universal Process, Nice, France). Peak sprinting speed during the initial 15 minutes of the game was 30.1 km.hr\(^{-1}\), which was 9% faster than during the final 15 minute interval of the game. The ability to repeatedly run at high speeds was impaired and prolonged recovery times were observed in the second half, particularly in sprints longer than 30 metres in length. This indicates that fatigue can inhibit performance as the game progresses.

Other mechanisms of fatigue have also been observed during a decline of sprint performance during match play. Mohr et al. (2004) showed a significant correlation between the decreased sprint performance in the initial stages of the second half of a match and muscle temperature of soccer players. In addition, research into the depletion of energy stores after soccer match play have shown substantial variation in intramuscular glycogen depletion, averaging approximately 50% decline after 90 minutes of soccer match play (Agnevik, 1970; Saltin, 1973; Leatt, 1986). As a result, the depletion of intramuscular glycogen stores also explains the reduction in on-field physical performance observed in soccer players during match play.

In summary, a reduction in sprint performance has been shown to occur as time progresses through a soccer match. This indicates that fatigue is a significant factor and affects the physical performance of soccer players, particularly late in a match.
1.2.2.7 Agility

It has been shown that elite first division soccer players have approximately 1000 changes in playing activities during a game, often involving highly agile movements (Reilly & Thomas, 1976; Bangsbo, 1994). Withers et al. (1982) has shown that elite Australian Professional Division One soccer players make an average of 50 high speed turns per game. Other movements that occur during a game requiring a component of agility include tackles, running with the ball, jumping and heading the ball and getting up from the ground. On average, elite soccer players execute 10.9-14.0 tackles (Withers et al., 1982; Ekblom, 1986), 30 dribbles of the ball for an average of 2.9 s, 8.9-9.9 headers (Rico & Bangsbo, 1992), 15.5 jumps and 5.3 instances where players get up from the ground per game (Reilly & Thomas, 1976).

The underlying factors that contribute to agility during a game situation are varied and have been previously described by Young et al. (2002). Running technique and the strength and power of the player have been identified as key factors affecting change of direction speed (Young et al., 2002). Interestingly, the running technique of team sport athletes has been shown to be different to sprint athletes, possibly due to differences in body composition (Norton & Olds, 1996) and the demand for multidirectional running (Sayers, 2000). Straight line running speed has also been suggested by Young et al. (2002) to be a factor underlying agility. However, studies that have investigated the interrelationship between speed and agility of soccer players have found inconsistent findings. Significant correlations have been found between players’ performance in field tests for maximal speed and agility (Pauole et al., 2000). In contrast, a number of studies have shown no relationship between field test scores for straight line running speed and agility (Mayhew et al., 1989; Buttifant et al., 1999; Little & Williams, 2005a; Little & Williams, 2005b). Accordingly, further research with highly
sensitive movement analysis technology during actual match play is needed to clarify the relationship between speed and agility of soccer players.

Young et al. (2002) also outlined a number of perceptual and decision making skills as additional factors affecting agility during match play. The initiation of an agile movement by a soccer player during a match is often associated with an offensive tactical action or a reaction to an opponent or match situation. Perceptual and decision making factors affecting agility include the ability to scan the field (Savelsbergh et al., 2005), anticipate by reading various pertinent cues (Savelsbergh et al., 2002), recognition of various patterns of play (Smeeton et al., 2004) and knowledge of situations based on a schema of prior learning (Poulter et al., 2005).

The importance of a player to have a superior capacity to execute agile movements during soccer match play can be indirectly observed by examining the results from investigations into the agility performance of players in field-based agility tests across different playing divisions and positions. Superior performances in field-based tests for agility have been observed in professional division one players representing the first team versus the reserves team, indicating that agility is an important component of successful performance and more agile movements are probably occurring during match play at higher playing levels (Power et al., 2005). In addition, research has shown superior agility in elite soccer players in field-based tests compared to the general population (Raven et al., 1976; White et al., 1988). Research by Power et al. (2005) into differences in test scores of agility in field-based tests on English professional division one players has resulted in only a trend \( (P=0.06) \) to support differences in agility for various playing positions. Therefore, while soccer players are more agile in field-tests in the higher playing divisions, there is insufficient data available to differentiate players of different playing positions.
In summary, soccer players at the elite level have superior ability to execute agile movements and this may be affecting the number, frequency and intensity of multidirectional movements during a game.

1.2.2.8 Acceleration

The ability of a soccer player to produce movements of varying speeds is known to impact the on-field physical performance during soccer match play (Luhtanen, 1994). More specifically, high speed actions during soccer match play require a combination of acceleration, speed and agility. Acceleration is the rate of change in velocity that allows a player to reach maximum velocity in a minimum amount of time (Little & Williams, 2005b). However, the magnitude of the effect of a superior capacity to accelerate and decelerate on the frequency and rate of acceleration during match play remains poorly understood. The only study to date that has reported acceleration rates of players during match play was by Erdmann (1993). The method used, however, was hand digitisation of player position at a sample rate of only one sample per second to calculate displacement, velocity and acceleration. Data from this study suggested that elite male soccer players can accelerate up to $4 \text{ m.sec}^{-1}$ during match play. However, due to the limitations in sample rate, acceleration during brief explosive movements less than 1-2 seconds may not have been accurately detected. Consequently, the acceleration of soccer players during a match remains undetectable and not well understood. This is primarily due to the inability of current technologies to operate at very high sample rates to detect short-term ballistic movements made by players during a soccer match.

Thomas and Little (2005) investigated acceleration using an isolated, electronically timed, field-based sprint test on professional soccer players over 10 m. Results from this investigation showed professional soccer players to have a highly developed ability to accelerate. However, no differences for acceleration over 10 m were found in different
playing levels and position in English Premier League footballers (Power et al., 2004). These studies, however, used electronic timing lights to record split times over the 10 m sprint tests rather than sampling movement numerous times over the 0 – 10 m mark at high sample rates to detect acceleration of the player. In addition, stride rates and lengths were not measured, casting further doubt over the ability of the methodology used by these investigators to discriminate important subtle differences in acceleration between elite soccer players.

In summary, acceleration and deceleration are arguably one of the most critical movements made by soccer players and have rarely been measured during a match. The underlying ability to accelerate has been shown to be enhanced in elite players and is therefore likely to affect the ability to move quickly around the field and should be considered when analysing performance.

1.2.2.9 Strength

Many activities during a soccer match are forceful and ballistic. The effectiveness of activities such as tackling, jumping, kicking, changing direction, accelerating and decelerating are partly dependent on the player’s muscular strength (Reilly & Thomas, 1977; Oberg et al., 1986; Cabri et al., 1991; Cometti et al., 2001). At present, muscular strength cannot be directly measured during match play. Laboratory-based tests have been conducted by researchers using isokinetic tests which detect the rate of force production of the limb against a moving lever to evaluate the strength of players (Reilly & Thomas, 1977; Oberg et al., 1986; Leatt et al., 1987; Cabri et al., 1991; Bangsbo, 1994; Cometti et al., 2001). Another method of detecting strength has been to use a kicking field test for maximal speed (Cabri et al., 1991; Taïana et al., 1993; Bangsbo, 1994). However, to date, the effect of muscular strength of soccer players on the magnitude of ballistic, high speed movements during match play has not been established.
High levels of muscular strength have been found in elite soccer players compared to the
general population (Bangsbo, 1994; Wisløff et al., 1998). Interestingly, Bangsbo et al. (1994)
found no relationship between kicking performance in elite male soccer players and scores in
laboratory-based isokinetic strength tests, indicating that critical movements such as kicking
are a function of strength, but are also affected by other technical and physiological factors.
Similar observations have been found in elite Danish players after varying types of strength
training (Trolle et al., 1993). In contrast, Cabri et al. (1991) examined the effect of strength
training on kicking performance in elite youth soccer players compared to a control group.
Significant improvements were found in kicking performance after strength training,
indicating that strength is important for the development of forceful movements during soccer
match play. The discrepancies in observations may be due to the speed of contraction during
the isokinetic strength tests used. For example, the angular velocity of the lower leg is
approximately 17.5 rad.s\(^{-1}\) which is significantly higher than the angular velocity of the lower
leg during isokinetic strength tests. This data was also supported by Taïana et al. (1993) who
found improvements in kicking performance in fourth division French soccer players after 10
weeks of strength training of the lower limbs.

The importance of strength as a determinant of successful physical performance can be
indirectly evaluated by examining the muscle strength of players at varying playing levels.
Reilly and Thomas (1977) found regular first team players had higher levels of muscular
strength than reserve team players. This was also supported by findings by Oberg et al. (1986)
and Cometti et al. (2001) who found professional soccer players to have higher isokinetic
muscle strength test scores than amateur players.
In summary, highly developed muscular strength is a common physical attribute of soccer players, particularly in with players of a higher playing standard. However, no studies to date have thoroughly investigated the direct relationship between an improvement in muscle strength of soccer players on the ability to produce fast and forceful movements during a match. Despite this inadequacy of data, based on the physical attributes of professional players, the underlying strength of a player is likely to affect the powerful movements made during a match.

1.2.2.10 Training status

The overall fitness level and the types of training done by the player is critical for enhancing the athletic performance and minimising the effects of fatigue during match play. To date, one study by Helgerud et al. (2001) has reported the effect of aerobic endurance training on the locomotion during match play. Nineteen elite Norwegian male junior soccer players underwent an endurance training program for 8 weeks and showed an improvement in laboratory test scores for VO$_{2\text{max}}$, blood lactate threshold, running economy. Match analysis showed results on the distance covered by players during a match increased by 20%, number of sprints increased by 100%, number of involvements with the ball increased by 24% after the training intervention. These measures, however, are general indicators of on-field physical performance and researchers were not able to detect any observed improvements in running speeds, acceleration, agility or sport specific actions, primarily due to the limited technology that was used to precisely detect locomotion during match play.

Results of studies that have investigated the effect of aerobic training interventions on soccer players have been shown to improve both laboratory and field tests for aerobic capacity (Nowacki & Preuhs, 1993; Rebele & Soares, 1997; Helgerud et al., 2001; Impellizzeri et al., 2005a). Interestingly, studies have also shown aerobic training to have minimal or no effect
on endurance performance tests of well trained soccer players (Odetoyinbo & Ramsbottom, 1997; Dunbar, 2002; Impellizzeri et al., 2005a). Similarly, strength training interventions on soccer players have shown both improvements and unchanged performance in strength tests following resistance training (Cabri et al., 1991; Taïana et al., 1993; Trolle et al., 1993; Bangsbo, 1994). A possible explanation for the discrepancies observed in training studies could be the differences in the initial training status of the subjects, the timing of the tests during the training year, the differences in playing levels of subjects and the varying tests protocols used by researchers in these studies. It should be noted that the degree of transfer of performance in laboratory and field-based tests to the playing field is also not well understood.

In summary, the limited data on the relationship between the training status and the on-field performance of soccer players suggests that training improves the work rate or physical performance during a match. As a result, the current level of fitness of a player should be considered when evaluating the physical performance during match play.

1.3 Measurement techniques used for the analysis of soccer performance

1.3.1 Player locomotion measurement systems

Measurement techniques used by investigators to analyse the on-field physical performance of soccer players have ranged from various manual methods to the use of more sophisticated technology such as video cameras, computer software programs and satellite Global Positioning Systems (GPS). Investigations using these technologies are summarised in Table 1-3. The purpose of this section is to comprehensively describe the existing technologies used by researchers on soccer players. In particular, this section will discuss the ability of the current state of the art to comprehensively and accurately detect all types of movements that a player makes during a match.
Table 1-3. A review of the various technologies used by investigators to measure on-field locomotion in the football codes.

<table>
<thead>
<tr>
<th>Type of technology</th>
<th>Investigator/s</th>
<th>Subjects</th>
<th>No. matches</th>
<th>Application of the technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand and/or voice notation to record player activities</td>
<td>Reilly &amp; Thomas (1976)</td>
<td>English 1st division soccer players (n=40)</td>
<td>51 matches</td>
<td>Used voice recording to record player movement on a colour coded playing field to detect distance run</td>
</tr>
<tr>
<td></td>
<td>Davis &amp; Fitzclarence (1979)</td>
<td>VFL Australian Rules Football players (n=31)</td>
<td>5 training</td>
<td>Timed and counted training activities using hand timing</td>
</tr>
<tr>
<td></td>
<td>Brodie (1981)</td>
<td>Soccer Referees</td>
<td>24 matches</td>
<td>Used voice recording to record movement types</td>
</tr>
<tr>
<td></td>
<td>Ekblom (1986)</td>
<td>Swedish 1st Division soccer players (n=40)</td>
<td></td>
<td>Noted down player trajectory on a paper representation of the field.</td>
</tr>
<tr>
<td></td>
<td>Asami et al. (1988)</td>
<td>Japanese first division soccer referees (n=7) &amp; foreign FIFA referees (n=7)</td>
<td>17 matches</td>
<td>Used hand tracing onto a scaled map of a soccer pitch and used a curvimeter to determine length of the traced lines to get distance travelled.</td>
</tr>
<tr>
<td>Markings on playing field to detect player location</td>
<td>Thomas &amp; Reilly (1976)</td>
<td>English 1st division soccer players (n=40)</td>
<td>51 matches</td>
<td>Mowed grass on playing field into coded zones and recorded where players ran</td>
</tr>
<tr>
<td></td>
<td>Craig et al. (1979)</td>
<td>SANFL Australian football umpires (n=3)</td>
<td>1 match</td>
<td>Markings on the playing field to detect distances ran</td>
</tr>
<tr>
<td>Video camera and post-game analysis of stride length</td>
<td>Reilly &amp; Thomas (1976)</td>
<td>English 1st division soccer players (n=40)</td>
<td>51 matches</td>
<td>Distance was calculated by counting the number of strides and multiplying by the predetermined stride length for various running activities</td>
</tr>
<tr>
<td></td>
<td>Withers et al. (1982)</td>
<td>Australian National Soccer League players (n=20)</td>
<td>2 matches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bangsbo (1992)</td>
<td>Danish 1st division soccer players (n=4)</td>
<td>34 matches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Catterall et al. (1993)</td>
<td>1st class English soccer Referees (n=13)</td>
<td>13 matches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harley et al. (2002b)</td>
<td>1st class English soccer Referees (n=14)</td>
<td>14 matches</td>
<td></td>
</tr>
<tr>
<td>Video camera and digitisation of player position into x-y co-ordinates on the field</td>
<td>Van Gool et al. (1988)</td>
<td>Belgian collegiate soccer players (n=7)</td>
<td>1 match</td>
<td>Projected and digitised x-y coordinates of the player on-field position to determine distances</td>
</tr>
<tr>
<td></td>
<td>Erdmann (1993)</td>
<td>Polish 3rd division soccer players (n=22)</td>
<td>1 match</td>
<td>Filmed (wide angle lens) and traced the displacement of the player onto a screen to determine distance covered</td>
</tr>
<tr>
<td></td>
<td>Kan et al. (2004)</td>
<td>Japan and UAE National soccer teams (n=20)</td>
<td>2 matches</td>
<td>Filmed (wide angle lens) and converted into x-y on-field co-ordinates using 3D imaging software</td>
</tr>
<tr>
<td></td>
<td>Fernandes &amp; Caixinha (2004)</td>
<td>-</td>
<td>-</td>
<td>Filmed using panning camera and corrected for player Position by calibrating the pitch and using algorithms</td>
</tr>
<tr>
<td>Computerised notation systems with customised touch pad/ mouse movements</td>
<td>Treadwell (1988)</td>
<td>Australian 1st class rugby union &amp; collegiate soccer players (n=24)</td>
<td>17 soccer &amp; 7 rugby union</td>
<td>Used a microcomputer and customised A3 sized touch-sensitive pad divided into 128 cells to record matches and time in each movement category</td>
</tr>
</tbody>
</table>

continued on next page
Table 1-3. continued

<table>
<thead>
<tr>
<th>Type of technology</th>
<th>Investigator/s</th>
<th>Subjects</th>
<th>No. matches</th>
<th>Application of the technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera and/or potentiometers</td>
<td>Ohashi et al. (1988)</td>
<td>Japanese National (n=2) &amp; J-League (n=2) players &amp; J-League (n=2) players</td>
<td>1 match</td>
<td>Players filmed constantly with potentiometers on side of cameras to detect speed of movement First match that was used for analysis of speed of movement.</td>
</tr>
<tr>
<td></td>
<td>Ohashi et al. (1993)</td>
<td>Japanese University 2nd division players (n=3)</td>
<td>1 match</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D’Ottavio &amp; Castagna (2002a)</td>
<td>Italian 1st division soccer Referees (n=33)</td>
<td>33 matches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D’Ottavio &amp; Castagna (2002b)</td>
<td>Italian 1st division soccer Referees (n=4)</td>
<td>4 matches</td>
<td>In this study, distance was measured for distance from first touch of ball after the ball lands.</td>
</tr>
<tr>
<td></td>
<td>Ohashi et al. (2002)</td>
<td>-</td>
<td>1 match</td>
<td>Triangular surveying technique using a potentiometer and transmits data into a computer for calculation of position.</td>
</tr>
<tr>
<td>Video &amp; computerised systems</td>
<td>Mayhew &amp; Wenger (1985)</td>
<td>American professional soccer players (n=3)</td>
<td>4 matches</td>
<td>Manual computer entry of time spent in each activity</td>
</tr>
<tr>
<td>for logging match events</td>
<td>Yamanaka et al. (1988)</td>
<td>Japanese National, 1st division and collegiate soccer players (n=49)</td>
<td>-</td>
<td>Players were filmed and analysed for time in each activity using customised computer software</td>
</tr>
<tr>
<td></td>
<td>Deutsch et al. (2002)</td>
<td>New Zealand 1st Grade ‘Super 12’ Rugby Players (n=67)</td>
<td>2 seasons of matches</td>
<td>Video taped then used video editing system to log the different activities (modified method)</td>
</tr>
<tr>
<td></td>
<td>Reilly &amp; Thomas (1976)</td>
<td>Soccer players (n=226)</td>
<td>226 x 15 min</td>
<td>Keyboard overlay and customised software</td>
</tr>
<tr>
<td></td>
<td>O’Donoghue et al. (2005)</td>
<td>Northern Ireland senior Gaelic football players (n=55)</td>
<td>-</td>
<td>Verbally coded then used a notepad computer with a keyboard overlay and customised software</td>
</tr>
<tr>
<td></td>
<td>O’Donoghue &amp; King (2005)</td>
<td>-</td>
<td>-</td>
<td>Using Trak performance software, player location was tracked using a computer mouse and locomotion was then determined</td>
</tr>
<tr>
<td></td>
<td>Burgess et al. (2006)</td>
<td>Australian Prof division One soccer players</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Edgecomb &amp; Norton (2006)</td>
<td>Elite youth and senior (n=30) Bulgarian soccer players</td>
<td>-</td>
<td>Used video camera and “SIMI” motion analysis system</td>
</tr>
<tr>
<td>Video and motion analysis Systems</td>
<td>Bachev et al. (2005)</td>
<td>Italian Division 1 (n=28)</td>
<td>1 match</td>
<td>AMISCO player tracking system</td>
</tr>
<tr>
<td>Global Positioning System (GPS)</td>
<td>Bangsbo &amp; Mohr (2005)</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hennig &amp; Briehle (2000)</td>
<td>-</td>
<td>-</td>
<td>Global Positioning System (GPS) for player tracking</td>
</tr>
</tbody>
</table>
Manual methods

Manual methods for documenting and notating human movement patterns originated in the early 1900's to record complex movements during dance (Morris, 1928; Wailes, 1928). In particular, Morris (1928) used elaborate symbols for recording the direction and speed of locomotion in ballet. Sport Scientists later adopted similar hand notational methodologies in the 1970's to record movements in sport, particularly in the various football codes (Jaques & Pavia, 1974; Reilly & Thomas, 1976; Thomas & Reilly, 1976; Craig et al., 1979; Davis & Fitzclarence, 1979).

Reilly and Thomas (1976) studied the movement patterns of English First Division players over 51 matches using a voice recording system to record player movements on a colour coded playing field to detect the distance ran. Similarly, Brodie (1981) used voice recordings to record the movement types of professional soccer referees. Hand tracing methods were also used in some investigations to trace the player’s running trajectory on the field on a scaled map of the soccer pitch (Ekblom, 1986; Asami et al., 1988). Post analysis of the tracings was then used to determine the length of the traced lines to get the total distances travelled. These methods, however, were time consuming and did not detect the brief, ballistic and sport specific movements commonly performed on soccer players. In addition, hand tracing of the running trajectory of a player is open to different interpretations of the player’s location and relies on the skill of the recorder to accurately observe and then hand-trace the player’s position on the field. This method often requires the recorder to watch both the player on the field and record their movement, which can result in the recorder not watching the player at all times. This increases the likelihood of the recorder to miss some brief and ballistic movements made by the player when the recorder is looking away. The use of voice recording methods to verbally dictate and record the movement of players enables the recorder to continuously watch the player. However, delays in verbalising high speed
activities, for example, could result in significant errors in the estimation of locomotion over the course of a match. The method of colour coding of the pitch employed by Thomas and Reilly (1976) improved the recorder’s ability to observe and identify the player’s location on the field, reducing the error associated with this observational technique. Similar work was also done by Craig et al. (1979) who also placed markings on the field to detect the distance ran by Australian Rules Football Umpires during a match.

In summary, these manual and hand or voice-based locomotion recording methods are only estimates of player movements and rely heavily on the skill of the recorder to accurately approximate player locomotion. In addition, these methods are often time consuming, labour-intensive and only detect general movement characteristics like the distance travelled, where a player ran on the field and the types of locomotion. Importantly, the manual methods used by investigators failed to detect the speed of movement, particularly when a player is performing a brief, high speed, multidirectional effort.

1.3.1.2 Cameras

The use of video camera technology has been a popular method employed by researchers to permanently record the activities and locomotion of players, enabling researchers to conduct detailed post-game analysis. To date, researchers have creatively used camera-based technologies to record player movements on the field using a variety of techniques. A popular method for calculating distances travelled by players during a match was developed by Reilly and Thomas (1976). In this study, players’ stride lengths for different types of locomotion were experimentally predetermined before a match. The number of steps performed by the players during a game were filmed, counted and then converted into a score for the total distance travelled during a game, using the pre-determined stride length method. This method was also used by a number of other researchers (Withers et al., 1982; Bangsbo,
1992; Catterall et al., 1993; Harley et al., 2002b). In particular, Withers et al. (1982) completed a comprehensive evaluation of Australian National Soccer Players \((n=20)\) over two matches in the Australian National Soccer League. Bangsbo (1992) later followed with a milestone research study on Danish first division soccer players over 34 matches, comprehensively describing the nature of physical activity during first division soccer matches. While many studies investigated the locomotion demands during this time period, studies that used this methodology resulted in the most comprehensive analyses of locomotion due to the ability to analyse each step. This process was, however, a time consuming analysis procedure. In addition, this method also required the analyst to subjectively judge the speed of the movement and classify the mode of locomotion in order to assign a predetermined stride length to each step. Since soccer match play has been shown to require multiple efforts occurring less than two seconds, using steps in multiple directions and involves movements of different stride lengths during acceleration and deceleration phases (Bangsbo et al., 1991; Reilly & Thomas, 1976), some validity errors are occurring in these studies. This indicates the need for a system to precisely detect each step in order to accurately solve locomotion during soccer match play.

Studies using video camera technology have also used post game digitisation of player location on the field to evaluate the distance travelled during match play (Van Gool et al., 1988; Erdmann, 1993; Fernandes & Caixinha, 2004; Kan et al., 2004). Van Gool et al. (1988) projected and digitised the \(x\) and \(y\) coordinates of Belgian collegiate soccer players \((n=7)\) on the field to determine the running trajectory and distances travelled during a match. Erdmann (1993) filmed all 22 players on the field using a video camera fitted with a wide angle lens and traced the displacement of the players on the field. Kan et al. (2004) used similar video camera technology to assess the Japan and United Arab Emirates national soccer teams during two matches using a more sophisticated 3D imaging software to trace the running trajectory.
of players. The trajectory of the players could have been detected between 20-25 samples per second using video recordings. These studies only reported general distances travelled by players, rather than a detailed breakdown of running speeds, accelerations and other activities achieved during match play, indicating the limited capacity of this methodology to detect player locomotion.

Investigations using video camera technology to track player movement on the field during soccer match play have also used cameras with attached potentiometers and displacement transducers to detect the degree of movement of the camera filming the player on the field (Ohashi et al., 1988; Olsen & Larsen, 1997; D'Ottavio & Castagna, 2002a; D'Ottavio & Castagna, 2002b; Ohashi et al., 2002). This technology works by filming the player constantly by moving and pointing the camera at the player as he moves around the field. The attached potentiometers detect the displacement and speed of movement of the camera and the resultant distance and speed of the player movement is then calculated. This technique relies on the person filming so that the player is exactly in the middle of the camera screen at all times. Due to the ballistic and high speed nature of movements made by soccer players, the precision of holding the camera lens exactly on the player to accurately detect speeds is somewhat difficult and requires a high level of skill. This source of imprecision reduces the validity of detecting high speeds and locomotion during match play.

Investigations on the locomotion characteristics of soccer players have also used integrated video and computer software systems to log and record player movements during match play (Mayhew & Wenger, 1985; Yamanaka et al., 1988; Deutsch et al., 2002; O'Donoghue & King, 2005; O'Donoghue et al., 2005; Burgess et al., 2006; Edgecomb & Norton, 2006). Mayhew and Wenger (1985) videotaped American professional soccer players during a series of matches and used software to detect the time spent in each locomotion speed, ranging from
walking to sprinting. Yamanaka et al. (1988) also used basic customised computer software to evaluate the time spent by Japanese National, first division and collegiate soccer players at different locomotion speeds during match play from video tapes. Studies in the early 2000’s by researchers used sophisticated and customised computer software and specialised keyboards for logging match events and tracing physical activity of players. Deutsch et al. (2002) modified the method used by Reilly and Thomas (1976) by using video recordings and a video editing system to log the locomotion of New Zealand first grade rugby players. O’Donoghue et al. (2005) developed a computer keyboard overlay system and customised software to log locomotion events. The same system was used by O’Donoghue and King (2005) who tracked Northern Ireland senior Gaelic football players. The problem with these computer software systems was that they were only slightly more automated than manual methods of notating physical activity. In addition, while these software systems are very good for recording, storing and quickly retrieving player activities, they still suffer from a dependence on the technical ability of the recorder to accurately observe and record the movements from the video tape onto the customised keyboards. A recent study by Burgess et al. (2006) used a computer based software program, Trak Performance® (Sportstec, Australia), for tracking player movements on the field using a scaled down computerised diagram of the soccer pitch and video recordings of a player during match play. This technology subsequently categorises and quantifies the player movements as the match progresses. However, this system is essentially an automated version of the systems used by Ekblom (1986) and Asami et al. (1988) who hand-traced the running trajectory of the player, and still suffers from the same experimental limitations. Results from a study by Edgecomb and Norton (2006) showed that the operator’s level of proficiency in using computer software-based tracking systems became more accurate as the experience of the operator increased. In addition, results from this study indicated that technology overestimated the total distance ran by the player by 5.8%, indicating there are significant limitations with these
types of methods as a solution for tracking the locomotion of soccer players during match play.

In summary, the use of video camera technology and various post game analysis methodologies has limited validity and reliability. While the analysis component of the technology used in these studies has become more automated and sophisticated, these systems still suffer from human error in the filming and recording process.

1.3.1.3 Satellite Global Positioning Systems (GPS)

An investigation by Schutz and Chambraz (1977) was one of the first studies to propose and investigate human activity using the space-based satellite system for global positioning (GPS) developed by the government of the United States of America. Subsequently, other investigators have since successfully trialled the use of GPS for studying the biomechanics of human locomotion (Schutz & Herren, 2000; Terrier et al., 2000). More specifically, the measurement of various simple gait parameters has been investigated by a number of researchers (Terrier et al., 2001; Larsson, 2003; Terrier & Schutz, 2003; Terrier & Schutz, 2005; Terrier et al., 2005). Assessment of sports performance in orienteering (Larsson & Henriksson-Larsen, 2001; Larsson et al., 2002) and cross country skiing (Larsson & Henriksson-Larsen, 2005) was conducted using GPS measurement of locomotion and displacement. The first reported trial of GPS as a method for tracking physical performance and locomotion during soccer match play was by Hennig (2000). Research to date on the locomotion characteristics of soccer players using GPS, however, has been limited due to the various technical limitations and difficulties of using GPS. For example, one possible reason for the lack of published data on soccer players using GPS is the difficulty of convincing elite first division soccer players to wear a GPS transmitter device during actual match play. Commercial GPS tracking systems such as the SPI10 (GPS Sports, Australia) are presently
somewhat bulky (110 g) and must be worn using shoulder straps to attach the device to the middle of the player’s back. In addition, approval from the governing body of various football leagues also needs to be given before research of this nature can happen, which can be difficult for some researchers. Furthermore, many of the stadiums used by professional soccer leagues around the world are indoors, eliminating the potential use of GPS as a solution for tracking soccer players during match play. In addition, the use of GPS technology to detect the high speed, ballistic movements or accelerations of soccer players during match play is limited, since most conventional GPS devices can sample at only one sample per second. The majority of high speed movements made by first division soccer players during a match last less than two seconds (Burgess et al., 2006) which equates to only 1-2 samples per high speed movement made.

The development of high-precision satellite positioning systems, however, has allowed scientists to measure a location on the earth at a high frequency with very high precision, from 5 – 20 Hz, using phase differential positioning methods (Terrier et al., 2000). However, the same application problems as those previously mentioned are still present for using such systems inside indoor stadiums. In addition, the need for a nearby base station to compute differential displacement calculations is also another limitation of such technology.

In summary, the use of GPS for tracking the movements of soccer players during match play has been limited in its application. The new high precision GPS devices give rise to potential gait analysis during match play. However, wearing the technology in its present form in elite first division matches is somewhat invasive and suffers from an inability to work indoors.

1.3.2 Difficult variables to measure during soccer match play

The majority of investigations into the on-field physical performance of soccer players during match play have examined generic variables such as the distances covered, number and
frequencies of high intensity sprints and the contribution of different types of locomotion to the overall distances travelled. However, very few investigators have been able to successfully detect and describe the nature of high speed acceleration and decelerations, the running gait of players, the orientation of players on the field, kicking mechanics and other ballistic soccer specific movements. These movements are also very important and should be included for consideration when comprehensively analysing the on-field performance. The purpose of this section, therefore, is to review various attempts by investigators to describe these additional movements, the limitations of the technologies used and the importance of including these measurements into a match analysis.

1.3.2.1 Acceleration and deceleration

Elite soccer coaches are particularly interested in developing their players' abilities to accelerate and decelerate, since this fitness component is used at critical times in a match to possess a ball or to evade an opponent. The acceleration rates of elite soccer players have rarely been estimated (Erdmann, 1993). Failure to include the acceleration and deceleration rates of players in a performance analysis leaves it incomplete and perhaps excludes an effective way of evaluating physical performance during a match.

None of the previously described technologies used to track soccer players have the sample rate or capability to sensitively measure acceleration and deceleration. A more effective tracking system would not only detect the acceleration of the body, but also distinguish the differences in running gait that cause some players to be faster, deviate or decelerate better than others.

The most critical factor for a successful tracking system to detect acceleration is its sensitivity or sample rate. The nature of acceleration in human biomechanics is that it can change
quickly and should, therefore, be sampled at a very high rate. The system used by Erdmann (1993) sampled at only one Hz, which gives limited scope to determine precise accelerations and decelerations during short term activities. A laboratory-based kinematic measurement systems, such as the Ariel Performance Analysis System (Ariel Dynamics, USA), does detect the acceleration of body segments at 8 – 60 Hz (Kivi et al., 2002), but is limited in its application in soccer due to the short measurement range of its camera system. Inertial and magnetic-based locomotion measurement systems which can operate at > 100 Hz can precisely evaluate the acceleration of body segments through space, (Hayes et al., 1983; Willemsen et al., 1990b; Brage et al., 2003; Mercer et al., 2003; Moe-Nilssen & Helbostad, 2004). These technologies, however, have not been adequately adapted for application into real time measurement during elite sports performance.

If a tracking system was able to precisely and sensitively measure the displacement and resultant acceleration and deceleration of the player's body and limbs during a match, every movement made could be captured and analysed. This would give rise to a superior and more capable real time performance analysis system. The potential to analyse and improve the performance of players would be significantly improved. At present, however, the current technology available to coaches and sport scientists in the field is inadequate and incapable of measuring these important performance characteristics during a match.

1.3.2.2 Running gait

A key function of speed, agility and acceleration of a soccer player during match play is running technique (Young et al., 2002; Little & Williams, 2005b). Young et al. (2002) identified the foot placement and the adjustment of strides to accelerate and decelerate as important components of agility. In addition, Little and Williams (2005b) identified the ability to perform strides at very high frequency as important components of generating very
high running velocities. Despite the extensive investigations on the total distances travelled by soccer players, no studies have thoroughly investigated the kinematics of their running gait mechanics, including a detailed analysis of foot placement, stride rate, length and frequency. The measurement of running gait during soccer match play will, therefore, assist to differentiate players with superior speed, agility and acceleration.

Research into running gait kinematics of soccer players has been limited to manually counting the number of strides of players during a match from video footage (Withers et al., 1982; Bangsbo, 1992; Catterall et al., 1993; Harley et al., 2002b). Consequently, there is little evidence to discriminate the reasons why some soccer players are more agile than others, have faster acceleration and decelerations and reach higher velocities during a match. One possible explanation is that superior agility is associated with superior running gait kinematics (Young et al., 2002). In addition, detecting the effect of a player’s running gait on the ability to make initial movements and the subsequent magnitude of forward propulsion will provide new possibilities to explain a player’s ability to accelerate and perform highly agile movements during critical moments of a match such as avoiding or deceiving an opponent. Terrier et al. (2000) used a high-precision differential GPS device to successfully detect locomotion at a sampling rate of 5 Hz during walking experiments. These investigators were able to detect the stride frequency from changes in vertical lift of the body and combine this data with walking speed to estimate stride length. However, the ability of GPS, when sampling at 5 Hz, to detect running gait while sprinting at top speed or when a player is quickly accelerating and decelerating is limited. Recent laboratory studies on gait have typically sampled at over 100 Hz (Miyazaki, 1997; Tong & Granat, 1999; Brage et al., 2003; Mercer et al., 2003; Le Masurier et al., 2004). Subtle differences in stride rate, length and foot placement need to be captured at very high sample rates to be accurate. At present, there
are no field-based gait analysis systems that can detect gait at high sample rates of greater than 100 Hz.

A gait tracking system that could measure gait biomechanics would be entirely novel and would facilitate a new way to explain not only important details of stride mechanics, but also why some players are faster and more agile than others during a match.

1.3.2.3 Orientation

The orientation or direction that a player is facing during a game has been measured by investigators to determine if a player is running forward, backwards or sideways during a match (Reilly & Ball, 1984; Reilly & Bowen, 1984; Bangsbo, 1992; Reilly, 1994a; Reilly, 2003). Tracking systems that measure global position on the field and not the orientation fail to identify if a player is not running forwards. This is particularly true for popular GPS tracking systems used on soccer players. While they can determine a player is moving, they cannot detect if a player is running backwards, for example. GPS systems assume all movement is in the forwards direction, which has been shown by previous researchers to not be the case for soccer players during a match.

If a new tracking system could determine player orientation, coaches could evaluate the direction a player is facing in relation to other key players, team mates, defensive counterparts and the ball, which is an essential component of pattern-recognition skill in soccer (Williams et al., 2006). To date, the primary method used by researchers to measure the orientation of a player on the field in relation to other opponents during a match has been to mathematically calculate body angles from video tapes of World Cup Soccer Matches (Suzuki & Nishijima, 2005). This method is time consuming and not automated, limiting its application for regular use in professional soccer matches.
In summary, the measurement of orientation primarily allows investigators to detect the type and direction of movement. Consequently, the orientation of the player should also be measured to allow comprehensive evaluation of the physical performance of soccer players during match play.

1.3.2.4 Kicking mechanics

Studies on kicking biomechanics have only been conducted in laboratory-based settings. At present, there is no system that can quantify and evaluate the biomechanics of kicking in three dimensions during a match. Research has shown for a player to impact the ball successfully, the pelvis, leg and foot must be orientated for optimal impact, particularly as the knee extends prior to ball contact (Levanon & Dapena, 1998). In addition, a superior ability to alter the stance during the kicking action in relation to the ball position, improves the balance, knee joint kinematics and subsequent accuracy of the kick (Kellis et al., 2004). The resultant contact of the foot with the ball significantly affects the ball velocity (Nunome et al., 2002).

Studies into the kinematics of soccer kicking have involved the use of high speed motion analysis camera systems which rely on the detection of reflective markers placed on the players limbs in a small laboratory space (Dorge et al., 2002; Nunome et al., 2002). To date, the lack of investigations into the kinematics of soccer kicking during a game is primarily due to the limitations of the high speed motion analysis cameras to detect the reflective markers on the player’s body over long distances when playing on a soccer field.

1.3.2.5 Ballistic soccer-specific movements

There are a number of important movements performed by a soccer player during a game other than running, walking, jogging and sprinting. Researchers have attempted to quantify these movements, such as tackles, headers, jumps, kicking, getting up from the ground, passes of the ball and dribbling the ball (Reilly & Thomas, 1976; Withers et al., 1982; Treadwell, 1988; Bangsbo et al., 1991; Rico & Bangsbo, 1992). In addition, the movement of soccer
players during match play such as intercepting the ball involves ballistic and multidirectional running efforts at high speeds (Reilly & Bowen, 1984).

At present, there is no field-based system that can automatically detect these types of soccer specific movements. Limited research to date has primarily used manual counting methods from either direct observation or video recordings. Studies on sport specific movements of elite professional soccer players during match play have shown the average number of tackles made by a player during a soccer game to be 10.9 (Bangsbo et al., 1991) and 14 tackles per game (Withers et al., 1982). The number of headers, striking the ball with the head, made during a match was approximately 9 times (Withers et al., 1982; Bangsbo et al., 1991). English first division players have been found to jump an average of 15.5 times and get up from the ground 5.3 times during the course of a match (Reilly & Thomas, 1976). Professional soccer players have also been shown to pass the ball to another player an average of 35.3 times and kick the ball at the goal approximately 1-2 times per match (Reilly & Thomas, 1976; Rico & Bangsbo, 1992). All of this data was collected by investigators who manually counted each action.

The actions performed while in possession of the ball are critical and should be distinguished in a match analysis (James et al, 2004). Research has shown English professional players to travel 1.7% of the total distance covered, or an average of 158 m, in possession of the ball (Reilly & Thomas, 1976). Interestingly, Withers et al. (1982) found Australian professional soccer players to only travel 51.4 m with the ball during a match. A possible reason for this discrepancy could be the measurement error associated with predicting distances covered during a match. Another investigation into the time spent possessing a ball during match play showed elite Danish professional players to spend an average of 1.3 minutes with the ball in possession with a range of 0.3 to 3.1 minutes (Rico & Bangsbo, 1992). Danish players were
also found to dribble the ball an average of 30 times per match for an average of 2.9 seconds per dribble. Dribbling the ball has been shown to alter the running stride of the player since players contact the ball with their foot approximately every 3 strides (Reilly & Ball, 1984). Finally, research into ballistic sprinting during a match has shown elite Danish professional soccer players to intercept the ball an average of 14.5 times per match (Rico & Bangsbo, 1992). These investigations into the match specific activities have primarily used manual quantification methods such as counting of efforts from video recordings of matches, estimating distances by evaluating the number of strides with the ball and various computer software systems for logging events.

Existing technologies such as GPS cannot detect actions such as jumping, getting up from the ground or distinguish if a player was in possession of the ball due to an altered stride pattern. A new automated method that could detect these sport specific movements would enable a highly specific analysis of all movements made during a match. These actions are considered by researchers to be important for success and failure to include them in an analysis would leave it incomplete (Hughes et al., 1988; Lawlor, 2004; Hughes & Churchill, 2005; Hughes & Franks, 2005). However, to date, there has been no system developed to capture and quantify these actions prior to, during and after the possession of the ball in an automated and accurate way.

1.4 Problem definition

At present, there are some player tracking technologies that can measure the general movements made by soccer players, such as running speed, distance travelled, times spent in different modes of movement such as walking, jogging, running and sprinting. However, the literature review revealed that there are a number of missing components of physical
performance and actions that a player executes that are either rarely or never measured due to the limitations of these tracking technologies.

The movement characteristics of soccer players that are currently difficult to measure include:

(i) the acceleration and deceleration of the player;
(ii) the biomechanics of the player's running gait;
(iii) the orientation and direction of the player on the field;
(iv) the kicking biomechanics; and
(v) the various ballistic soccer specific actions.

A match analysis technology that does not measure these characteristics fails to comprehensively analyse the complete performance and only general conclusions on the physical performance of a player during a match can be made. Importantly, a coach cannot fully understand the quantity and quality of all efforts made by a player during a match and, therefore, cannot definitively analyse the success of the performance.

Therefore, the primary research questions associated with analysing the physical performance of soccer players are summarised in Figure 1-1. They include:

1. What movements should be measured? (identified in Chapter 1)
2. How should the movement data be analysed? (Chapter 2)
3. How should the movements be measured? (addressed in Chapter 3)
4. What new technology solution can potentially measure these movements? (Chapter 4)
5. Is the technology solution valid and reliable? (Chapter 4)
6. Does the technology solution meet the unique design requirements for measuring the physical performance of soccer players? (Chapter 4)
If the above design requirements can be met and the sensor can perform sensitive three-dimensional motion analysis of a soccer player's limbs, then a comprehensive and real time match analysis can be facilitated. More specifically, if the displacement of the foot could be measured precisely at high speeds, the velocity, direction, gait, displacement, orientation and sport specific measurements could all be captured. This would give coaches a new ability to
comprehensively consider all factors in the analysis of the on-field physical performance of soccer players. If this problem were to be solved, such a system could give rise to new ways to regularly analyse performance, a new level of understanding of the contributing factors to successful physical performance and, ultimately, improved physical preparation and performance of elite soccer players during match play.
CHAPTER 2

How to interpret and analyse the performance of soccer players
2.1 Analysing Performance

One of the primary objectives of this thesis was to develop a new method to capture, analyse and interpret the physical performance of soccer players and to determine a system for identifying the training requirements needed to physically prepare players. A new Soccer Performance Analysis (SPA) system for evaluating performance was established first to ensure that any hardware technology developed to measure on-field performance was capable of capturing the required data and functioning effectively in this system. The performance analysis system is illustrated in Figure 2-1.

![Figure 2-1. The Soccer Performance Analysis (SPA) system for evaluating the on-field physical performance of soccer players during match play](image)

To effectively analyse performance, the data obtained during a match for a player should be compared to a pre-determined expected standard of performance to establish if it has met or even exceeded expectations. A primary aim of this system, therefore, was to predict and analyse the physical performance during a match. This process is essentially what coaches
have been instinctively doing in the past in their minds to evaluate if a player is having a good match. During a match, coaches are typically considering the player's underlying physical ability, the playing environment, opponent, match tactics and previous performances in those playing circumstances to determine their expectations (Merrick, 2006). If they observe the player not meeting or exceeding their expectations, their opinion of the player's performance is then established.

This chapter, therefore, explains this new system for analysing performance, describes what data needs to be collected and taken into account and a method for determining training requirements, based on a player's physical performance during a match. This chapter also ensures that a comprehensive examination of the performance analysis problem has occurred before designing a suitable hardware solution for capturing the physical performances of players during a match.

2.2 Match Data Requirements

2.2.1 On-field Movements

There are many different types of movements performed during a match by a soccer player. Figure 2-2, illustrates a new multilayered system that breaks movement down into different layers of complexity. This figure demonstrates that movements during a match are constrained and affected by the environment and the game rules. In addition, movements made by players often involve sport specific actions that seem to be critical for successful execution of skills. As a result, to solve the movement of a soccer player during a match, this complete system must be measured to ensure comprehensive evaluation of all on-field movements.
Figure 2-2. The complex system of movements made by a soccer player during a match

Level 1 in Figure 2-2 incorporates the complete match system, including the playing environment, the player's team mates and the opposition players. These components are all important variables that affect the types of movements made by a player. Level 2 indicates that there is an underlying layer of rules and constraints to this system that limits where a player can move on a field. For example, the offside rule limits how far forward attacking
players may move on the field, when involved in play. Level 3 of the system describes the generic movements that can be measured. These include stand, walk, jog, run and sprint. The number and frequency of efforts as well as the distance covered are also general indicators of player movement. Much of the match analysis conducted on soccer players to date has focused on quantifying these basic markers of player movement. However, there are many other sport specific actions, detailed in Level 4, that are important for successful performance that also need to be considered when analysing performance.

Basic locomotion is a function of stride rate and length and is known as a player's locomotive gait. Foot placement and the trajectory are also components of gait biomechanics. The measurement of these components of gait can discriminate why some players are faster, more effective and efficient movers than others (Terrier et al., 2005). There are also a number of game specific actions that are critical components of successful skill execution. These include kicking a ball, dribbling a ball, tackling an opponent, heading a ball, jumping for height, getting up from the ground, passing the ball to another player, receiving a ball, changing direction or evading an opponent (Bangsbo, 1994). In addition, the orientation of a player and the global position of a player on the field are important components of tactical play during a match. Very few investigations have focused on measuring these movement components. No investigation to date has simultaneously examined all of these factors due to limitations in prior measurement technologies. As a result, many of the investigations on player movements during a match (summarised in Tables 1-1 and 1-2) have simply measured movements detailed in level 3 of the system, the basic movements of a player. Therefore, investigations to date on the on-field movements of soccer players have lacked in complexity and comprehensiveness. This hole in the literature explains why many aspects of physical performance of soccer players are still poorly understood and performance has rarely been comprehensively analysed by coaches or sport scientists of elite soccer teams.
A new system for measuring the physical performance of soccer players must, therefore, simultaneously measure all movements, including the sport specific actions and the gait of players.

2.2.2 Player Characteristics and Capacities

In Chapter 1, the characteristics and capacities of elite soccer players were comprehensively described and contrasted. These characteristics include the player's body composition, gender, aerobic power, anaerobic power, speed, speed-endurance and fatigue, agility, acceleration and deceleration, strength and training status. All of these underlying components contribute to the physical performance of soccer players during match play. For example, a soccer player with a very highly developed level of aerobic power is expected to perform considerably more physical efforts throughout a match, particularly in the later stages, compared to a player who is not as highly trained. This relationship between the different physical characteristics and the physical performance attained during match play is currently poorly understood due to the lack of technology to accurately quantify physical performance during a match. However, successful prediction of performance standards could be developed with a comprehensive analysis system, including a process for evaluating the performance of a player against their physical characteristics. Therefore, recording of player characteristics at the time of the match should be measured and used during the subsequent analysis of match movement data.

The physical characteristics and capacities of a soccer player, detailed in Figure 2-3, should be constantly measured over time, since they are altered with training, competing and various other interventions (Helgerud et al., 2001; Hoff et al., 2002). In addition, the interrelations between different physical characteristics and capacities of players and their effect on the physical work performed during a match should also be considered.
Figure 2-3. The player characteristics and capacities underlying the on-field physical performance of soccer players during match play.

The player characteristics and capacities have been simplified into categories (1.1-1.10) in Figure 2-3. However, each capacity has multiple subcomponents. Body composition refers to the player's stature, mass, body fat levels, body shape and proportion. Aerobic power is determined by an athlete's ability to consume and transport oxygen as well as the metabolic energy production during performance. Factors such as the player's muscle characteristics and substrate availability also affect endurance performance. Anaerobic energy production is particularly important because of the high intensity, intermittent nature of exercise intensity.
Like the aerobic system, the underlying muscle morphology and substrate availability are also important contributing factors to performance. Speed, agility and acceleration are fitness components often needed when a player has, or is attempting to gain possession of the ball. The running technique, body shape, balance and anticipation skills all contribute to a player's multidirectional quickness around the field. A player's explosive strength, power and fatigue resistance are also important underlying physical capacities and are dependent on inherent muscle morphology and training status.

Many of these subcomponents of fitness are difficult to measure due to the invasive techniques required. However, several of these subcomponents can be accurately tracked using standardised laboratory and field-based fitness tests. With regular fitness assessment and on-field performance evaluation, these relationships can be established for each player. Similar methods for predicted biological systems have been employed by Varela et al. (1974). As sport science fitness assessment technology progresses, the ease and regularity of measuring these physical capacities will also improve.

Since playing performance is so dependent on the underlying fitness capacities of a player, the current fitness level of a player should be considered when predicting, analysing and interpreting the on-field physical performance.

2.2.3 The Performance Environment

There are many factors that make up the playing environment during a soccer match. These can include physical properties such as the ambient air temperature, elevation above sea level, solar radiation, wind speed and direction, humidity, playing pitch type, ground hardness, pitch surface quality and dimensions. In addition, tactical and technical factors, particularly the match tactics, positional roles and the style of play used by both teams are also contributing
factors to the playing environment. The playing environment also includes other non-physical properties such as the crowd size and characteristics, the proficiency of the playing opponents, the rules and boundaries of the game and how they are officiated. Other factors include the involvement of the crowd behaviour, the location of the stadium (home versus away) and the significance of the match (round game versus final). These factors have been shown to have an effect, to varying degrees, on physical performance and the outcome of a match (Pollard, 1986). There has been extensive research on the effects of environmental conditions such as the heat, on the physical performance of humans in the laboratory setting (Falk et al., 1998; Hargreaves & Febbraio, 1998; Parkin et al., 1999; Backx et al., 2000; Noakes, 2000; Mohr et al., 2004; Sunderland & Nevill, 2005). However, the effects of various outdoor environmental conditions on player work rates during a soccer match remains poorly understood due to the lack of technology to regularly measure the decline in player work rates during matches. The environmental conditions, player position, competition level and match tactics should, therefore, be recorded and used during the analysis of player on-field movement data.

The contributing factors to the playing performance environment have been grouped and comprehensively described in Figure 2-4. Each of the playing environment factors have many subcomponents. In contrast to some of the physical capacity subcomponents, most of these environmental factors can be easily measured and incorporated into an analysis for consideration. The various subcomponents of player position, competition level and environmental conditions are simple to record. Match tactics such as the player formation, styles of play, substitutions, fatigue and tactics require the measurement of the work rate and global position of the player on the field. A movement tracking system and relatively sophisticated software is required for this type of analysis. Other factors such as the decision
making capacity and anticipation of a player can be measured and evaluated under standardised and controlled testing conditions.

Figure 2-4. The contributing factors to the playing environment during soccer match play

In review, the performance environment dictates the competitive nature and player involvement in a match and should, therefore, be considered when analysing and interpreting the on-field physical performance of a soccer player. As the number of matches measured in different playing conditions increases, the ability to predict the effects of the playing environment on player on-field work rates will be improved.
2.3 Analysis of match data

The analysis process should essentially determine if the physical performance of a player is satisfactory or not. The analysis should logically record the physical characteristics of the player and the playing environment. This data should be compared against previous data for the player or against a predetermined normative standard of players of a similar playing position, tactical role, playing environment, standard of competition and physical characteristics. This process is illustrated in Figure 2-5. Consequently, all data should be stored for future comparisons and predictions. The strength of these predictions will increase as more data in varied playing conditions is collected.

![Diagram](image)

**Figure 2-5.** The process of identifying and predicting an expected standard of physical performance of soccer players prior to match play

Once a performance standard has been identified, it is compared against the actual physical performance data achieved during the match. The comparison of the predicted versus actual performance and identification of areas of deficit or in need of improvement through training
or other interventions is identified. Coaches and sport scientists working with professional teams have typically collected on-field movement data and simply reported back the data to the athletes, rather than use a performance analysis system to rate performance (Merrick, 2006). Although this analysis process has been simplified for explanation purposes, it is a very complex process and requires a database and computer software system of considerable capacity.

2.4 Determining Training Requirements From Match Data

Once the predicted and actual physical performance has been compared, the ability of the player to meet the expected performance standard can be determined. Consequently, any deficits in physical performance can be easily identified and various training interventions can be applied in order to reduce the deficit between predicted and actual performance. On the other hand, if the actual performance is greater than the predicted levels, then the training interventions have been successful for improving and optimising the physical performance of the player during match play. This process has been illustrated in Figure 2-6.

The process for determining training requirements is complex, but can be simplified into a two-step process. Once the deficit in performance is identified, the underlying physical capacity responsible for that particular performance component is identified. For example, if a player has a significant drop off in speed as a match progresses, beyond expected for the respective playing environment, the underlying speed and endurance capacity of the player is identified as needing improvement. The existing training program is then evaluated for speed endurance content and an increased emphasis on speed endurance is incorporated into a new modified training program. The specific types of training typically done with soccer players are listed under section 7.2 in Figure 2-6. The duration, intensity and frequency of training as well as the type of training to be completed is then selected and executed.
In summary, while this SPA system has been discussed in a simplistic way, the process of predicting and comparing actual performance is extremely complex. The relationships between the player characteristics, the performance environment and the subsequent recorded physical activities during match play are currently poorly understood. At present, technology
barriers are preventing regular analysis of on-field physical performance and are limiting the understanding of these relationships. Without a process like the SPA system, coaches and sport scientists are limited in their capacity to collect on-field performance data and conduct meaningful analysis. As technology improves and this type of analysis becomes regular, the ability of sport scientists and coaches to predict and interpret performance of players will be improved. The SPA system provides the first comprehensive method for interpreting and analysing the on-field movements of players and also sets a framework for new hardware technology development to quantify all on-field movements made.

2.5 Risk Analysis of the SPA system

A quantitative risk analysis for the SPA system was conducted. Results from this risk analysis are listed in Table 2-1. While the SPA system is logically designed and promises to form an excellent framework for analysing player on-field performance, there is considerable software development needed to implement this system with professional soccer teams.

Obtaining data on player characteristics for most elite professional soccer teams is very low risk, since most clubs have access to physiological fitness assessment equipment. Measurement of the performance environment, including data on the player's position, competition level and environmental conditions is simple. However, the SPA system relies on identifying player position data in order to recognise the tactics employed during the match. While this thesis attempts to solve this problem in later chapters, without a suitable player tracking system, an alternative rating system for match tactics would need to be employed. The development of a scalable database and software system for storage and retrieving historical match data and prediction of performance standards requires considerable resource investment and poses a high risk to the system if not developed. The development of training recommendations critically requires prior analysis by the SPA system of on-field data.
to identify any deficiencies in physical performance during a match. Similarly, significant hardware and software development is needed to generate training program requirements. An alternative is to have the sport scientist and coach manually interpret the findings of the SPA system's analysis and construct a training program using existing software systems.

Table 2-1. Risk Analysis of the Soccer Performance Analysis (SPA) System

<table>
<thead>
<tr>
<th>Information Asset</th>
<th>Threat</th>
<th>Vulnerability</th>
<th>Probability</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Player Characteristics</td>
<td>Measurement of body composition, aerobic &amp; anaerobic power, strength, acceleration, agility, speed, fatigue &amp; training status.</td>
<td>Lack of access to sport science fitness assessment equipment. Invasive &amp; time consuming testing procedures.</td>
<td>Very Low</td>
<td>Significant – some expenditure of resources required.</td>
</tr>
<tr>
<td>Performance Environment</td>
<td>Measurement of player position, competition level &amp; environmental conditions.</td>
<td>Lack of access to performance environment measurement equipment.</td>
<td>Very Low</td>
<td>Significant – some expenditure of resources required.</td>
</tr>
<tr>
<td></td>
<td>Measurement of match tactics.</td>
<td>Currently no on-field player position tracking system. No software to distinguish different playing tactics.</td>
<td>Very High*</td>
<td>Damaging – significant expenditure of resources to develop a new tracking system and analysis software.</td>
</tr>
<tr>
<td>Historical Database</td>
<td>Storage and retrieval of player information.</td>
<td>Lack of access to significant data in the early stages of player data collection.</td>
<td>High</td>
<td>Significant – requires significant effort to establish database &amp; computer software system.</td>
</tr>
<tr>
<td>Performance Standard Prediction &amp; comparison</td>
<td>Performance prediction</td>
<td>Accuracy of performance standard prediction and comparison</td>
<td>High</td>
<td>Significant – requires investment into computer software system to run prediction models</td>
</tr>
<tr>
<td>Training Recommendations</td>
<td>Determination of training requirements from player performance data.</td>
<td>Lack of access to player performance data from matches.</td>
<td>Very High*</td>
<td>Damaging – significant expenditure of resources Required to develop a new player tracking system.</td>
</tr>
<tr>
<td></td>
<td>Access to software to generate training program requirements &amp; construct new programs.</td>
<td></td>
<td>High</td>
<td>Significant – requires significant effort to establish database &amp; computer software system.</td>
</tr>
</tbody>
</table>

*risk assessment conducted prior to the development of the tracking system in this thesis

If the above risks are addressed, the SPA system will provide an effective solution for sport scientists and coaches to capture, interpret and analyse performance and implement suitable training program interventions on soccer players. Ultimately, if executed effectively, this system will result in optimal training configuration and can potentially provide the framework to accelerate the physical development and performance of soccer players.
CHAPTER 3

How to comprehensively measure the movements of a soccer player
3.1 Solving the Movements of Soccer Players

Chapter 2 defined what was required to analyse the physical performance of soccer players. Figure 2-2 outlined the types of movements typically made by players during a match. These included basic locomotion, short-term ballistic movements, soccer specific actions and the gait of the player. In order to detect all of these movements, some critical measurements must be made by the player movement tracking technology. These required measures are illustrated in Figure 3-1 and include:

(i) Displacement and velocity of movements made by the player
(ii) Global position of the player on the field
(iii) Body orientation or the direction facing
(iv) Short-term, ballistic movements sampled at very high frequency.

![Diagram of movement types and measures](image.png)

Figure 3-1. The required measures for detecting all movements made by soccer players during match play
To date, the majority of techniques used by investigators to measure the on-field movements have successfully detected the velocity and the displacement or global position of the player (summarised in Tables 1-1 and 1-2). However, a system that can also detect the player orientation and can sample at very high frequencies will significantly improve the ability to detect the direction of movement, including forwards and backwards locomotion and distinguish ballistic and sport specific actions. If placed on the foot, the sensor will also detect the running gait of the player. The purpose of this chapter, therefore, is to examine the types of technologies that can make these measurements and the operational requirements to successfully function in the elite soccer playing environment.

3.2 An Analysis of Existing Technologies to Measure Player Movement

In order to evaluate the potential of existing technologies to measure player movement, or the need for brand new equipment technology to be developed to measure basic, sport specific and locomotive gait movements detailed in the previously mentioned system, a review of the current state of the art and its capability is necessary.

3.2.1 Current state of the art

As reviewed in Chapter 1, various technologies have been used by investigators to assess human locomotion and activity. Commercial products have recently become available for tracking human locomotion. The range and features of these technologies have been summarised in Table 3-1. These products range from new technologies such as inertial and magnetic sensors to traditional systems like GPS and camera-based systems. Traditional GPS and camera-based systems used by investigators have been limited to describing general movements of a player due to either limited sample rate (5-10 Hz) or sensitivity. This limits their potential use as a solution to measuring all player movements, including sport specific actions. However, the miniature size and very high sampling capacity of recent inertial and
Table 3-1. A review of the various technologies currently commercially available to assess locomotion during sporting performance.

<table>
<thead>
<tr>
<th>Category</th>
<th>Product</th>
<th>Company</th>
<th>Country</th>
<th>Description</th>
<th>Technical Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer-Based Tracking Technology</td>
<td>Polar Foot Pod</td>
<td>Polar Electro</td>
<td>Finland</td>
<td>Accelerometer and equations used to estimate stride length</td>
<td>1/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.polar.com">www.polar.com</a></td>
<td></td>
<td>based on foot flight times during running. Attaches to shoe.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SDM Triax Elite</td>
<td>Nike</td>
<td>USA</td>
<td>Accelerometer combined with heart rate monitor estimates</td>
<td>1/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.nike.com">www.nike.com</a></td>
<td></td>
<td>Distances, speeds and times for running. Attaches to shoe.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Actigraph</td>
<td>The ActiGraph</td>
<td>USA</td>
<td>Uni-axial accelerometer for assessment.</td>
<td>size: 2 x 1.5 x 0.6 in accelerations 0.05-2.0 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.theactigraph.com">www.theactigraph.com</a></td>
<td></td>
<td></td>
<td>size 1.1 x 1.06 x 0.39 in</td>
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<tr>
<td></td>
<td>Actical</td>
<td>Mini-Mitter</td>
<td>USA</td>
<td>Uni-axial accelerometer for assessment</td>
<td>sample 45 days</td>
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<tr>
<td></td>
<td></td>
<td><a href="http://www.minimitter.com">www.minimitter.com</a></td>
<td></td>
<td>of daily activity assessment/energy expenditure</td>
<td>size: 26x27x10 mm; 16 g</td>
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<tr>
<td></td>
<td>Actiwatch</td>
<td>Mini-Mitter</td>
<td>USA</td>
<td>Uni-axial accelerometer for assessment</td>
<td>11 days at 1 min intervals</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.minimitter.com">www.minimitter.com</a></td>
<td></td>
<td>of daily activity assessment/energy expenditure</td>
<td>40 samples /s; 62 days</td>
</tr>
<tr>
<td></td>
<td>ActiTrac</td>
<td>IM systems</td>
<td>USA</td>
<td>Uni-axial accelerometer for measurement of daily living</td>
<td>15 s samples, 5.5 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.imsystems.net">www.imsystems.net</a></td>
<td></td>
<td>activity demands</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BioTrainer Pro</td>
<td>IM Systems</td>
<td>USA</td>
<td>Uni-axial accelerometer for measurement of daily living</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.imsystems.net">www.imsystems.net</a></td>
<td></td>
<td>activity demands</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TriTrac-R3D</td>
<td>Hemokinetics Inc.</td>
<td>USA</td>
<td>Tri-axial accelerometer for measurement of daily living</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.reining.com">www.reining.com</a></td>
<td></td>
<td>activity demands</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RT3</td>
<td>Stay Healthy</td>
<td>USA</td>
<td>Tri-axial accelerometer for measurement of daily living</td>
<td>1 s samples/3 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.stayhealthy.com">www.stayhealthy.com</a></td>
<td></td>
<td>activity</td>
<td>2.3 oz, 2.8&quot;x2.2&quot;x1.1&quot; in</td>
</tr>
<tr>
<td></td>
<td>CT1</td>
<td>Stay Healthy</td>
<td>USA</td>
<td>Uni-axial accelerometer for measurement of daily living</td>
<td>1 s samples/30 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.stayhealthy.com">www.stayhealthy.com</a></td>
<td></td>
<td>activity</td>
<td>2.3 oz, 2.8x2.2x1.1 inches</td>
</tr>
<tr>
<td></td>
<td>IDEEA</td>
<td>Minisun</td>
<td>USA</td>
<td>5 x bi-axial accelerometers for measuring human movement</td>
<td>10 samples/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.minisun.com">www.minisun.com</a></td>
<td></td>
<td></td>
<td>size: 7x5.4x1.7 cm; 59 g &amp;</td>
</tr>
<tr>
<td></td>
<td>CSA 7164</td>
<td>CSA Inc</td>
<td>USA</td>
<td>Small uniaxial accelerometer for assessing daily activity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.csa.com">www.csa.com</a></td>
<td></td>
<td></td>
<td>size: 18x15x3 mm; 2 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.1x4.1x1.5 cm, 42.6 g</td>
</tr>
<tr>
<td>Gyroscope-Based Accelerometers and</td>
<td>Traqua</td>
<td>Australian Institute of Sport</td>
<td>USA</td>
<td>Tri-axial accelerometer and gyroscope for tracking swimmers</td>
<td>200 samples/s</td>
</tr>
<tr>
<td>Tracking Technology</td>
<td></td>
<td><a href="http://www.ausport.gov.au">www.ausport.gov.au</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DMU-VG</td>
<td>Crossbow</td>
<td>USA</td>
<td>3 x uni-axial accelerometers, 3 uni-axial gyroscopes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.crosbow.gov.au">www.crosbow.gov.au</a></td>
<td></td>
<td></td>
<td>12x10x15 cm</td>
</tr>
<tr>
<td></td>
<td>DMU-IMU</td>
<td>Crossbow</td>
<td>USA</td>
<td>3 x uni-axial accelerometers, 3 uni-axial gyroscopes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.crosbow.gov.au">www.crosbow.gov.au</a></td>
<td></td>
<td></td>
<td>7x8x9 cm</td>
</tr>
</tbody>
</table>

continued on next page
### Table 3-1 continued

<table>
<thead>
<tr>
<th>Category</th>
<th>Product</th>
<th>Company</th>
<th>Country</th>
<th>Description</th>
<th>Technical Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Positioning Systems (GPS)</td>
<td>SPI10</td>
<td>GPS Sports</td>
<td>Australia</td>
<td>GPS measurement device (110g) 1Hz sample rate</td>
<td>1/s GPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.gpsports.com.au">www.gpsports.com.au</a></td>
<td></td>
<td>GPS chip collects data for 4 h for assessment of sport</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Timex Bodylink</td>
<td>Timex</td>
<td>USA</td>
<td>Combine GPS, HR monitor and data recorder designed primarily for recording running distances and speeds</td>
<td>1/s GPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.timex.com">www.timex.com</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Foretrex 201</td>
<td>Garmin Ltd</td>
<td>USA</td>
<td>Portable GPS unit for monitoring global position. Wide area augmentation capable (ground stations for correction)</td>
<td>83.8 x 43.2 x 15.2 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.gme.net.au">www.gme.net.au</a></td>
<td></td>
<td>78 g, 30 s samples</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SPI10 elite</td>
<td>GPS Sports</td>
<td>Australia</td>
<td>GPS measurement device (1Hz) with accelerometer</td>
<td>1/s GPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.gpsports.com.au">www.gpsports.com.au</a></td>
<td></td>
<td>For assessment of outdoor team sport play</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aust. Institute of Sport</td>
<td><a href="http://www.ausport.gov.au">www.ausport.gov.au</a></td>
<td>GPS measurement device (1Hz) with accelerometer for Assessment of rowing performance</td>
<td>1/s GPS</td>
</tr>
<tr>
<td></td>
<td>Rover</td>
<td>Citech holdings Pty Ltd</td>
<td>Australia</td>
<td>GPS and tri-axial accelerometer for tracking position and physiological variables</td>
<td>1/s GPS. Real time data</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.citechholdings.com">www.citechholdings.com</a></td>
<td></td>
<td>100/s accelerometer</td>
<td></td>
</tr>
<tr>
<td>GPS and Accelerometer-Based Tracking Technology</td>
<td>SPI10 elite</td>
<td>GPS Sports</td>
<td>Australia</td>
<td>GPS measurement device (1Hz) with accelerometer</td>
<td>1/s GPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.gpsports.com.au">www.gpsports.com.au</a></td>
<td></td>
<td>For assessment of outdoor team sport play</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aust. Institute of Sport</td>
<td><a href="http://www.ausport.gov.au">www.ausport.gov.au</a></td>
<td>GPS measurement device (1Hz) with accelerometer for Assessment of rowing performance</td>
<td>1/s GPS</td>
</tr>
<tr>
<td></td>
<td>Rover</td>
<td>Citech holdings Pty Ltd</td>
<td>Australia</td>
<td>GPS and tri-axial accelerometer for tracking position and physiological variables</td>
<td>1/s GPS. Real time data</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.citechholdings.com">www.citechholdings.com</a></td>
<td></td>
<td>100/s accelerometer</td>
<td></td>
</tr>
<tr>
<td>Inertial Navigation Systems (INS)</td>
<td>MTx*</td>
<td>Xsens</td>
<td>Netherlands</td>
<td>3 degrees of freedom motion and orientation tracker tri-axial accelerometers, gyroscopes and magnetometers</td>
<td>38x53x21mm; 30g</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.xsens.com">www.xsens.com</a></td>
<td></td>
<td>120 samples /s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MTI*</td>
<td>Xsens</td>
<td>Netherlands</td>
<td>3 degrees of freedom motion and orientation tracker tri-axial accelerometers, gyroscopes and magnetometers</td>
<td>58x58x22mm; 50g</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.xsens.com">www.xsens.com</a></td>
<td></td>
<td>120 samples /s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MT9-B*</td>
<td>Xsens</td>
<td>Netherlands</td>
<td>3 degrees of freedom motion and orientation tracker tri-axial accelerometers, gyroscopes and magnetometers</td>
<td>39x54x28mm; 35g</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.xsens.com">www.xsens.com</a></td>
<td></td>
<td>25-512 samples /s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MT6-B*</td>
<td>Xsens</td>
<td>Netherlands</td>
<td>3 degrees of freedom motion and orientation tracker tri-axial accelerometers, gyroscopes and magnetometers</td>
<td>39x54x28mm; 35g</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="http://www.xsens.com">www.xsens.com</a></td>
<td></td>
<td>25-512 samples /s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shadowbox*</td>
<td><a href="http://www.shadowbox-live.com">www.shadowbox-live.com</a></td>
<td>USA</td>
<td>triaxial accelerometer, gyroscope, magnetometer &amp; GPS</td>
<td>600 samples /s</td>
</tr>
<tr>
<td>Camera-Based Motion Tracking Systems</td>
<td>AMISCO</td>
<td>Sport Universal</td>
<td>France</td>
<td>multiple cameras mounted in stadium. Computer software tracks players on the field</td>
<td>6 samples /s</td>
</tr>
</tbody>
</table>

*system is not portable, wireless and remote  
^system is not miniature
magnetic sensors makes them more suitable for modification and application to recording high speed movements and analysing the physical performance of players. This section, therefore, focuses primarily on the current state of the art in the novel area of inertial and magnetic sensor technology for assessing movement.

An accelerometer is an instrument for measuring acceleration, detecting and measuring vibrations, or for measuring acceleration due to gravity or inclination. Accelerometers register the dynamic acceleration caused by a change of velocity during locomotion as well as gravity as a static vertical component. Accelerometers are available in a wide variety of ranges up to thousands of g. Single axis, dual axis, and three axis accelerometer models are commercially available. Accelerometer-based technology was first used experimentally by Morris (1973) for the measurement of body movements at very high sample rates. Early experiments by Schmidt et al. (1977) applied the use of three uniaxial accelerometers in gait analysis. Since this time, accelerometer technology has been used extensively by investigators in the measurement of running and walking gait analysis experiments (Hayes et al., 1983; Willemsen et al., 1990a; Willemsen et al., 1990b; Brage et al., 2003; Mercer et al., 2003; Moe-Nilssen & Helbostad, 2004). These prototypes have been large, invasive and unable to work remotely and unsuitable for use in elite sport. A comprehensive review of the use of accelerometer technology in motion analysis experiments has been listed in Table 3-2. This table lists the various research organisations, a description of sensors that they have used and how they have applied the use of inertial sensors to human movement analysis.

Researchers have reported other limitations of accelerometers, particularly fluctuating offset due to changes in temperature or mechanical structure (Meijer et al., 1991). In addition, problems arise when using accelerometers as inclinometers, due to accelerometers
### Table 3-2. A review of the accelerometer and gyroscope-based sensor technologies for assessing movement.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Research Organisation</th>
<th>Description of sensor/s used</th>
<th>Application of technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Morris (1973)</td>
<td>University of Oxford, UK</td>
<td>6 x uni-axial accelerometers</td>
<td>Assessment of body movements</td>
</tr>
<tr>
<td>1977</td>
<td>Smidt et al. (1977)</td>
<td>University of Iowa, USA</td>
<td>3 x uni-axial accelerometers (Stratham Instruments)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1979</td>
<td>Mital &amp; King (1979)</td>
<td>Wayne State University, USA</td>
<td>9 x uni-axial accelerometers</td>
<td>Assessment of body parts - head</td>
</tr>
<tr>
<td>1983</td>
<td>Hayes et al. (1983)</td>
<td>Harvard Medical School, USA</td>
<td>4 x tri-axial accelerometers</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1990</td>
<td>Willemsen et al. (1990a)</td>
<td>University of Twente, Netherlands</td>
<td>4 x uni-axial accelerometers (Kyowa AS-5G)</td>
<td>Functional Electrical Stimulation (FES)</td>
</tr>
<tr>
<td>1990</td>
<td>Willemsen et al. (1990b)</td>
<td>University of Twente, Netherlands</td>
<td>8 x uni-axial accelerometers (Kyowa AS-5GA)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1996</td>
<td>Veitink et al. (1996)</td>
<td>University of Twente, Netherlands</td>
<td>2 x uni-axial accelerometers</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1996</td>
<td>van den Bogert et al. (1996)</td>
<td>University of Calgary, Canada</td>
<td>4 x tri-axial accelerometers (ENTRAN EGAXT-*-10)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1997</td>
<td>Lötters et al. (1998a)</td>
<td>University of Twente, Netherlands</td>
<td>1 x new symmetrical tri-axial accelerometer</td>
<td>General Medical applications</td>
</tr>
<tr>
<td>1997</td>
<td>Bülten et al. (1997)</td>
<td>University of Technology, Netherlands</td>
<td>3 x uni-axial accelerometers</td>
<td>Assessment of daily living activity</td>
</tr>
<tr>
<td>1998</td>
<td>Lötters et al. (1998b)</td>
<td>Bronkhorst High-Tech, Netherlands</td>
<td>3 x uni-axial accelerometers (ICSensors 3021-010-P)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>1998</td>
<td>Busser et al. (1998)</td>
<td>McRoberts BV, Netherlands</td>
<td>3 x uni-axial accelerometers</td>
<td>Assessment of physical work</td>
</tr>
<tr>
<td>1998</td>
<td>Moe-Nilsen (1998b)</td>
<td>University of Bergen, Norway</td>
<td>1 x tri-axial accelerometer (Logger Technology)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2000</td>
<td>Nouillot et al. (2000)</td>
<td>Université Paris-Sud, France</td>
<td>2 x tri-axial, 1 uni-axial accelerometer (ENTRAN ECG D)</td>
<td>Postural Analysis</td>
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<tr>
<td>2000</td>
<td>Uswatte et al. (2000)</td>
<td>University of Jena, Germany</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Assessment of body parts - extremities</td>
</tr>
<tr>
<td>2000</td>
<td>Sirard et al. (2000)</td>
<td>University of Massachusetts, USA</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Assessment of daily living activity</td>
</tr>
<tr>
<td>2001</td>
<td>Alusi et al. (2001)</td>
<td>Central Middlesex Hospital, UK</td>
<td>1 x uni-axial accelerometer (Entran EGAX-5/L2M)</td>
<td>Assessment of body parts - extremities</td>
</tr>
<tr>
<td>2001</td>
<td>Baselli et al. (2001)</td>
<td>Politecnico di Milano, Italy</td>
<td>4 x uni-axial accelerometers (Analog Device ADXL05EM3)</td>
<td>Assessment of body parts - head</td>
</tr>
<tr>
<td>2001</td>
<td>Strath et al. (2001)</td>
<td>University of Tennessee, USA</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2002</td>
<td>Matthews et al. (2002)</td>
<td>University of South Carolina, USA</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2002</td>
<td>Metcaif et al. (2002)</td>
<td>University of Plymouth, UK</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2002</td>
<td>Strath et al. (2002)</td>
<td>University of Tennessee, USA</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2002</td>
<td>Tudor-Locke et al. (2002)</td>
<td>Arizona State University East, USA</td>
<td>1 x tri-axial accelerometer (Hemokinetics Tritrac-R3D)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2002</td>
<td>Campbell et al. (2002)</td>
<td>University of British Columbia, Canada</td>
<td>1 x tri-axial accelerometer (Hemokinetics Tritrac-R3D)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2003</td>
<td>Le Masurier &amp; Tudor-Locke (2003)</td>
<td>Arizona State University East, USA</td>
<td>1 x uni-axial accelerometer (CSA 7164 2.2)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2003</td>
<td>Mercer et al. (2003)</td>
<td>University of Nevada, USA</td>
<td>2 x uni-axial accelerometers (Kistler 6828B50)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2003</td>
<td>Powell et al. (2003)</td>
<td>University of Wales, UK</td>
<td>1 x tri-axial accelerometer (Stayhealthy, RT3)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2003</td>
<td>Schmidt et al. (2003)</td>
<td>University of Massachusetts, USA</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2003</td>
<td>Yngve et al. (2003)</td>
<td>Karolinska Institute, Sweden</td>
<td>1 x uni-axial accelerometer (ActiGraph 7164 WAM)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2003</td>
<td>Brage et al. (2003)</td>
<td>University of Southern Denmark, Denmark</td>
<td>1 x uni-axial accelerometer (CSA 7164)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>Year</td>
<td>Source</td>
<td>Research Organisation</td>
<td>Description of sensor/s used</td>
<td>Application of technology</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>-----------------------</td>
<td>------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>2004</td>
<td>Le Masurier et al. (2004)</td>
<td>Arizona State University East, USA</td>
<td>1 x uni-axial accelerometer (CSA 7164 2.2)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2004</td>
<td>Treuth et al. (2004)</td>
<td>John Hopkins Bloomberg School of Public Health, USA</td>
<td>1 x uni-axial accelerometer (ActiGraph 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2004</td>
<td>Van Coevering et al. (2005)</td>
<td>University of Minnesota, USA</td>
<td>1 x uni-axial accelerometer (ActiGraph 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2004</td>
<td>Welk et al. (2004)</td>
<td>University of North Texas, USA</td>
<td>1 x uni-axial accelerometer (ActiGraph 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2004</td>
<td>King et al. (2004)</td>
<td>University of Texas at El Paso, USA</td>
<td>1 x uni-axial accelerometer (ActiGraph 7164), (Hemokinetics Tritrac-R3D)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2005</td>
<td>Mâsse et al. (2005)</td>
<td>National Cancer Institute, USA</td>
<td>1 x uni-axial accelerometer (Manufacturing technologies, ActiGraph 7164 WAM)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2005</td>
<td>Schmitz et al. (2005)</td>
<td>University of Minnesota, USA</td>
<td>1 x uni-axial accelerometer (Manufacturing technologies, ActiGraph 7164 WAM)</td>
<td>Assessment of daily living Activity</td>
</tr>
<tr>
<td>2005</td>
<td>Strath et al. (2005)</td>
<td>Uni. of Wisconsin-Milwaukee, USA</td>
<td>1 x uni-axial accelerometer (ActiGraph 7164)</td>
<td>Assessment of daily living Activity</td>
</tr>
</tbody>
</table>

**Gyroscope-based Movement Assessment Systems**

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Research Organisation</th>
<th>Description of sensor/s used</th>
<th>Application of technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>Miyazaki (1997)</td>
<td>Tokyo medical &amp; Dental Uni., Japan</td>
<td>1 x Gyroscope (Murata ENV05S)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1999</td>
<td>Tong &amp; Granat (1999)</td>
<td>University of Strathclyde, Scotland</td>
<td>1 x Gyroscope (Murata ENC05EA)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2002</td>
<td>Najafi et al. (2002)</td>
<td>Swiss Federal Inst. of Tech., Switzerland</td>
<td>1 x Gyroscope (Murata ENC03J)</td>
<td>Assessment of daily living activity</td>
</tr>
</tbody>
</table>
requiring acceleration to be sufficiently small in comparison to the gravity (Baten et al., 1996; Bouten et al., 1997; Kemp et al., 1998). In addition, accelerometer signals do not contain information about their rotation about the vertical and therefore do not give a complete description of their orientation. Early experiments to increase the accuracy of inclination measurements during activity used gyroscopes in combination with accelerometers (Barshan & Durrant-Whyte, 1995; Baten et al., 1996). A gyroscope is a device for measuring orientation or angular velocity ($\omega$), based on the principle of conservation of angular momentum. By integrating the angular velocity, the change in orientation can be mathematically estimated (Bortz, 1971; Ignagni, 1990). Luinge (2002) developed a Kalman filter that fuses the information of a triaxial accelerometer system with a triaxial gyroscope system to measure the orientation of a human body segment (Figure 3-2). The problem with this method was that the error in rotation around the vertical could not be significantly reduced.

![Figure 3-2](image.png)

**Figure 3-2.** The structure of a Kalman filter estimation. Adapted from Luinge & Veltink (2005). Both the accelerometer and the gyroscope systems are used to make an estimate of the global vertical unit vector ($Z$). The difference between the two estimates is written as a function of orientation error ($\theta_e$) and offset error ($b_e$). A Kalman filter estimates $\theta_e$ and $b_e$ using this function together with the error covariances of the orientation ($Q_\theta$), offset ($Q_b$) and inclination estimation ($Q_{Z_G}$ and $Q_{Z_A}$). These estimated errors are used to correct the estimated orientation.
The inclusion of triaxial magnetometers was later used in combination with a triaxial accelerometer to measure orientation (Kemp et al., 1998). A magnetometer is a scientific instrument used to measure the both the magnitude and direction of the earth’s magnetic field. More specifically, the use of a triaxial vector magnetometer allows the magnetic field strength, inclination and declination to be uniquely defined. Following this, a number of investigators have combined magnetometers with accelerometers and gyroscopes (Frey III, 1996; Foxlin, 1998; Bachmann et al., 2001; Pfau et al., 2005; Roetenberg et al., 2005). Bachmann et al. (2001) used a quaternion-based complementary filter algorithm for processing the output data and to determine the posture of a body in real-time. Figure 3-3 describes the structure of the quaternion filter estimation used in this experiment. However, the hardware used in this experiment was not miniature or wireless and required extensive cabling on the subject, limiting its application in the field and for sport. However, if a new miniature inertial sensor could be designed that could work in both high and low speed movements and could operate wirelessly, then this type of solution could be highly applicable for detecting the high speed, multidirectional movements during soccer match play.

**Figure 3-3.** The structure of a quaternion-based orientation filter. Adapted from Bachmann et al. (2001). The filter inputs are from three-axis angular rate sensor (p, q, r), a three-axis accelerometer (h₁, h₂, h₃), and a three-axis magnetometer (b₁, b₂, b₃). The output is a quaternion representation of the orientation of the tracked object.
Table 3-3. A review of various combinations of magnetic and/or inertial sensor technologies for assessing movement.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Research Organisation</th>
<th>Description of sensor/s used</th>
<th>Application of technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>Barshan &amp; Durrant-Whyte (1995)</td>
<td>Bilkent University, Turkey</td>
<td>2 x gyroscopes (GEC Avionics START; Murata ENV-05S), 1 x tri-axial accelerometer (ENTRAN EGCX3-A)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1996</td>
<td>Wu &amp; Ladin (1996)</td>
<td>Pennsylvania State University, USA</td>
<td>1 x gyroscope, 1 tri-axial accelerometer</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>1996</td>
<td>Baten et al. (1996)</td>
<td>University of Twente, Netherlands</td>
<td>1 x tri-axial accelerometer (ICSensors), 1 x gyroscope (Murata)</td>
<td>Assessment of body parts – back</td>
</tr>
<tr>
<td>1996</td>
<td>Frey III (1996)</td>
<td>US Naval Postgraduate School, USA</td>
<td>1 x tri-axial flux-gate magnetometer (Develco DEVE86), 1 x tri-axial accelerometer, 1 x tri-axial gyroscope, 1 x tri-axial magnetometer (inertia cube)</td>
<td>Assessment of body parts - back and extremities</td>
</tr>
<tr>
<td>1998</td>
<td>Foxlin (1998)</td>
<td>Intersense Inc., USA</td>
<td>1 x tri-axial accelerometer, 1 x tri-axial gyroscope, 1 x tri-axial magnetometer (Murata ENC05E)</td>
<td>Assessment of body parts – head</td>
</tr>
<tr>
<td>1998</td>
<td>Kemp et al. (1998)</td>
<td>University Hospital Leiden, Netherlands</td>
<td>1 x tri-axial accelerometer (ICSensors ICS3031-002), 1 x magnetometer (Nonvolatile Electronics NVS5B15S)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2000</td>
<td>Xiaoping et al. (2000)</td>
<td>US Naval Postgraduate School, USA</td>
<td>1 x differential GPS, 1 x crossbow DMU-VG six-axis inertial meas. unit</td>
<td>Vehicle navigation and tracking</td>
</tr>
<tr>
<td>2001</td>
<td>Bachmann et al. (2001)</td>
<td>Miami University, USA</td>
<td>1 x tri-axial accelerometer (Crossbow CXL04M3), 1 x tri-axial magnetometer (Honeywell HMC2003), 3 x gyroscopes (Tonkin CG-16D)</td>
<td>Assessment of body parts – extremities</td>
</tr>
<tr>
<td>2001</td>
<td>Veltink et al. (2001)</td>
<td>University of Twente, Netherlands</td>
<td>1 x tri-axial accelerometer (Analog Devices ADXL-05), 1 x gyroscope (Murata ENC05E)</td>
<td>Assessment of body parts - extremities</td>
</tr>
<tr>
<td>2002</td>
<td>Mayagoitia et al. (2002)</td>
<td>Staffordshire University, UK</td>
<td>8 x uni-axial accelerometers (IC Sensors 3021-005-P), 1 x gyroscope (Murata ENC-05EB)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2002</td>
<td>Luinge (2002)</td>
<td>University of Twente, Netherlands</td>
<td>1 x tri-axial accelerometer (Analog Devices ADXL-05), 1 x tri-axial gyroscope (Murata ENC05)</td>
<td>Assessment of body parts</td>
</tr>
<tr>
<td>2003</td>
<td>Veltink et al. (2003a)</td>
<td>University of Twente, Netherlands</td>
<td>2 x two-axial accelerometers (Analog Devices ADXL 210), 3 x gyroscopes (Murata ENC-03J)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2003</td>
<td>Veltink et al. (2003b)</td>
<td>University of Twente, Netherlands</td>
<td>2 x two-axial accelerometers (Analog Devices ADXL 210), 3 x gyroscopes (Murata ENC-03J)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2004</td>
<td>Luinge &amp; Veltink (2004)</td>
<td>University of Twente, Netherlands</td>
<td>1 x tri-axial accelerometer (Analog Devices ADXL-05), 1 x gyroscope (Murata ENC05E)</td>
<td>Assessment of body parts - extremities</td>
</tr>
<tr>
<td>2005</td>
<td>Luinge &amp; Veltink (2005)</td>
<td>University of Twente, Netherlands</td>
<td>1 x tri-axial accelerometer (Analog Devices ADXL-05), 1 x gyroscope (Murata ENC05E)</td>
<td>Assessment of body parts – extremities</td>
</tr>
<tr>
<td>2005</td>
<td>Roetenberg et al. (2005)</td>
<td>Xsens, Netherlands</td>
<td>1 tri-axial accelerometer (Analog Devices ADXL202E), 1 tri-axial magnetometer (Philips KMZ51/52), 1 x gyroscope (Murata ENC03J)</td>
<td>Assessment of body parts - extremities</td>
</tr>
<tr>
<td>2005</td>
<td>Pfau et al. (2005)</td>
<td>Xsens, Netherlands</td>
<td>1 tri-axial accelerometer (Analog Devices ADXL202E), 1 tri-axial magnetometer (Philips KMZ51/52), 1 x gyroscope (Murata ENC03J)</td>
<td>Gait Analysis</td>
</tr>
<tr>
<td>2009</td>
<td>unpublished</td>
<td>Shadowbox, Inc, USA</td>
<td>1 tri-axial magnetometer, gyroscope, magnetometer, GPS</td>
<td>Sports Analysis</td>
</tr>
</tbody>
</table>
Table 3-3 is a summary of various combinations of magnetic, acceleration and inertial sensors for assessing movement. A description of the types of sensors used in these experiments and the application of the sensors is also detailed in this table.

The problem with all of the technologies listed in Table 3-3 is that they are not extremely miniature, light weight, free of cables, portable, robust and built to simultaneously store and transmit data in real time. This makes them unsuitable for tracking elite soccer players in their present form. In addition, while commercially available magnetic and inertial tracking systems have recently become available, their size, mass and invasiveness continues to impair their ability for use in elite sport.

### 3.2.2 Measurement capability of current state of the art

Most of the existing technologies are limited in their ability to detect the movements of a soccer player during a match. These technologies, including cameras, GPS, accelerometers and accelerometers with gyroscopes, and their capacities to measure different movement types are summarised in Table 3-4. Their capabilities are contrasted against a potential new miniature and wireless magnetic and inertial navigation system.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Stand</th>
<th>Walk</th>
<th>Jog</th>
<th>Run</th>
<th>Sprint</th>
<th>Distance</th>
<th>Global Position on the Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>yes#</td>
<td>yes#</td>
<td>yes#</td>
<td>yes#</td>
<td>yes#</td>
<td>estimated</td>
<td>estimated</td>
</tr>
<tr>
<td>GPS</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Accelerometer + Gyroscope</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Potential Miniature Magnetic &amp; Inertial System*</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

*Theoretical, since no miniature magnetic and inertial navigation system currently exists

* manually recorded
Theoretically, the existing methodologies in Table 3-4 can detect the mode of exercise if they were to be adapted to detect soccer players. However, they are generally limited in their capacity to detect displacement and global position on the field due to either the fundamental way they detect movement or due to their current sensor accuracy. For example, any technology that relies on an accelerometer to detect displacement is limited, since accelerometers that are moving in six degrees of freedom are non-directional. While some applications of accelerometers, such as foot pedometers (Crouter et al., 1998; Tudor-Lock et al., 2002; Le Masurier and Tudor-Lock, 2003) estimate displacement using prediction equations based on foot flight time measured by the triaxial accelerometers, these sensors do not measure the displacement from first principals and are, therefore, likely to exhibit a considerable estimation errors in some data analysis situations.

The majority of research on elite soccer players to date has focused on detecting general movements described in the system in Figure 3-1 using somewhat limited technologies. However, a customised and miniaturised magnetic and inertial navigation system that combines sensors such as three axis accelerometers, magnetometers and gyroscopes, appears to be a better solution for detecting general movements made by soccer players.

Figure 3-1 listed a range of sport specific movements that have rarely been detected by investigators studying the movements of soccer players. Table 3-5 explains why existing technologies have been ineffective at measuring these sport specific movements of soccer players. Their mechanisms for detecting motion suffers primarily from not being automated, they use limited estimation methods which are subject to error, are ineffective at measuring subtle displacement of the player or do not sample at a significant rate to discriminate movements at high speed. Only magnetic and inertial tracking technologies are theoretically
<table>
<thead>
<tr>
<th>Technology</th>
<th>Stride Rate</th>
<th>Stride Length</th>
<th>Foot placement &amp; Trajectory</th>
<th>Kick</th>
<th>Dribble</th>
<th>Tackle</th>
<th>Header</th>
<th>Jump</th>
<th>Get up</th>
<th>Pass ball</th>
<th>Evade</th>
<th>Orientation</th>
<th>Relative Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>yes(^1)</td>
<td>no</td>
<td>no</td>
<td>yes(^1)</td>
<td>yes(^1)</td>
<td>yes(^1)</td>
<td>yes(^1)</td>
<td>yes(^1)</td>
<td>yes(^1)</td>
<td>yes(^1)</td>
<td>yes(^1)</td>
<td>estimated</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>DGPS</td>
<td>yes(^2)</td>
<td>yes(^2)</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes(^2)</td>
<td>no</td>
<td>no</td>
<td>yes(^2)</td>
<td>yes(^3)</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Accelerometer</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Accelerometer + Gyroscope</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Potential Miniature Magnetic and inertial system*</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) manually recorded  
\(^2\) successfully measured these characteristics at only low locomotion speeds (Terrier et al., 2000)  
\(^3\) not detectable when player is stationary  
*Theoretical, since no miniature magnetic and inertial navigation system currently exists
able to simultaneously measure both running gait and sport specific movements. At present, however, this remains unproven.

GPS is the most common method used by elite soccer teams to measure the movements of their players. However, table 3-5 clearly indicates why it is not a suitable method for solving soccer performance, since its sample rate limits it from detecting stride rate and length. A running stride of a soccer player during a sprint effort can occur in less than a second, resulting in potential lost running gait data. In addition, this also prevents the detection of actions such as kicking, dribbling and tackling because they can occur quickly (less than one second) and therefore may not be detected if they occur between samples made by the GPS system. Differential GPS technologies have been shown to detect gait variations at low movement speeds sampling at 6 Hz, but are limited to detecting gait at higher movement speeds (Terrier et al, 2000). When contrasted against a potential new miniature inertial and magnetic system, GPS also appears unable to detect orientation in some circumstances, particularly when the player is not moving. Magnetic and inertial measurement systems overcome this by using a digital compass, a magnetometer, which measures orientation of the sensor in relation to the earth's magnetic field, theoretically making it suitable for detecting which way a player is facing and the orientation of a player's body or limb in relation to the field or another player.

In summary, the development of a new miniature magnetic and inertial system is an excellent solution for measuring general and specific movements of players, particularly when contrasted against the capacities of existing technologies listed in Tables 3-4 and 3-5.
3.3 Operational Requirements for a New Player Motion Tracking System

Based on the capabilities of the existing technologies to track the movement of soccer players, there are a number of new operational requirements that are needed in order to measure not only general movements, but the sport specific actions and running gait movements listed in the system in Figure 3-1. The purpose of this section, therefore, is to explain some of the operational requirements for solving the complete system of movements of a player during a match. Table 3-6 summarises the key operational requirements, including the performance, utilisation and environmental operations parameters for a new locomotion tracking system.

Table 3-6. Key operational requirements for a new player motion tracking system

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample rate &gt;100Hz</td>
<td>Data storage capacity &gt; 120 min of data</td>
</tr>
<tr>
<td>Battery capacity to last &gt;120 min</td>
<td>Work indoors</td>
</tr>
<tr>
<td>Miniature in size &lt;40 mm²</td>
<td>Light weight &lt; 50 g</td>
</tr>
<tr>
<td>Remote/portable/no cables</td>
<td>Can track displacement and orientation</td>
</tr>
<tr>
<td>Potential to be calibrated</td>
<td>Can be attached to a limb</td>
</tr>
<tr>
<td>Reliable to less than 5% error</td>
<td>Operates in any environment (0–50°C)</td>
</tr>
<tr>
<td>Shockproof</td>
<td>Water resistant</td>
</tr>
<tr>
<td>No sensor cross talk</td>
<td>Can distinguish different movements, including gait</td>
</tr>
</tbody>
</table>

3.3.1 High sample rate and data storage capacity

Regardless of the type of technology selected for measuring player motion, it is important that the technology has sufficient data processing and storage capacity, is portable and is easily wearable for optimal use (Chen & Bassett, 2005). However, the frequency of data collected or sample rate should be based on the research question and the type of activity to be monitored, rather than the hardware limitations (Ward et al., 2005). Investigations into gait analysis systems have shown that higher sample rates improve the accuracy of gait detection (Polk et al., 2005). Pappas et al. (2005) showed that a sample rate of greater than 50 Hz was sufficient for accurately detecting the phases of gait in humans. In addition, Peysar et al (2001) supported this finding with determining that a sampling frequency of greater 50 Hz improved the accuracy of the detection of gait parameters compared to lower sample rates.
Table 3.7. Number of steps taken by runners in 1 second for different locomotion speeds. Adapted from Watkins (2007).

<table>
<thead>
<tr>
<th>Locomotion</th>
<th>Speed (km/hr)*</th>
<th>Number of steps/second**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk</td>
<td>4</td>
<td>1.13</td>
</tr>
<tr>
<td>Jog</td>
<td>8</td>
<td>1.25</td>
</tr>
<tr>
<td>Low Speed Run</td>
<td>12</td>
<td>1.37</td>
</tr>
<tr>
<td>Moderate Speed Run</td>
<td>16</td>
<td>1.43</td>
</tr>
<tr>
<td>High Speed Run</td>
<td>21</td>
<td>1.58</td>
</tr>
<tr>
<td>Peak Velocity**</td>
<td>31.9</td>
<td>1.91</td>
</tr>
</tbody>
</table>

*Speeds (4-21 km/hr) based on findings by Bangsbo (1991) and peak velocity recorded by Bangsbo and Mohr (2005) **Stride rates of recreational runners on a treadmill (Watkins, 2007).

Table 3.7 summarises the number of steps taken by runners in 1 second at different locomotion speeds. This table shows that technologies operating at 1 Hz cannot detect every step, regardless if the soccer player is walking or sprinting. For this reason, technologies sampling at 1 Hz or less, including standard GPS systems, are ineffective at detecting gait and therefore can only be used to detect general movement patterns on the field. Table 3.8 shows the number of possible data points per step at different sample rates and locomotion speeds. A sampling rate of 50 Hz equates to a minimum of 25 samples per step, regardless of the locomotion speed. Interestingly, technologies that can operate at 1 Hz can only capture one sample every 2 steps if a soccer player is sprinting.

Table 3.8. The number of possible data points per step for different sample rates and locomotion speeds.

<table>
<thead>
<tr>
<th>Sample rate (Hz)</th>
<th>4 km/hr**</th>
<th>8 km/hr**</th>
<th>12 km/hr</th>
<th>16 km/hr</th>
<th>21 km/hr</th>
<th>31.9 km/hr**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hz</td>
<td>0.89</td>
<td>0.8</td>
<td>0.73</td>
<td>0.7</td>
<td>0.63</td>
<td>0.52</td>
</tr>
<tr>
<td>10 Hz</td>
<td>8.9</td>
<td>8.0</td>
<td>7.3</td>
<td>7.0</td>
<td>6.3</td>
<td>5.2</td>
</tr>
<tr>
<td>25 Hz</td>
<td>22.1</td>
<td>20.0</td>
<td>18.2</td>
<td>17.5</td>
<td>15.8</td>
<td>13.1</td>
</tr>
<tr>
<td>100 Hz</td>
<td>89.0</td>
<td>80.0</td>
<td>73.0</td>
<td>70.0</td>
<td>63.0</td>
<td>52.0</td>
</tr>
</tbody>
</table>

*Based on stride times of recreational runners on a treadmill (Watkins, 2007) **estimated using linear regression
High speed motion analysis systems have been used to detect human gait during laboratory-based experiments (McCullock et al., 1993; Riley et al. 2007). These systems can operate well over 100 Hz and have very good accuracy. However, they are only suitable for indoor laboratory experiments since they require subjects to wear reflective markers and low levels of background light in the data collection environment. These systems would not be suitable in the field due to the inability of these systems to operate over long distances and the error caused by direct sunlight or light towers in typical soccer stadiums.

Current systems used in the field to detect locomotion during sporting performance have been summarised in Table 3-1. It is important to consider the sampling rate of each of these technologies. At present, GPS tracking equipment used by researchers have been able to detect player location on the field at 1 Hz (Edgecomb & Norton, 2006; Wisbey & Montgomery, 2006). There are, however, investigations into the study of the biomechanics of human locomotion have used differential GPS tracking systems that can sample at several times per second at a theoretical precision better than 0.6 cm.s\(^{-1}\) using fixed base stations (Terrier et al., 2000). While these systems are preferential to standard GPS for detecting high speed movements during soccer match play, other limitations of GPS technology such as sensor drift, inability to detect orientation, ability to work only in outdoor environments and the invasive nature of current receiver units prevent GPS from being a suitable option for tracking the motion of soccer players during match play.

Accelerometer technology has been used extensively by investigators in the measurement of running and walking gait analysis experiments (Hayes et al., 1983; Willemsen et al., 1990a; Willemsen et al., 1990b; Brage et al., 2003; Mercer et al., 2003; Moe-Nilssen & Helbostad, 2004). Accelerometers are able to sample at very high frequencies of up to 1000 Hz (Mercer et al., 2003) with high precision (Moe-Nilssen, 1998b). This potentially makes the use of
accelerometry a highly suitable technology for detection of high speed, multidirectional movements during soccer match play.

The inclusion of gyroscope technology to detect the angular velocity about its own axis was first used by Miyazaki (1977). This system detected angular velocity at 150 deg.sec\(^{-1}\) to approximate stride length during gait analysis. Similar to accelerometers, this technology now has the potential to detect motion at very high sample rates of over 100 Hz. Used independently, however, this system has limited application in the detection of motion during soccer match play due to the errors associated with estimating stride length. Gyroscopes used in some recent experiments (Table 3-2) can operate at several hundred degrees per second, making them much more suitable for the detection of body parts of soccer players during match play compared to previous measurement techniques with slower sample rates.

The various combination of magnetic and inertial sensors used to detect motion of the body during activity have been summarised in Table 3-3. These sensors also have a far superior ability to sample positional data of soccer players at high sample rates (>100 Hz), compared to other methods such as GPS and manual methods (approximately 1 Hz).

Experiments on the ankle kinematics during running have shown the ankle to turn at a peak dorsiflexion velocity of 4.4-4.6 rad.s\(^{-1}\) or 263.58 deg.s\(^{-1}\) at a running velocity of 4.5 m.s\(^{-1}\) (Buczek & Cavanagh, 1990). For this reason gyroscopes with a capacity to measure 300 degrees per second and sample at 100 Hz would be needed to adequately detect running (up to 18km/hr) by soccer players. In order to detect high speed running and sprinting, a gyroscope that could detect 527 deg.s\(^{-1}\) would be needed based on the ankle kinematic data by (Bucczek & Cavanagh, 1990). Interestingly, data from these authors suggest that the knee peak flexion
and extension is almost double that of the ankle. However, to detect human gait, the displacement of the ankle and foot is primarily needed.

Another consideration for determining the optimal sample rate of a measurement device is the ability of a sensor and data logging technology on the soccer player to store the data. For example, the finite memory capacity of a data logger, storing data at very high sample rates, may limit the time that a sensor could operate for before the data storage capacity was exhausted. Since a soccer match lasts at least 90 minutes, selecting a sample rate which will not exhaust the memory capacity of the technology is an important factor for consideration.

In conclusion, the sample rate and data storage capacity is critical to detecting high speed and subtle movements of a soccer player for the complete duration of a soccer match. While there have been technologies applied to gait analysis which can indeed sample at very high rates, these technologies used by investigators are limited in their capacity, particularly to store data, work in the field and operate remotely for extended periods of time. Since the minimum sample rate required is at least 50 Hz to not only track the global position of the player, but the running gait of the player, a sample rate of 100 Hz would double the minimum requirements. A new miniature system for tracking soccer players that could sample at this rate for the duration of a soccer match would make it as sensitive as laboratory-based motion tracking equipment and highly capable of sensitively detecting player motion.

3.3.2 Extended battery life

The majority of investigations into the analysis of human gait have investigated discrete, short term movements such as walking and running (Winter et al., 1976; Aminian et al., 1995; Tong & Granat, 1999; Terrier et al., 2001; Scholten et al., 2002; Brage et al., 2003; Crouter et al., 2003; Mercer et al., 2003; Terrier & Schutz, 2003; Conger et al., 2005). Tracking systems
used in previous experiments have been limited by the battery life of the system (Phillips et al., 2001). However, a number of systems have been designed with extended sampling of human motion in mind (Miyazaki, 1997; Moe-Nilssen, 1998a; Tong & Granat, 1999). Figure 3-4 illustrates the typical playing times for a standard soccer match. While the playing time is typically 90 minutes, the addition of injury time, the half time break as well as extra time and penalty kicks, if needed, can take up to 150 minutes. The inclusion of a battery which can last a minimum of 90 minutes and up to 150 minutes is, therefore, an essential requirement of a capable new soccer locomotion tracking system.

![Figure 3-4. Typical playing times for a soccer match.](image)

3.3.3 Work in any environment and robustness

There are over 200 countries that currently play FIFA approved international soccer matches in considerably different environmental conditions. These include varying altitudes, temperatures, moisture levels, wind speeds, light, electromagnetic levels and stadium types and pitch conditions. Consequently, a new locomotion tracking system needs to be able to operate in virtually any environmental condition.
The accuracy of some inertial sensors used in locomotion tracking devices, particularly accelerometers, is affected by the ambient temperature that they operate in (Meijer et al., 1991). As a result, the ability to operate in extreme heat, solar radiation and cold conditions is an important consideration for accuracy of locomotion tracking. Other factors such as electromagnetic and mechanical disturbance are often associated with outdoor use and can also affect inertial sensing devices (Meijer et al., 1991). GPS tracking devices can be limited when the line of sight between the GPS receiver and the satellite transmitter is obstructed. This is particularly prevalent in very cloudy conditions or when a stadium grandstand and roof structure obstructs the transmission of signals between the GPS transmitter and receiver. Consequently, GPS technology does not work in indoor stadiums, limiting its application to monitoring professional soccer players in international soccer matches. In addition, sensors need to be waterproof to prevent the contamination of the electronics by moisture from rain, snow or high humidity levels.

The ballistic movements performed by players during match play, including sprinting, jumping, kicking and colliding are ballistic and pose high loads on those tracking devices that are physically placed on the soccer player. As a result, the tracking system needs to be shock proof and able to withstand impact without physical damage to the unit and its components.

In summary, the environmental conditions during soccer match play can play a large role in the effectiveness and accuracy of the locomotion tracking device and should be factored into the design of any new tracking device for measuring the locomotion of soccer players. The varying environmental conditions that international soccer matches are played in renders most current tracking technologies as ineffective for measuring locomotion during soccer match play.
3.3.4 Miniature, Light weight and uninvasive

An increase in residual mass placed on the body increases the energy demand and intensity of exercise to overcome the body’s inertia, particularly in the acceleration phases of exercise (Olds et al., 1993; Norton & Olds, 1996). For example, additional body mass will cause a normal male athlete to expend 4 kJ for each extra kg for every km travelled (Norton & Olds, 1996). For this reason, a locomotion tracking system of substantial weight will cause additional energy expenditure and potentially cause premature fatigue during match play. It is therefore preferential that the tracking system is of minimal size and mass (ideally less than 50 g) if placed on the body. Interestingly, Terrier et al. (2000) investigated the effects of a differential GPS tracking device on the intra-gait variation and found no additional effects when the device weighing 4 kg was placed on the back of the player. Vertical lift of the trunk values were, however, slightly higher than previous studies, indicating that the placement of the backpack containing the GPS device may not have been fixed perfectly to the back. While this systematic error does not challenge the use of GPS, the additional energy expenditure of carrying an extra 4 kg over a 90 minute period during a soccer match, however, would be increased by approximately 192 kJ, highlighting the need for miniaturisation of such devices. If a tracking system was to be placed on the extremities of a soccer player to detect stride length and frequency, for example, then the size and mass of the tracking device should be considerably less than this in order to not affect normal running gait more than the normal variation observed in running and walking.

In addition to the physiological and biomechanical impact of a tracking system being placed on the body of a soccer player, the psychological impact of wearing the device on the player should also be considered. Slight movement of the tracking system during periods of high acceleration or deceleration could cause distraction and upset the concentration of the player
During match play. For this reason, the unit should be miniature enough to a point where it is virtually undetectable by the player when worn, particularly if it is placed on the body’s extremities. In addition, it should be placed in a position on the body that allows for snug attachment of the unit to minimise the movement of the unit. While commercial GPS systems have been miniaturised down to fit inside a wrist watch, the majority of GPS systems used in recent investigations into the tracking of football players have been somewhat large and have to be strapped onto the back of the player using straps that go under the arms (Edgecomb & Norton, 2006; Wisbey & Montgomery, 2006), which may cause additional distraction.

In summary, a smaller and lighter tracking or locomotion measurement device for measuring the movements made by soccer players during a match, is less likely to cause additional energy expenditure, impede normal running mechanics and distract the player.

3.3.5 Simultaneous data storage and transmission

Table 3L1 summarised the commercially available equipment for evaluating the biomechanics of human locomotion during sporting performance. In particular, this table outlines the conventional and high-precision GPS tracking equipment available to store positional data for later download onto a computer for analysis. In addition, Tables 3-1 and 3-2 include technologies that have used accelerometer-based technology to measure body movements and human gait. Investigators have used data loggers attached to various inertial sensing hardware in order to store positional data. Data was then downloaded onto a computer for analysis.

Investigations into the locomotion demands of soccer players during match play were summarised in Tables 1-1 and 1-2 and have generally used manual and time consuming methods after the completion of the match to determine the locomotion characteristics of
players during match play. To date, no system has been developed to simultaneously store and transmit positional data for real time analysis of movement by soccer players during a game. Analysis of physical performance during match play in real time permits potential tactical intervention by coaches to improve performance. For example, a player may be either substituted, receive coaching instruction, change tactical roles or playing position on the field if the physical performance is not meeting a particular standard. For this reason, it is optimal that locomotion tracking systems store data on board and transmit positional and movement data for immediate analysis during match play.

Common telemetry systems used by researchers to monitor physiological variables such as heart rate (Van Gool et al., 1983; Ali & Farrally, 1991; Bedini et al., 1996; Creagh et al., 1998; Eston et al., 1998), body core temperature (Fuller et al., 1999) and oxygen consumption (Kawakami et al., 1992) have been used to relay real time information to investigators for immediate analysis and evaluation. The problem with the majority of these telemetry systems was that the data was transmitted through short-range telemetry which can often be out of receiver range or be interrupted by electrical interference. Consequently, there is a need for a new locomotion tracking system that can simultaneously store the data locally on the soccer player for the complete duration of the match and simultaneously transmit data to a remote location when in range of a receiver, resulting in no loss of data if the telemetry signal is interrupted. This is necessary in case a player runs out of telemetry range and the tracking system can continue to measure and transmit the positional data once the player runs back into range of the telemetry receiver.

In summary, there is a need for a locomotion measurement device that has a high capacity to store positional data for extended periods and simultaneously transmit the data in real time via short-range telemetry to a remote receiver for immediate analysis during soccer match play.
3.3.6 Calibration and error correction

It is important that any field-based locomotion tracking device can be calibrated back to first principals so that data error ranges can be reported. This is especially important in the interpretation of player performance to determine if improvements are significant.

Sensors such as accelerometers are very suitable for the measurement of human locomotion due to their size, sensitivity, portability and data collection and processing capacity. However, as previously mentioned, a problem with accelerometers is that they can suffer from fluctuating offset. This can be due to change in ambient temperature which the sensor is operating in or small changes in the mechanical structure of the sensor. Methods of calibration and sensor correction have been proposed ranging from testing the sensor on motorised vibrating tables made specifically for calibration of accelerometers (Powell et al., 2003) through to practical implicit methods (Lötters et al., 1998b).

Investigations using accelerometer-based locomotion tracking systems have described various types of calibration or validation methods for optimal implementation (Bouten et al., 1997; Freedson et al., 1998; Lötters et al., 1998b; Nichols et al., 1999; Foerster & Fahrenberg, 2000; Welk et al., 2000; Welk et al., 2003; Luinge & Veltink, 2004; Freedson et al., 2005; Matthew, 2005; Strath et al., 2005; Ward et al., 2005; Welk, 2005). More specifically, Lötters et al. (1998b) proposed a practical and implicit calibration method when using accelerometers to track daily activity. This method successfully reduced the fluctuating offset of the accelerometer due to either temperature change or mechanical wear in the accelerometer mechanism. A high pass filter was used to determine quasistatic periods, in which the subject was standing almost still. Once the accelerometer output was measured for several periods in several orientations, the offset and gain could be estimated. In general, most accelerometers
are reliable, with studies reporting a coefficient of variability (CV) of approximately 3% for
most accelerometer models used to detect general human activity levels (Chen & Bassett,
2005; Welk, 2005). After calibration, correction factors must be applied to data collected to
reduce the sensor error (Welk, 2005). To date, limited research has been conducted to
compare the reliability of different accelerometer-based locomotion measurement systems
(Welk et al., 2004). Further investigation has been recommended in this area to compare
different makes and models of accelerometers (Ward et al., 2005).

Similarly, investigations of other field measurement devices that use combinations of inertial-
based measurement components (Miyazaki, 1997; Kemp et al., 1998; Mayagoitia et al., 2002)
or GPS devices (Wubbena et al., 1997; Menge et al., 1998; Mader, 2000) have described a
range of different calibration methods to reduce and correct for sensor drift. In addition,
methods for calibration of magnetic sensors have been previously used to adjust the magnetic
sensors to the location specific characteristics of the earth’s magnetic field (Sinav, 2002).

In summary, simple and cost-effective calibration methods also need to be incorporated into a
new player movement tracking system to allow for convenient evaluation of equipment,
accurate data collection and better interpretation of locomotion data over time.

3.3.7 Placement of the sensor

Motion tracking devices have been placed on various locations on the body during the
analysis of human activity. To date, the majority of commercial GPS units have been
designed to be worn in the middle of the back using a shoulder strap system (Morrissey, 2005;
Badel, 2006; Edgecomb & Norton, 2006; Wisbey & Montgomery, 2006). In addition, some
GPS units can now operate in a wrist watch (Forerunner 305, Garmin, USA). Furthermore,
pedometer systems for estimating running distances (Polar RS400, Polar Electro, Finland;
Nike Foot Pod, Nike, USA) are generally laced onto the running shoe to evaluate running strides. Accelerometer-based systems for measuring human activity have been placed on the hip and back (Bouten et al., 1997; Hendelman et al., 2000; Nichols et al., 2000; Swartz et al., 2000; Brage et al., 2003; Rodriguez et al., 2005). Limitations in the recording range of inertial hardware technology used in experiments on the analysis of daily activity have led to sensor placement issues. Hip mounted accelerometers, for example, have been unable to capture certain high static categories of activity or complex movement patterns that combine dynamic and static movements (Matthew, 2005). Trost et al. (2005) advised that the placement of inertial sensors on the wrist or ankle should be avoided during the monitoring of daily locomotion and activity. However, this recommendation prevents the evaluation of stride rate, length and frequency data and limits the direct measurement of locomotion. This suggestion was possibly related to compliance of subjects rather than the measurement of locomotion. Sensor placement issues were also investigated by Yngve et al. (2003), who found the placement and settings of the MTI accelerometer (Manufacturing Technology Inc., USA) to affect the output of the device and resultant measurement of activity during laboratory and field assessment of activity. One possible solution to this problem is the placement of multiple sensors on the body. However, Trost et al. (2005) suggested that the burden from wearing multiple sensors on the body may limit the application of motion sensors. This could potentially be an issue during elite soccer match play, where the tracking device should be uninvasive and virtually undetectable to the player during match play.

If a new locomotion tracking system were to be worn on or near the foot, a new level of understanding of the running gait and factors affecting it will be determined. There are a number of underlying determinants of running gait that can be measured. The underlying factors determining step rate and step length have been illustrated in Figure 3-5. By
measuring these factors, why a soccer player is faster, more agile and has better running gait characteristics than other players, for example, can be determined.

Figure 3-5. Determinants of step rate and step length during locomotion. Adapted from Hay (1994)

Several investigations have conducted gait analysis during activity by attaching large accelerometer-based sensors to either the foot (Willemsen et al., 1990a; McCulloch et al., 1993; Wu & Ladin, 1996; Mayagoitia et al., 2002) or tibia (Lafortune, 1991). The collection of information during a soccer match, including locomotion and several soccer specific skills, such as kicking, dribbling, trapping and passing the ball, would be highly beneficial for not only tracking the locomotion on the playing field, but evaluating the effectiveness of soccer
specific activities during match play. As a result, it is recommended that a locomotion tracking system should be able to track the location and movement parameters as well as perform a real time 3D motion analysis of running gait and technical skills during a match. However, the device should not obstruct the action of kicking and should not contact the ball. In summary, the placement of the sensor is an important consideration for a tracking device to thoroughly evaluate locomotion and physical performance during match play. If the sensor is unobtrusively placed on the foot or even built into a shoe, the gait and sport specific actions could also be measured and evaluated during match play.

3.3.8 Requirements of elite soccer coaches

In order to complete a comprehensive requirements analysis from multiple perspectives, a select group of successful Australian professional soccer coaches \((n=3)\) were asked to complete a questionnaire designed to identify their requirements for analysis of the on-field physical performance during soccer match play. Individual responses can be found in Appendix 5: Elite Coach Questionnaire Results in this thesis. Coaches were from elite youth and elite senior professional division one clubs. All coaches were of level 3 standard under the Australian National Coaching Accreditation Scheme. One professional coach had a current UEFA coach licence, the highest internationally recognised accreditation for professional soccer coaches. In addition to having excellent professional coaching qualifications, the inclusion criterion for involvement in this questionnaire was a minimum of 12 months of experience in measuring and interpreting data collected on the on-field locomotion of soccer players during match play using commercially available technology. To the best of our knowledge at the time of data collection, the coaches surveyed were the only coaches regularly using player tracking systems in professional soccer in Australia. Prior to conducting this study, an informed consent form was signed by participants. Ethics approval was also granted to conduct this questionnaire.
Coaches were asked how important various physical characteristics of soccer players were for successful physical performance during a match. While all physical characteristics in the questionnaire were rated at least highly important by all coaches, characteristics such as anaerobic power, speed and speed-endurance were rated as most critical for successful performance. This indicates that some inherent physiological capacities are more important than others and are likely to be taken into account by current elite coaches when evaluating the on-field physical performance of players.

Coaches were also asked what affect the playing environment, including the player position, environmental conditions and tactics, has on the physical performance of professional level soccer players during a match. All coaches agreed that player position should be considered when analysing the physical performance of players. From their observations and experiences, coaches referred to their observations that some positions such as midfielders covered more distance and do more physical work than other players, indicating that this variable has an impact on the expected physical performance of players during a match. One coach indicated that player position and activity level is also closely related to team strategy since a midfield can have a number of tactical roles during a match. For example, one coach referred to different styles of play, including either defending from the front of the field or back off and allow the opposition time and space to pass the ball, each situation resulting in different physical work rates and required effort. Competition level was also generally agreed amongst the coaches to have an impact on the physical performance, since matches at lower levels often exhibit different levels of stress, tactical demand and skill standard. Coaches also commented that elite performers were more affected by the playing environment than lower grade competitors. In addition, there was agreement that the different environmental conditions, such as heat, humidity and altitude, affect the work rate of players during a match.
Coaches referred to the pitch condition as an important factor in successful execution of fine motor skills. To date, no researchers have investigated the effect of different playing surfaces on the work rate and activity patterns of players during a match.

Each coach was asked if they had used player tracking technology to measure the on-field activity of their players during match play. All coaches had used GPS tracking systems for at least 12 months. Interestingly, a number of professional coaches were approached to participate in this questionnaire. However, very few elite professional soccer coaches were using player locomotion tracking technology, resulting in a low number of eligible participants for this questionnaire. Coaches were using the GPS technology to record player movement patterns, speeds and distances travelled during a match. Interestingly, one coach responded that the distances of sprints and time between sprints were more important than the total distance travelled during a match. Due to the sample rate of the commercially available GPS systems, this technology is, therefore, inadequate for accurately measuring time between sprints.

Coaches were asked to report on the limitations of the player tracking technology, which in all cases were GPS tracking devices. While battery life, robustness and data storage capacity of the devices that they used were not generally a limitation, coaches reported a number of other deficiencies of the GPS devices that they were using. The size, invasiveness and location on the body were all reported to be significant limitations of these technologies in their current form. In addition, the cost, telemetry capacity to receive real time data and the accuracy and reliability of the units were also reported by the coaches to be a limitation.

In summary, elite professional coaches agreed that the consideration of the physical characteristics is an important component of analysing physical performance. Consideration
of the performance environment is also important when evaluating the work rate and locomotion patterns of players during a match. Indeed, while some elite coaches were successfully quantifying locomotion of players during matches in order to evaluate the quality and quantity of physical performance, the technology that they were using was limited and not suitable for comprehensively quantifying all sport specific on-field activities.

3.4 Selection of Technology Type for Solving Player Movements

The purpose of this section is to identify the most appropriate technology for solving all types of movement in the system illustrated in Figure 3-1. This evaluation process has eliminated redundant technologies and identified system requirements and capabilities and a course of action to develop hardware technology to comprehensively measure the movements of soccer players during match play.

Table 3-9 lists the results of an evaluation matrix that contrasts and compares the existing movement analysis technologies, their ability to meet the prioritised design properties and their overall suitability score for measuring player locomotion and movements. Section 3.3 of this thesis identified the performance requirements or properties of a new locomotion analysis system that would comprehensively measure all movements made by a player during a match. These performance requirements included a high sample rate, accurate sensors, high memory capacity, miniature size, ability to work in any environment, light weight, can attach to the foot or leg, is uninvasive, robust and portable (without cables), has a high battery life and can detect player orientation. A subjective weighting factor was applied to each of these properties, primarily based on the technical requirements for a system for solving the high speed, ballistic movements of a player during a match. Each of the possible technology types were then scored out of ten for each property, which was then multiplied by a weighting factor and totalled. This process gave each type of technology a score for total suitability for
incorporation as a new solution for tracking and measuring all types of movements listed in Figure 3-1 and later incorporation into the SPA analysis system.

The results in Table 3-9 show that the development of a new miniature magnetic and inertial navigation system is the most suitable solution for comprehensively measuring the motion of soccer players. In theory, a magnetic and inertial navigation system that meets all of the design requirements had the highest total suitability score and would therefore be the most suitable technology option for tracking player motion during a match. It scored very highly in the top priority technical properties such as sample rate, high accuracy, memory capacity and the ability to work in any environment. The accelerometer and gyroscope technologies also scored highly due to their high sample rate capability, while the camera, GPS and DGPS technologies were ruled out as a possible solution primarily due to their inability to sample at greater than 100 Hz and their inability to work in any environment, such as indoor stadiums and remote venues. In addition, the magnetic and inertial navigation system also scored highly in its size and univiasiveness, ability to attach uninvasively to the players ankle or limb and its potential robustness. The magnetic and inertial navigation system scored well for its ability to detect the orientation of the player or limbs during a match.

In summary, based on the requirements analysis of this chapter and the evaluation matrix in Table 3-9, the development of a new miniature magnetic and inertial navigation motion tracking system is theoretically the most viable solution for solving the physical performance of soccer players, including basic movements, brief ballistic efforts, sport specific actions and gait analysis during a match. However, the capability and suitability of this technology for tracking human motion and the difficult to measure movements: gait and sport specific actions needs to be proven. To date, there is no system commercially available that meets all the design requirements identified for successful operation in the soccer match environment.
Table 3-9. Suitability of the tracking technologies to meet the prioritised design properties.

<table>
<thead>
<tr>
<th>Prioritised Design Property</th>
<th>Weighting Factor</th>
<th>Camera-based system</th>
<th>GPS</th>
<th>DGPS</th>
<th>Accelerometer</th>
<th>Accelerometer + Gyroscope</th>
<th>Magnetic and Inertial Navigation System*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Score</td>
<td>Weighted Score</td>
<td>Score</td>
<td>Weighted Score</td>
<td>Score</td>
<td>Weighted Score</td>
<td>Score</td>
</tr>
<tr>
<td>Detects displacement,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>orientation of limbs &amp; gait</td>
<td>15%</td>
<td>5.0</td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sample rate &gt;100 Hz</td>
<td>13%</td>
<td>2.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.1</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>High precision/reliability</td>
<td>12%</td>
<td>5.0</td>
<td>0.6</td>
<td>5.0</td>
<td>0.6</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Small size &amp; mass/uninvasive</td>
<td>12%</td>
<td>10.0</td>
<td>1.2</td>
<td>2.0</td>
<td>0.2</td>
<td>2.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Remote, portable, wireless</td>
<td>12%</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>8.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Works in any environment</td>
<td>10%</td>
<td>5.0</td>
<td>0.5</td>
<td>5.0</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Attach to ankle &amp; limbs</td>
<td>8%</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Robust</td>
<td>6%</td>
<td>10.0</td>
<td>0.6</td>
<td>8.0</td>
<td>0.5</td>
<td>8.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Memory capacity</td>
<td>6%</td>
<td>3.0</td>
<td>0.2</td>
<td>4.0</td>
<td>0.2</td>
<td>6.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Battery Life</td>
<td>6%</td>
<td>10.0</td>
<td>0.6</td>
<td>5.0</td>
<td>0.3</td>
<td>5.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Total Suitability Score 100% 4.7 2.0 2.2 7.4 7.4 9.0

*Theoretical, since no portable, remote and miniature magnetic and inertial navigation system exist
CHAPTER 4

Experimental Results

Publication from this Chapter:


(A keynote presentation was given on the development of the MAIN sensor prototype and the sensor precision experiment in this chapter)
4.1 Research Questions

In theory, Table 3-9 demonstrated that magnetic and inertial navigation motion tracking technology was the most suitable solution for measuring the movements of soccer players. Advances in the field of inertial sensors have made it possible for acceleration and magnetic devices to conduct limited measures of human gait and movements of body parts in a laboratory setting. Previous experiments by Frey III (1996), Foxlin (1988), Kemp et al. (1998), Bachmann et al. (2001), Roetenberg et al. (2005) and Pfau et al. (2005) have employed somewhat invasive sensor systems that included various combinations of accelerometers, gyroscopes and magnetometers to detect motion at particularly high sample rates. However, questions still remain about the validity and reliability of magnetic and inertial motion tracking technology; its ability to detect ballistic and subtle sports specific actions; and its ability to be modified to meet the design requirements for elite sport so that it can operate in a professional soccer match environment.

Therefore, the following research questions were developed:

1. Can a magnetic and inertial navigation motion tracking system perform valid measures of soccer specific movements compared to a criterion measure?
2. Can a magnetic and inertial navigation motion tracking system perform valid measures of gait compared to a criterion measure?
3. Can a method be developed to identify sports specific actions performed by a soccer player from magnetic and inertial navigation motion tracking system data?
4. Can a new uninvasive, light weight and miniature magnetic and inertial navigation (MAIN) motion tracking system be developed to meet more of the previously identified design requirements, compared to commercially available systems? Does the miniaturisation affect the precision of the new magnetic and inertial navigation motion tracking system?
4.2 The measurement of soccer specific movements

The purpose of this study was to ascertain the validity of the three-dimensional displacement data obtained from a magnetic and inertial navigation motion tracking system, Shadowbox™ (Shadowbox, Park City, USA), using displacement data derived from a three-dimensional motion capture system, Vicon MX™ (Vicon Motion Systems Ltd, Oxford, UK), as a criterion measure. The Shadowbox™ is a commercially available system and was used in this experiment for initial proof of concept. It is important to note that this magnetic and inertial motion tracking system was not miniature and could not be used as a final solution for motion tracking due to its size and mass. However, it did have highly functional inertial and magnetic sensor components (a triaxial accelerometer, gyroscope and magnetometer). One male subject (n=1) performed a series of soccer specific actions including: a kick (drive) of a ball, one-touch pass of a ball and a slide tackle with a magnetic and inertial navigation motion tracking system secured to his right ankle to obtain three-dimensional displacement data for each of these actions. Corresponding criterion three-dimensional data was simultaneously obtained from the Vicon MX™ system during these actions. The Vicon MX™ system has previously been used by researchers as a criterion measure for three-dimensional motion tracking (Glazier and Irwin, 2001).

4.2.1 Methods

One healthy male competitive soccer player (age = 26 yrs; mass = 78 kg; stature = 181 cm) volunteered and consented to act as a subject in this study. A full explanation of the purpose of the study and experimental procedures were provided before testing commenced. The subject's task was to perform a kick (drive) of a ball, one-touch pass of a ball and a slide tackle while his motion was tracked at the same time by the Shadowbox™ and Vicon MX™ motion analysis systems.
4.2.2 Data Collection

The magnetic and inertial navigation system, Shadowbox™ (dimensions: 9 x 6 x 2 cm, mass: 132 g), was securely attached to the right ankle of the subject using adhesive tape (Figure 4-1). The Shadowbox™ was turned on immediately prior to performing each of the soccer specific actions. Data was collected at a sample rate of 600 Hz. In addition, 27 reflective markers were placed on the subject using the Vicon plug-in-gait method (Riley et al., 2007). The marker configuration on the body is illustrated in Appendix 6. A camera-based Vicon MX™ motion analysis system was placed around the data collection space (~7m x 4m). The experimental setup and data collection space is pictured in Figure 4-2. The Vicon MX™ system included 6 x MX-T20 cameras (2.0 megapixel resolution/500 frames per second) and 4 x MX-T40 cameras (4.0 megapixel resolution/370 frames per second). The cameras also included 10 near infrared high power surface strobes for detecting the reflective markers placed on the body. Importantly, a reflective marker was placed on the Shadowbox™ to track its actual location in the data collection space and evaluate its ability to estimate the three-dimensional displacement during each of the actions. Prior to the experiment, the Vicon MX™ system was calibrated using a calibration wand. Testing was conducted indoors, since the Vicon MX™ system operates best in low light conditions.

Figure 4-1. Attachment of the Shadowbox™ magnetic and inertial motion sensor to the ankle
(1) The Shadowbox™ magnetic and inertial motion sensor.
(2) Attachment of the Shadowbox™ magnetic and inertial motion sensor to the right ankle and placement of the reflective marker.
Figure 4-2. Experimental setup of Vicon MX™ motion capture cameras around the testing area. Camera placements are numbered 1-10. Cameras 5-7 are situated outside the photograph. Each of these cameras make up the motion capture testing area.

4.2.3 Data Processing

Immediately after each action, data from the Shadowbox™ was downloaded via USB connecting cable to a PC using the RideTracker™ software version 1.7 (Shadowbox, Park City, USA). Data was then exported into secondary proprietary analysis software (Shadowbox, Park City, USA). This software used the methods of Bachmann et al. (2001), a quaternion based orientation filter, to get a representation of the three-dimensional displacement of the Shadowbox™ on the ankle during each action.

Data from the Vicon MX™ for each marker was processed using the Vicon Nexus™ software version 1.4.116 (Vicon Motion Systems, Oxford, UK). The displacement of the ankle for both the Shadowbox™ and the Vicon MX™ were graphed and compared using Matlab (version 7.10) and Originlab (version 8.1) software respectively.

4.2.4 Data Analysis

A Pearson correlation coefficient (R) \( R = \frac{\text{covariance}_{XY}}{\text{stddev}_X \cdot \text{stddev}_Y} \) and the variance explained \( R^2 \) was calculated to determine the strength of the relationship between the
magnetic and inertial navigation motion analysis system, Shadowbox™, and the criterion method, the Vicon system MX™, for each action.

4.2.5. Results

Figures 4-3, 4-5 and 4-7 illustrate the comparative three-dimensional displacement data for the Shadowbox™ and the Vicon MX™ data for the kick (drive) of a ball, one touch pass of a ball and a slide tackle, respectively. Stick figure diagrams generated by the Vicon MX™ system show the whole body biomechanics. Three-dimensional graphs of the displacement of the right ankle were also compared for both motion tracking systems. Figures 4-4, 4-6 and 4-8 show the relationship between the two motion analysis systems for each of the sport specific actions. Appendix 7 illustrates the pitch, roll and heading data for each of the actions.

![Ankle trajectory of the kick (drive) of a ball: Vicon MX™ versus Shadowbox™.](image)

**Figure 4-3.** Ankle trajectory of the kick (drive) of a ball: Vicon MX™ versus Shadowbox™.
(1) Whole body kinematics of the kick (drive) of the ball (using Vicon MX™ data). (2) Ankle trajectory of the kick (drive) (using Vicon MX™ data). (3) Ankle trajectory of the kick drive (using Shadowbox™ data)
Figure 4-4. The correlation of the ankle displacement data during a kick (drive): Vicon MX™ versus Shadowbox™.

\[y = 1.0875x - 0.0008\]
\[R^2 = 0.9323\]

Figure 4-5. Ankle trajectory of the one-touch pass of the ball: Vicon MX™ versus Shadowbox™.
(1) Whole body kinematics of the one-touch pass of the ball (using Vicon MX™ data). (2) Ankle trajectory of the one-touch pass of a ball (using Vicon MX™ data). (3) Ankle trajectory of the one-touch pass of a ball (using Shadowbox™ data).
Figure 4-6. Correlation of the ankle displacement data during a one-touch pass: Vicon MX™ versus Shadowbox™.

(1) Vicon MX™

(2) Vicon MX™

(3) Shadowbox™

Figure 4-7. Ankle trajectory of the Slide Tackle: Vicon MX™ versus Shadowbox™.
(1) Whole body kinematics of the slide tackle (using Vicon MX™ data).  (2) Ankle trajectory of the slide tackle (using Vicon MX™ data).  (3) Ankle trajectory of the slide tackle (using Shadowbox™ data)
Table 4-1 summarises the coefficient of variation and Pearson correlation between the Shadowbox™ and Vicon MX™ systems for each of the actions. These data indicate that the Shadowbox™ magnetic and inertial navigation motion tracking system had a very strong relationship with the criterion method when measuring sports specific actions. The magnetic and inertial navigation tracking system, therefore, has very high validity against a criterion method when measuring short term, ballistic, sports specific actions.

Table 4-1. Validity of the Shadowbox™ for detecting ankle displacement during soccer specific movements. Coefficient Pearson Correlations were calculated using the methods of Hopkins (2000).

<table>
<thead>
<tr>
<th>Action</th>
<th>Pearson Correlation (R)</th>
<th>Variance Explained (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kick (drive) of ball</td>
<td>0.97</td>
<td>0.93</td>
</tr>
<tr>
<td>One-touch pass of ball</td>
<td>0.96</td>
<td>0.92</td>
</tr>
<tr>
<td>Slide Tackle</td>
<td>0.97</td>
<td>0.95</td>
</tr>
</tbody>
</table>
4.3 The measurement of gait

The purpose of the second study was to determine the validity of three dimensional data obtained from the Shadowbox™ magnetic and inertial navigation motion tracking system during walking and running gait using an Optojump™ gait assessment system (Microgate, Bolzano, Italy) as a criterion. One male subject (n=1) walked and ran along an indoor athletic track with a Shadowbox™ attached to the right ankle to obtain three dimensional displacement for both walking and running. Gait analysis data was obtained from the Optojump™ system that was placed on each side of the running lanes. The Optojump™ has been previously shown to have excellent accuracy and validity (Lehance et al., 2005) for measuring gait and was therefore selected as the criterion method.

4.3.1 Methods

One healthy male competitive soccer player (age = 26 yrs; mass = 78 kg; stature = 181 cm) volunteered to act as a subject. As in the previous experiment, informed consent was obtained and all test procedures were explained. The subject walked and ran through the testing area while his gait was tracked by the Shadowbox™ and Optojump™.

4.3.2 Data Collection

The Shadowbox™ system was attached to the ankle according to the methods illustrated in Figure 4-1.

The Optojump™ consisted of a transmitter strip and receiver strip. Each strip was 9 m (9 x 1m segments) in length. The strips were placed in parallel on either side of the sprint lane (Figure 4-9). Each 1 m segment contained 100 light emitting diodes (LED's) which were positioned 3 mm from the ground level at 10 mm intervals.
4.3.3 Data Processing

Data from the Shadowbox™ was downloaded and processed according to the methods described in section 4.2.3. From the three-dimensional displacement data, stride length for the right foot was calculated using the change in distance between each heel strike.

Data from the Optojump™ on stride length for walking and running was determined using the Optojump Next™ Software (version 1.0.7.9). The data for stride length estimates for the Shadowbox™ and Optojump™ were compared.

4.3.4 Data Analysis

The typical error of the estimate (Hopkins, 2000) in raw units (mm) and as a coefficient of variation (%CV) were determined for each trial. A Pearson correlation (R) and the variance explained ($R^2$) was calculated to determine the strength of the relationship between the two sets of data.
4.3.5 Results

Figure 4-10 illustrates (i) the displacement, in metres, of the ankle in the x, y and z axis during straight line walking and the (ii) roll, pitch and heading angles during walking using the Shadowbox™ motion tracking system. The change in y axis displacement was used to estimate stride length for each trial.

![Figure 4-10. Displacement and roll, pitch, heading of the ankle during straight line walking using the Shadowbox™ magnetic and inertial motion tracking system. Plots of 3D displacement (i) and roll, pitch, heading (ii) are generated using MATLAB (version 7.10).]
Figure 4-11 also illustrates (i) the displacement, in metres, of the ankle in the x, y and z axis during straight line running and the (ii) roll, pitch and heading angles during running using the Shadowbox™ motion tracking system. Similar to the walking experiment, the change in y axis displacement was used to estimate stride length for each trial.

![Diagram of displacement and roll, pitch, heading of the ankle during straight line running using the Shadowbox™ magnetic and inertial motion tracking system. Plots of 3D displacement (i) and roll, pitch, heading (ii) are generated using MATLAB (version 7.10).](image)
Table 4-2 lists the stride lengths and the statistical analysis for walking and running for the Shadowbox™ and the Optojump™. The typical error between the measurement systems for walking was significantly better than for running, 0.49 cm and 9.6 cm respectively between steps. The relative typical error for walking and running was 0.3% and 6.6% respectively.

Table 4-2. Validity of the Shadowbox™ for detecting walking and running gait. Typical error statistics were conducted using the methods of Hopkins (2000).

<table>
<thead>
<tr>
<th>Stride Length: Walking (cm)</th>
<th>Stride Length: Running (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shadowbox</td>
<td>Optojump</td>
</tr>
<tr>
<td>Step 1 (cm)</td>
<td>87</td>
</tr>
<tr>
<td>Step 2 (cm)</td>
<td>168</td>
</tr>
<tr>
<td>Step 3 (cm)</td>
<td>171</td>
</tr>
<tr>
<td>Step 4 (cm)</td>
<td>170</td>
</tr>
<tr>
<td>Step 5 (cm)</td>
<td>165</td>
</tr>
<tr>
<td>Typical Error (cm)</td>
<td>0.49 cm</td>
</tr>
<tr>
<td>Typical Error (%)</td>
<td>0.3%</td>
</tr>
<tr>
<td>Pearson Correlation (R)</td>
<td>1.00</td>
</tr>
<tr>
<td>Variance Explained (R²)</td>
<td>0.99</td>
</tr>
</tbody>
</table>

4.4 The recognition of sport specific actions from magnetic and inertial motion tracking system data

The magnetic and inertial tracking technology has been proven to precisely measure three dimensional displacement of the ankle during sport specific actions in the previous experiments. Movement data from soccer players during a match, however, is somewhat randomised and varied. This gives rise to a new question – can a method be developed to identify soccer specific actions from random movement data? In order to answer this question, two similar sport specific actions, the jump and the header, were selected and compared. A qualitative whole body biomechanical analysis was conducted to identify any subtle technique differences between the actions using the Vicon MX™ motion analysis system. An experimental trial was then conducted to derive quantitative data on multiple jumps and headers. A set of key performance indicators for the jump and header were
developed. The key performance indicators were then evaluated for their effectiveness at identifying a jump and header from a randomised, repeated jump and header movement trial.

4.4.1 Methods

One healthy male competitive soccer player (age = 34 yrs; mass = 84 kg; stature = 183 cm) volunteered to act as a subject in this study. As in previous experiments, the movement trial procedure was explained. The subject was asked to perform two trials. Trial 1 comprised of 3 random movements. Trial 2 was also three random movements. The selection of movements (header or jump) and order of movements in each trial was completely randomised.

4.4.2 Data Collection

The magnetic and inertial navigation system, Shadowbox™, was secured to the right ankle of the subject and operated using the methods of the previous studies. The subject performed a total of three jumps and three headers over two trials: Trial 1 - jump, jump and header; Trial 2 - header, jump and header. During the trials, the subject's ankle motion was tracked by the Shadowbox™ motion analysis system.

4.4.3 Data Processing

Immediately after the experimental trial, data from the Shadowbox™ was downloaded and processed into displacement data using the methods of the previous experiments.

4.4.4 Data Analysis

A series of key performance indicators for both actions were developed by conducting a qualitative and quantitative comparison by calculating the cumulative displacement and velocity during the jumps and headers. Jumping and header trajectories were overlaid to find
typical trajectories. From these trajectories, curve fitting equations for the typical trajectory of a jump and header were then developed.

4.4.5. Results

Using the Vicon MX™ motion analysis system, an initial full body qualitative biomechanical analysis was conducted of the jump versus the header. Results from this experiment are illustrated by the stick figure strobes in Figure 4-12.

Jump:

![Jump](image)

Header:

![Header](image)

**Figure 4-12.** Whole body kinematics during a jump versus a header using the Vicon MX™ motion tracking system

Table 4.3 summarises the qualitative and quantitative biomechanical key performance indicators of the jump versus the header. The header had significantly different biomechanics at the hip and ankle joints. Because of the contact with the ball during the header action, there was a resultant forward flexion of the hip and displacement of the ankle forward at the point of peak jump height. This hip flexion can be seen in the stick figure diagram in Figure 4-12.
Table 4-3. A kinesiological analysis of the jump versus heading the ball. The primary joints and their actions during the movement are listed.

<table>
<thead>
<tr>
<th></th>
<th>Phase 1: From toe off ground to peak jump height</th>
<th>Phase 2: From peak jump height to ground contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>Jump</td>
<td>Header</td>
</tr>
<tr>
<td>Shoulder Action</td>
<td>Abduction</td>
<td>Forward Flexion</td>
</tr>
<tr>
<td>Hip Action</td>
<td>No Flexion</td>
<td>Flexion</td>
</tr>
<tr>
<td>Knee Action</td>
<td>No Flexion</td>
<td>No Flexion</td>
</tr>
<tr>
<td>Ankle Action</td>
<td>Sign. Plantar Flexion</td>
<td>Plantar Flexion</td>
</tr>
</tbody>
</table>

Figure 4-13 illustrates the three dimensional displacement for the two jumping trials. In trial 1, the subject performed a jump, jump then header. In trial 2, the subject performed a header, jump then header. There are obvious trajectory differences between the jumping and header movements.

Figure 4-13. Three-dimensional displacement of the Jump versus Heading the ball using the Shadowbox™. Trial 1: subject performed jump, jump, header. Trial 2: subject performed header, jump, header.
Curve fitting equations for the average or typical 3D trajectory of the ankle during heading the ball (i) and jumping (ii) were subsequently developed. These can be used to detect jumps or headers from random movement data during a match. Obvious differences exist in the ankle trajectory for both actions.

**Equation (i):**  
**Heading the ball:**  
\[ Y = B_0 + B_1X + B_2X^2 \]

Where:
- \( B_0 = -1.010 \)
- \( B_1 = 203.5 \)
- \( B_2 = -7338 \)

**Equation (ii):**  
**Jumping:**  
\[ Y = B_0 + B_1X + B_2X^2 + B_3X^3 \]

Where:
- \( B_0 = -9.110 \)
- \( B_1 = 1472 \)
- \( B_2 = -75926 \)
- \( B_3 = 1.270 e+006 \)

Figure 4-14 shows the results of all jumps and headers overlaid on a single graph. Average two-dimensional trajectories in the y and z planes were plotted for both actions.
From the three-dimensional data in Figure 4-13 it was clear that virtually no movement occurred in the x plane and was subsequently removed from the analysis. There were clear differences between the ankle trajectories of the two actions. Data points for headers (in blue) were consistently outside the boundaries of the average jumping trajectory (in red). Importantly, the trajectory results were consistent despite performing the actions randomly over two trials. Applying curve fitting equations to random movement trajectories during a match did, in this case, clearly distinguish between jumping and header actions, since none of the randomly performed jump trajectories complied with the header trajectories and vice versa.

Figure 4-15 illustrates the cumulative displacement of jumping versus header movements collected by the Shadowbox™ during the random movement trial. Jumps were completed in random order to minimise the order effect bias on the data.

Figure 4-15. Cumulative displacement of the ankle during a jump versus a header action measured by the Shadowbox™ motion tracking system
Figure 4-16 also illustrates the differences in speed for the jump versus the header. For both figures, significantly different displacement and speed of movement can be seen for each action.

Figure 4-16. Speed of the ankle during a jump versus a header action measured by the Shadowbox™ motion tracking system

4.5 A New Magnetic and Inertial Navigation (MAIN) Sensor System

The purpose of developing a new magnetic and inertial navigation (MAIN) sensor system was to attempt to meet more of the previously identified design requirements compared to the commercially available Shadowbox™ system used in prior experiments. This study also aimed to determine if meeting additional design requirements, particularly reducing the invasiveness via miniaturisation of the sensor, compromised the precision of measurement. The MAIN sensor system was designed in collaboration with Mr Kendall Hook from Vector Elite Pty Ltd (Melbourne, Australia) to meet the identified design specifications in Chapters 2 and 3.

A prototype of the MAIN sensor system was custom built using miniature, low cost inertial and magnetic measuring components and is pictured in Figure 4-17.
The MAIN sensor system for detection of human locomotion. The primary sensing components include a triaxial accelerometer (ADXL210E, Analog Devices, USA), 3 triaxial rate gyroscopes (ADXRS300, Analog Devices, USA) and a triaxial magnetometer (HMC1023, Honeywell, USA).

The MAIN sensor system measured 30 x 50 x 15 mm and weighed 19 g. This is 80% smaller in size and 86% lighter than the Shadowbox™ system. The primary components were a
triaxial accelerometer (ADXL210E, Analog Devices, USA), a triaxial gyroscope (ADXRS300, Analog Devices, USA) and a triaxial magnetometer (HMC1023, Honeywell, USA). The MAIN sensor system also contained a microprocessor (MSP430, Texas instruments, USA), a temperature sensor to correct for temperature drift, an analogue to digital (AD) converter, 16 megabytes (MB) of on-board flash memory and a rechargeable lithium-ion battery. The unit also contained a USB port for programming, emulation and battery charging. The circuit board of the MAIN sensor system was manufactured by Precision Australia Pty Ltd, Melbourne, Australia. The schematic design of the MAIN sensor system is illustrated in Figure 4-18.

Table 4-4 summarises the physical characteristics and capabilities of the MAIN sensor.

<table>
<thead>
<tr>
<th>Table 4-4. Summary of the physical characteristics and capabilities of the MAIN sensor system for measuring human motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer dynamic range</td>
</tr>
<tr>
<td>Gyroscope dynamic range</td>
</tr>
<tr>
<td>Magnetometer dynamic range</td>
</tr>
<tr>
<td>Data sampling rate</td>
</tr>
<tr>
<td>Analogue to digital converter</td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>Dimensions</td>
</tr>
<tr>
<td>Software Operating Platform</td>
</tr>
<tr>
<td>Sensor Output:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Sample Rate:</td>
</tr>
<tr>
<td>Dynamic range:</td>
</tr>
<tr>
<td>Bytes/sample:</td>
</tr>
<tr>
<td>Memory capacity:</td>
</tr>
<tr>
<td>Battery Capacity:</td>
</tr>
<tr>
<td>Battery Type:</td>
</tr>
</tbody>
</table>

One male subject (age = 32 yrs; mass = 92 kg; stature = 185 cm) was recruited to perform two separate experiments: a 20 second walking trial; and a free rotational experiment. These
studies collectively examined the precision of the MAIN sensor system during gait and as a potential whole body biomechanical assessment tool.

4.5.2 Data Collection

The MAIN sensor system was securely attached to the right ankle of the subject using adhesive tape at the level of the lateral malleolus of the ankle, as in previous experiments in this chapter. Data was collected at 100 Hz. In the first trial, the subject was instructed to stand still and upon a "go" signal walked in a straight line at a brisk pace for 20 seconds. Prior to starting, the subject was instructed to stand still and upon a "go" signal walked in a straight line at a brisk pace for 20 seconds. Prior to starting, the subject was instructed to execute rhythmical and consistent steps in order to reduce the biomechanical variation between steps. In the second experiment, the subject held the MAIN sensor system in his hand, with his arm fully extended vertically, then swung the sensor in a clockwise, windmill-type motion for six rotations in one direction (phase 1), then flipped the sensor onto another axis for another three rotations (phase 2). Figure 4-19 illustrates the orientation of the MAIN sensor during the free rotational experiment.

![Figure 4-19: Direction and orientation of the MAIN sensor system during the free rotational experiment.](image-url)

Phase 1

Phase 2
4.5.4 Data Analysis

Descriptive statistics of the data collected during the 20 second walking trial for each of the sensors were calculated. A scattergraph of each step from each sensor was developed to examine the data for outliers or erroneous data. The typical error (TE) of measurement was also calculated according to the method of Hopkins (2000). The mean % TE for all sensors was also calculated. Synchronised data from each of the sensors was also examined to evaluate if the MAIN sensor was able to detect the events and phase of a typical gait cycle during walking. Data from the free rotational experiment was also analysed for its precision, sensor drift or any inherent unreliability, by examining the change in means from the data collected by each sensor. This was calculated by log transforming, then averaging the difference scores between each rotation (Hopkins, 2000).

4.5.5 Results

The descriptive statistics of the data collected by the MAIN sensor system during the 20 second walking trial are summarised in Table 4-5.

Table 4-5: Descriptive Statistics for the MAIN sensor system data during a 20 second walking trial.

<table>
<thead>
<tr>
<th></th>
<th>Accelerometer</th>
<th></th>
<th>Gyroscope</th>
<th></th>
<th>Magnetometer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X axis</td>
<td>Y axis</td>
<td>Z axis</td>
<td>X axis</td>
<td>Y axis</td>
<td>Z axis</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>30760</td>
<td>32443</td>
<td>29833</td>
<td>1912</td>
<td>1888</td>
<td>1791</td>
</tr>
<tr>
<td></td>
<td>33578</td>
<td>34317</td>
<td>31423</td>
<td>2025</td>
<td>2051</td>
<td>1964</td>
</tr>
<tr>
<td><strong>25% Percentile</strong></td>
<td>33714</td>
<td>34460</td>
<td>31535.5</td>
<td>2040</td>
<td>2070</td>
<td>2096</td>
</tr>
<tr>
<td></td>
<td>33880</td>
<td>34808.3</td>
<td>31718</td>
<td>2055</td>
<td>2091</td>
<td>2131</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>37091</td>
<td>39106</td>
<td>36055</td>
<td>2120</td>
<td>2286</td>
<td>2324</td>
</tr>
<tr>
<td><strong>75% Percentile</strong></td>
<td>33744.7</td>
<td>34654.3</td>
<td>31558.6</td>
<td>2037.5</td>
<td>2076.7</td>
<td>2061.7</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>33744.7</td>
<td>34654.3</td>
<td>31558.6</td>
<td>2037.5</td>
<td>2076.7</td>
<td>2061.7</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>33744.7</td>
<td>34654.3</td>
<td>31558.6</td>
<td>2037.5</td>
<td>2076.7</td>
<td>2061.7</td>
</tr>
<tr>
<td><strong>Std. Deviation</strong></td>
<td>675.4</td>
<td>758.2</td>
<td>424.1</td>
<td>27.5</td>
<td>51.2</td>
<td>117.3</td>
</tr>
<tr>
<td><strong>Std. Error</strong></td>
<td>15.1</td>
<td>17.0</td>
<td>9.5</td>
<td>0.6</td>
<td>1.1</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Lower 95% CI of mean</strong></td>
<td>33715.1</td>
<td>34621.0</td>
<td>31540.0</td>
<td>2036.3</td>
<td>2074.4</td>
<td>2056.5</td>
</tr>
<tr>
<td><strong>Upper 95% CI of mean</strong></td>
<td>33774.3</td>
<td>34687.5</td>
<td>31577.2</td>
<td>2038.8</td>
<td>2078.9</td>
<td>2066.8</td>
</tr>
</tbody>
</table>
Figure 4-20: Sensor output from the MAIN sensor system during 7 consecutive steps
Figure 4-20 is a series of scattergraphs of data from each of the sensors for each step. Data had good repeatability, with very little incidence of apparent erroneous data or outliers beyond the normal variation typically observed in human gait.

The relative (%) typical error for each of the sensors between the steps is summarised in Table 4-6. The mean % TE indicates the overall reliability of the data for each sensor.

Table 4-6: Reliability of the between steps data collected by the MAIN sensor system during 7 consecutive steps

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Typical Error of Measurement (%)</th>
<th>Lower Confidence Limit</th>
<th>Upper Confidence Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Step 2-1</td>
<td>Step 3-2</td>
<td>Step 4-3</td>
</tr>
<tr>
<td>Accelerometer X</td>
<td>1.1</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Accelerometer Y</td>
<td>1.2</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Accelerometer Z</td>
<td>0.9</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Gyroscope X</td>
<td>0.8</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Gyroscope Y</td>
<td>1.1</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Gyroscope Z</td>
<td>2.3</td>
<td>0.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Magnetometer X</td>
<td>0.8</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Magnetometer Y</td>
<td>1.5</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Magnetometer Z</td>
<td>0.9</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Note: Degrees of freedom = 436. Typical error of measurement is expressed as a percentage using a log transformation of variables to get the relative error using the methods of Hopkins (2000). Typical error included both the technological error of the MAIN sensor system and the variation in technique between the steps.

Figure 4-21: The reliability of between steps data collected by the MAIN sensor system during 7 consecutive steps. Data was calculated using a log transformation of variables to get relative error using the methods of Hopkins (2000). Typical error of measurement included both the technological error of the MAIN sensor system and the variation in technique between steps. Data is reported as mean ± sd.
The mean % TEM for all sensors ranged from 0.6 to 1.4% error. The grand mean TE for all sensors was 0.88%. Figure 4-21 is a graph of the mean % TE between steps for each sensor.

Figure 4-22 is a detailed illustration of all sensor data during a single step from the walking trial. The phases of walking, including toe-off, swing and heel contact has previously been described by Hayes et al (1983). These phases have been superimposed onto Figure 4-18, based on typical identifiable markers in the data from previously published research. For example, at the moment of contact between the lower leg and the ground is called "heel contact" and this typically causes a spike in the accelerometer data (Wu & Ladin, 1996). This is clearly visible during each step.

**Figure 4-22.** Synchronised data collected on a single step by the MAIN sensor system during the walking trial. Data was collected by a triaxial accelerometer, triaxial magnetometer and triaxial gyroscope. Phases of the step cycle have been previously described Hayes et al. (1983) and are superimposed onto the graph.
Data from the free rotational experiment was illustrated for each of the sensors in Figure 4-23. Data for each of the sensors appeared in a highly predictable way during the experiment.

![Graph showing data from the MAIN Sensor System during the free rotational experiment.](image)

**Figure 4-23:** Data collected by the MAIN Sensor System during the free rotational experiment

Data was subsequently evaluated for any sensor drift or error. The change in means was calculated for each rotation in phase 1 and phase 2 of the study. The percent change in means for each sensor is expressed as means ± standard deviation in Figure 4-24. The overall % change in means for all rotations indicated a high level of precision. Change in mean data
from the accelerometers, gyroscopes and magnetometers was -0.7%, -0.2% and 1.1% respectively during phase 1 and -1.5%, 0.9% and 0.5% respectively for phase 2 of the experiment.

Figure 4-24. Change in means for each sensor during the free rotational experiment. Data is expressed as % change in mean ± sd. Change in means were calculated by averaging the log transformed difference scores between each rotation. Data includes % changes in means for rotations in phase 1 and 2 of the experiment.

4.5.6 Evaluation of the requirements met by the MAIN sensor system

Table 4-7 indicates the extent to which the previous experiments in section 4.5 and the design features of the MAIN sensor system met the design requirements identified in the system requirements analysis.

Results showed that all of the operation requirements were either directly tested and achieved or theoretically met due to the technical specifications of the sensors. The MAIN sensor system, therefore, is the first system of its kind to meet all the identified design requirements, without significantly affecting the precision of the three dimensional movement data.
Table 4-7. Results of the MAIN sensor system’s performance against the requirements analysis. Design requirements are taken from table 3-9.

<table>
<thead>
<tr>
<th>Prioritised design requirements</th>
<th>MAIN Sensor System Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detects displacement, orientation of limbs &amp; gait</td>
<td>requirement met</td>
</tr>
<tr>
<td>Sample rate &gt; 100 Hz</td>
<td>requirement met</td>
</tr>
<tr>
<td>High precision/reliability</td>
<td>requirement met</td>
</tr>
<tr>
<td>Small size &amp; mass/uninvasive</td>
<td>requirement met</td>
</tr>
<tr>
<td>Remote, portable, wireless</td>
<td>requirement met</td>
</tr>
<tr>
<td>Works in any environment</td>
<td>requirement met</td>
</tr>
<tr>
<td>Attaches to the ankle &amp; limbs</td>
<td>requirement met</td>
</tr>
<tr>
<td>Robust</td>
<td>requirement met</td>
</tr>
<tr>
<td>Memory capacity¹</td>
<td>requirement theoretically met</td>
</tr>
<tr>
<td>Battery Life¹</td>
<td>requirement theoretically met</td>
</tr>
</tbody>
</table>

¹Despite the experimental trials lasting on 9-20 seconds, the technical specifications of the sensors indicate that this requirement has been theoretically met.

4.5.7 Risk Analysis of the MAIN Sensor System

Table 4-8 is a quantitative risk analysis conducted on the MAIN sensor system to identify any issues or risk associated with using the MAIN sensor system on soccer players.

Table 4-8. Risk Analysis of the MAIN Sensor System

<table>
<thead>
<tr>
<th>Information Asset</th>
<th>Threat</th>
<th>Vulnerability</th>
<th>Probability</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Operation</td>
<td>Operation in extreme temperature</td>
<td>Sensor error in extreme hot or cold temperatures. Need gyroscope capacity up to 500 deg/sec.</td>
<td>Medium</td>
<td>Significant – effort needed to develop methods to correct drift. Serious – resources needed to incorporate gyroscope of this capacity when available. Damaging – sensor failure.</td>
</tr>
<tr>
<td></td>
<td>Measurement of high speed sprinting</td>
<td></td>
<td>Very high</td>
<td></td>
</tr>
<tr>
<td>Sensor Operation</td>
<td>Operation in any magnetic environment</td>
<td>Magnetometer becomes saturated (&gt; 20 gauss). Loss of signal during match (out of range).</td>
<td>Very Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Real Time Data transmission</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Software Capability</td>
<td>Battery Life</td>
<td>Battery is exhausted</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distinguish different sport specific movements</td>
<td>No software to recognise movement patterns.</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Sensor Accuracy</td>
<td>Sensor Drift</td>
<td>Accelerometer drift during measurement over long time periods.</td>
<td>High</td>
<td>Significant – some expenditure needed to develop Sensor correction methods.</td>
</tr>
<tr>
<td>Sensor Calibration</td>
<td>Static calibration</td>
<td>Accuracy of static calibration methods.</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dynamic calibration</td>
<td>Currently no dynamic calibration rig.</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Sensor Placement</td>
<td>Placement of the sensor on the player’s body</td>
<td>Sensor may come into contact with the ball.</td>
<td>High</td>
<td>Significant – some expenditure to incorporate the prototype into the shoe or shin guard.</td>
</tr>
<tr>
<td>Multiple Sensor Operation</td>
<td>Fusion of multiple sensors</td>
<td>Wearing a number of sensors may be too invasive &amp; not allowed by FIFA. No software available to process data from multiple sensors (if needed)</td>
<td>Medium</td>
<td></td>
</tr>
</tbody>
</table>

Significant – some expenditure of resources required to develop analysis software.
While the MAIN sensor system was successfully tested and proven, there is still considerable research and development needed to make the sensor commercially robust for regular use by professional soccer teams. The sensor was tested in typical room temperature conditions during the experimental trials. Soccer matches are often played in very hot and cold conditions. The MAIN sensor system does, however, have a temperature sensor on board and could be corrected for known temperature drift rates, based on laboratory experiments in different temperatures over time. This would require some expenditure of resources to conduct the experiments and incorporate into the system's software. While the MAIN sensor currently operates with high precision in its prototype form, methods to recalibrate the position of the sensor can be both simple, by placing the sensor regularly in a known position during the match, or complex and expensive by introducing new methods in the sensor design to correct out drift. Inertial and magnetic sensors have effective static calibration methods. However, the development of a dynamic calibration rig to perhaps spin the sensor at known speeds would require some expenditure of resources on hardware and software.

A limitation of the MAIN sensor system in its prototype form is its capacity of the gyroscope hardware to operate at greater than 300 degrees.s⁻¹. Until the capacity of the sensors of this size are improved to operate up to 500 degrees.s⁻¹, the MAIN sensor will only be able to operate at running speeds up to 18 km.hr⁻¹. However, the rate of improvement in sensors since the beginning of this project in 2001 has been significant. It will not be long before a high capacity gyroscope of this size is available. This will require some resources to incorporate it into the design of the MAIN sensor. Soccer matches are often played outdoors, in environments of different strength magnetic fields. If the sensor is operated in a magnetic field about 20 gauss, it will exceed the magnetometer's capacity and fail. Similar to the gyroscope, the developments in sensor technology will also reduce the probability of this risk in the future.
During a match a player will typically run out of range from the radio receiver since the patch antenna incorporated into the MAIN sensor system cannot transmit over excessive distances greater than approximately 150 m. In addition, interruption to the transmission of data could occur if a player is on the ground, perhaps if the sensor facing into the ground or is being blocked by another player.

The development of a software system to recognize the sport specific movements of soccer would need significant resources and biomechanical research. Models for actions like kicking a ball, receiving, dribbling and passing a ball can be predicted due to typical alterations in gait prior to and during these actions.

Placement of the sensor in prototype form has been simple, by strapping it to the ankle. However, the sensor does need to be incorporated into the player's equipment to further reduce the invasiveness and minimise the chance of contact with the ball and interruption to skill execution. This would require significant investment to further flatten the sensor to build it into the boot or shin guard. This modification is not inconceivable and would significantly enhance the appeal to players to wear it and minimise the chance of the sensor being disallowed by FIFA, particularly if it is not visible. It is possible that coaches and sport scientists may want to attach a number of sensors and fuse the data to conduct whole body biomechanical analysis. Significant resources would be needed to develop software and to make the device more wearable on the player's body.

If the above risks are addressed, the MAIN sensor system can be a highly effective and commercially robust hardware unit for regular use by elite professional soccer teams.
CHAPTER 5

Discussion and Conclusions
5.1 Discussion

The major findings in this thesis were that the magnetic and inertial navigation motion tracking technology: (1) can perform valid measures of soccer specific movements, including one-touch pass of a ball, slide tackle, kicking (drive) a ball, jumping and heading a ball, (2) can perform valid measures of gait, including walking and running, (3) can discriminate kinematic differences between short-term, ballistic soccer specific actions including jumping and heading a ball, (4) can be modified to meet the unique design requirements for operation in the elite soccer match environment without compromising the sensor precision and (5) is the first viable solution of its kind suitable for measuring the physical performance of soccer players.

*Measuring sport specific actions*

The results for ankle displacement data correlations between the Vicon MX™ (criterion) and Shadowbox™ inertial and magnetic tracking system during a kick (drive) of a ball, one-touch pass of a ball and slide tackle were $R^2=0.93$, $R^2=0.92$ and $R^2=0.95$ respectively. This indicates the data collected by the magnetic and inertial navigation motion tracking system had very high validity and precision. While previous investigations by Frey III (1996), Foxlin (1988), Kemp et al. (1998), Bachmann et al. (2001), Roetenberg et al. (2005) and Pfau et al. (2005) have used various combinations of more invasive, laboratory-based magnetic and inertial sensors to track human motion, this is the first study to ever validate a portable magnetic and inertial navigation system that incorporates a triaxial accelerometer, gyroscope and magnetometer against a criterion motion tracking system. To the best of our knowledge, no other study has ever remotely measured the limb kinematics of a player during soccer specific movements in the field. Previous studies listed in Table 1-1 have focused on general movements and speed of the player moving around the field. The problem with the tracking
systems used by these investigators is they only measured player global position on the field. However, the players in these studies may have been performing sports specific actions like heading the ball, jumping or other stationary actions. This soccer specific movement data was undetectable to these global positioning and camera-based systems used to track player movements and was, therefore, not quantified and used in these performance analyses. Combining field position data with sport specific movements made by the player is a significantly more comprehensive collection of player physical workload during a match. To date, the combination of measuring player position on the field and sports specific actions has never been achieved. This study has proven the magnetic and inertial navigation tracking technology to have the capability to detect and quantify the kinematics of soccer specific actions and, therefore, is a valid solution to solve this problem.

**Measuring gait**

Results from the measurement error calculations for stride length collected by the Shadowbox™ inertial and magnetic tracking system against the Optojump™ (criterion) were 0.49cm (0.3%) for walking and 9.6 cm (6.6%) for running. These results indicated the data collected on gait kinematics to also have high validity. As in the previous experiment on sports specific actions, this was the first validation study on this type of sensor against a criterion method during gait. Interestingly, the precision of the sensors was significantly higher during walking versus running. This may be due to the greater number of samples per step and a slower change in orientation and displacement of the sensors during walking. Due to the significant post-processing of data required to convert the raw signal output from the magnetic inertial navigation system to displacement data, limited numbers of trials were completed. Further study should focus on collecting more reliability and validity data on walking, jogging, running and sprinting in multiple directions. The combination of measuring
global position on the field, soccer specific movements and gait of a player moving around the field will make the quantification of player motion comprehensive and all inclusive.

Recognition of sports specific actions

Kinematic differences between sports specific actions were shown in a comparative study of somewhat similar soccer actions, jumping versus heading the ball. The magnetic and inertial navigation tracking system used in this experiment showed differences in the trajectory, displacement and speed of the ankle. Importantly, the jumping versus header trials were randomised over two separate trials so that a true representation of the typical trajectory was determined. It was clear from results in Figure 4-13 that the trajectories for the headers followed a very different path to the trajectories for jumping. The initial whole body biomechanical evaluation performed on a soccer player during a jump versus heading the ball test, using the Vicon MX™ system, showed why this difference occurred. There was significant hip flexion during the heading action compared to the jumping action (Figure 4-12). This resulted in the ankle moving forward during the up-phase of the header compared to the jump, which was more vertical in nature.

In order to find an automated way to discriminate between these two similar actions in future match analyses, a curve fitting equation was fitted to the typical jump and header trajectory. The trajectory was analysed in the y and z planes, since virtually no movement occurred in the x plane for these actions on these occasions. The header actions were overlaid and compared against the fitted curve for jumping in Figure 4-14. None of the header actions complied with the typical jump curve. The jump actions also did not comply with the typical header curve. The use of these equations, therefore, is a valid method for discriminating between the different trajectories of the header and jumping actions. This method could be used in future software applications to divide the movement data of a player into discrete
movements occurring around the field. Future software could also incorporate a database of typical sport specific actions that have predetermined ankle or foot trajectories and associated kinematic data. Movement data collected during a match could then be evaluated using a least squares method to match each movement against the sport specific movement database.

A new motion tracking system that meets the design requirements

A new magnetic and inertial navigation (MAIN) system was developed with significant modification and miniaturisation to meet more of the design requirements compared to the Shadowbox™ system and technologies used by previous investigators (Brodie, 2008) to detect sports biomechanics. In short, none of the existing technologies prior to this prototype development could be used by professional soccer players, primarily because they were too large and invasive to the subject and would interfere with performance. While the Shadowbox™ was used in the proof of concept studies and had high validity for tracking the player motion, it was 80% larger and had 85% greater mass (132 g) compared to the MAIN sensor system developed in this experiment. In addition, the size of the Shadowbox™ did not permit it to be built into existing player sporting equipment such as the shoe or shin pad. The battery life and operating capacity (continual data collection and storage for at least 90 minutes) also limited its application to measuring the physical performance of soccer players.

The MAIN sensor system was designed, manufactured, refined and tested over a number of years in order to get it small enough to be uninvasive to the subject wearing it. The final prototype was a highly functional system weighing only 19 g. Results from the walking gait trial showed an average technical error of measurement of 0.88% between strides, indicating very high precision.
Data from the gait assessment experimental trial showed that the MAIN sensor system was also able to detect the subtle phases and events that occur during gait. Data collected in this experiment is similar to those collected by Wu and Ladin (1996) who used an integrated kinematic sensor (accelerometer and gyroscope) to detect heel strike during walking experiments. Several other investigations have conducted gait analysis during activity by attaching similar inertial sensors to either foot (Willemsen et al., 1990a; McCulloch et al., 1993; Wu & Ladin, 1996; Mayagoitia et al., 2002) or tibia (Lafortune, 1991). However, these experiments were done using larger, non-portable, laboratory-style sensors that were cabled and not remote. This experimental trial was a test of the sensor's ability to remotely measure gait at a higher sensitivity (100 Hz) than any other field-based gait tracking device. Each of the gait phases identified by Hayes et al (1983) were clearly visible in the data.

An additional study to evaluate the MAIN sensor system's ability to measure upper body biomechanics was conducted and the overall change in means (<1.5%) between rotations of the arm also indicated a high level of sensor reliability.

A limitation of the experiments using the MAIN sensor system was the presentation of unprocessed signal output data using a sensor that was not calibrated to first principles prior to the experiment. While converting the data from raw signal output to three-dimensional displacement, using the methods of Bachmann et al. (2001), would have been interesting and advantageous, the research budget of this project did not permit additional software design and compilation. The research was funded personally by the PhD candidate and was, therefore, limited. However, the purpose of this experiment was to examine sensor functionality and precision. Both of these variables could be evaluated using raw signal output. The development of a custom calibration rig for calibration of the sensors as per the methods used by various investigators to calibrate accelerometers (Freedson et al., 1998;
Lötters et al., 1998b; Mathew, 2005; Welk, 1005), gyroscopes (Miyazaki, 1997; Mayagoitia et al., 2002) and magnetometers (Pfau et al., 2005) was also beyond the funding scope of this project.

**Risk Analysis**

The risk analysis of the MAIN sensor system addressed a number of potential risks or limitations of the sensor in its current form. Most significantly was the capacity of the gyroscope to measure high speed running and sprinting. Although all three sensors collected data well within their dynamic measurement range during the experiments, the Analog Devices gyroscope (ADXRS300) in the MAIN sensor system could only measure up to 300 deg.s$^{-1}$. Data from Buczek and Cavanagh (1990) showed that the angular velocity of the ankle peaks at 263 deg.s$^{-1}$ when running at a speed of 4.5 m.s$^{-1}$. When this data is extrapolated to sprinting, it would be reasonable to expect over 500 deg.sec$^{-1}$ if a player was moving at 9 m.s$^{-1}$. Bangsbo (1992) estimated elite soccer players to sprint at speeds in excess of 25-30 km.hr$^{-1}$ during a match. At the time of experimentation, Analog Devices Inc, USA, did not manufacture miniature gyroscopes of this capacity that could be incorporated into the MAIN sensor system. Consequently, data was only collected during locomotion at a brisk walking pace during the experimental trials. Interestingly, the angular velocity of the lower extremities measured using gyroscopes in previous experiments have ranged between -10 to 7 rad.s$^{-1}$ (Wu & Ladin, 1996) and -8 to 8 rad.s$^{-1}$ at the knee (Buczek & Cavanagh, 1990). The peak angular velocity of the ankle is substantially lower even at top speeds and the ankle and foot is the primary site needed for measurement of human gait, particularly to analyse the characteristics of gait described by Hay (1993). In its current form, the MAIN sensor system is a reliable and functional prototype. However, further work needs to be done on the sensor's ability to work in extreme temperatures over a long time, static and dynamic calibration methods, sensor placement and multiple sensor fusion. The risk analysis also identified that
considerable investment in software development is still needed to make the system commercially robust. This includes the development of biomechanical models and analysis software to distinguish different types of sport specific movements.

Performance Analysis

Data from match analyses is only useful if there is an effective way to interpret, analyse and convert it into meaningful feedback to coaches and athletes. The soccer performance analysis (SPA) system developed in Chapter 2 is designed to incorporate movement data from the MAIN sensor in a logical and systematic analysis process to determine if the physical performance was satisfactory. In addition, a model for developing training recommendations was also described. While this is the first systematic process ever presented to analyse soccer physical performance, there is still considerable software development work required to make it commercially robust. The risk analysis also showed that further work needs to be done on the development of a scalable database for storing and analysing player data in real time, performance standard prediction and providing training requirement recommendations. Once operational, this system will result in optimal training configuration and can potentially provide a system to accelerate the physical development and performance of soccer players.

Recommendations

This was the first successful trial of an inertial and magnetic navigation system that met all of the identified design requirements. Future studies should focus on incorporating the sensors directly into the shoe or shin pad to make it completely undetectable and to not interfere with kicking the ball. Importantly, wearing sensors in international competition is not permitted under FIFA rules. This type of technology, therefore, needs to be built into existing sporting equipment and approved by FIFA before using in professional soccer match environments. Future work in this area could focus on refining the hardware and software to make it user
friendly to coaches and athletes and also on the integration of player physiology data collected during a match. While heart rates and lactates have been collected during match play, real-time energy expenditure rates and fatigue levels would also provide added data to help with the physical performance evaluation process. A method to track the tactical performance of the team, including measuring the ball movements around the field, could also be incorporated. The development of such sensors into wearable garments or equipment could also reduce the invasiveness and improve the practicality of wearing multiple motion tracking sensors in the future.

In summary, this thesis has proven that magnetic and inertial navigation motion tracking technology can perform valid measures of soccer specific movements, including one-touch pass of a ball, slide tackle and kicking (drive) a ball, jumping and heading a ball. The technology can also perform valid measures of gait, including walking and running and can discriminate kinematic differences between short-term, ballistic, soccer specific actions. Modifying the technology to meet the unique design requirements for operation in the elite soccer match environment did not compromise the sensor precision and demonstrated it to be a viable solution for measuring the physical performance of soccer players. All of these findings are novel and have significant implications for revolutionising the sports performance analysis industry.
CHAPTER 6

Appendices
## Appendix 1. A review of the various technologies used by investigators to measure tactical and technical performance in team sports

<table>
<thead>
<tr>
<th>Type of technology</th>
<th>Investigator/s</th>
<th>No. matches</th>
<th>Competition Level</th>
<th>Application of the technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand collected statistics to record player activities</td>
<td>Reep &amp; Benjamin (1968)</td>
<td>3213 matches</td>
<td>English 1st Division</td>
<td>Hand collected statistics from 1953-1968 Investigated chance, strategy and tactics in football Using hand collected stats (Reep &amp; Benjamin, 1968) to assess determinants &amp; consequences of different styles of play as well as match statistics</td>
</tr>
<tr>
<td></td>
<td>Bate (1988)</td>
<td>16 matches</td>
<td>1982 Soccer World Cup</td>
<td>Hand recording of attacking moves onto scaled diagram of a pitch and x and y co-ordinates entered into a computer for analysis goal scoring strategies were hand coded and databased attacking success in relation to space and team strategy</td>
</tr>
<tr>
<td></td>
<td>Pollard (1988)</td>
<td>74 matches</td>
<td>1982 Soccer World Cup (n=32) and English Premier League (n=42)</td>
<td>Using hand collected stats (Reep &amp; Benjamin, 1968) to assess determinants &amp; consequences of different styles of play as well as match statistics</td>
</tr>
<tr>
<td></td>
<td>Ali (1988)</td>
<td>18 matches</td>
<td>Scottish Premier Division</td>
<td>Hand collected statistics from 1953 to 1968 to record player activities</td>
</tr>
<tr>
<td></td>
<td>Olsen (1988)</td>
<td>52 matches</td>
<td>1986 World Cup</td>
<td>Hand notation of attacking configurations based on markings on the pitch from video tapes. Divided pitch into areas and manually analyse goals video analysis was used to manually record the playing times of various match events</td>
</tr>
<tr>
<td></td>
<td>Pollard (1988)</td>
<td>74 matches</td>
<td>1982 Soccer World Cup Used method by (Reep &amp; Benjamin, 1968) to assess determinants &amp; consequences of different styles of play as well as match statistics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harris &amp; Reilly (1988)</td>
<td>24 matches</td>
<td>English 1st Division</td>
<td>Hand recording of attacking moves onto scaled diagram of a pitch and x and y co-ordinates entered into a computer for analysis goal scoring strategies were hand coded and databased attacking success in relation to space and team strategy</td>
</tr>
<tr>
<td></td>
<td>Jinshan et al. (1993)</td>
<td>52 matches</td>
<td>1992 Soccer World Cup</td>
<td>Hand notation of attacking configurations based on markings on the pitch from video tapes. Divided pitch into areas and manually analyse goals video analysis was used to manually record the playing times of various match events</td>
</tr>
<tr>
<td></td>
<td>Doggart et al. (1993)</td>
<td>4 matches</td>
<td>Inter-county level Irish Gaelic football</td>
<td>Hand recorded using shorthand code for match events</td>
</tr>
<tr>
<td></td>
<td>Lanham (1993)</td>
<td>479 matches</td>
<td>English Barclays Soccer League</td>
<td>Hand recorded using shorthand code for match events</td>
</tr>
<tr>
<td></td>
<td>Gerisch &amp; Reichelt (1993)</td>
<td>1 match</td>
<td>European Cup Soccer</td>
<td>Hand notation of goal scoring patterns</td>
</tr>
<tr>
<td></td>
<td>Garganta et al. (1997)</td>
<td>44 matches</td>
<td>European 1st Division Soccer teams</td>
<td>Hand notation of goal scoring patterns</td>
</tr>
<tr>
<td></td>
<td>Sasaki et al. (2002)</td>
<td>9 matches</td>
<td>Japanese National Rugby Team in World Cup qualifiers</td>
<td>Hand recording of plays and outcomes of plays</td>
</tr>
<tr>
<td></td>
<td>Abt et al. (2002)</td>
<td>703 matches</td>
<td>Australian NSL matches</td>
<td>Goal scoring patterns over a course of match hand recorded times of each goal</td>
</tr>
<tr>
<td></td>
<td>Hughes &amp; Jones (2005)</td>
<td>16 matches</td>
<td>Rugby World Sevens Series matches</td>
<td>Hand notation from video recordings of patterns of successful and unsuccessful teams</td>
</tr>
<tr>
<td></td>
<td>Taylor et al. (2005)</td>
<td>20 matches</td>
<td>English Premier League</td>
<td>Recorded information by hand and analysed on SPSS Hand notation system for recording goals and other match events as match progresses</td>
</tr>
<tr>
<td></td>
<td>Hughes &amp; Churchill (2005)</td>
<td>30 matches</td>
<td>2001 Copa America Soccer Championship</td>
<td>Hand recorded and enter data on shots on goal into Microsoft Excel for statistical analysis by GLIM program Used shorthand code for statistics and databased for analysis on goals for and against in soccer</td>
</tr>
<tr>
<td></td>
<td>Ensum et al. (2005)</td>
<td>48 matches</td>
<td>2002 Soccer World Cup</td>
<td>Hand recorded and enter data on shots on goal into Microsoft Excel for statistical analysis by GLIM program Used shorthand code for statistics and databased for analysis on goals for and against in soccer</td>
</tr>
<tr>
<td></td>
<td>Lanham (2005)</td>
<td>&gt;3000 matches</td>
<td>English Premier League</td>
<td>Hand recorded and enter data on shots on goal into Microsoft Excel for statistical analysis by GLIM program Used shorthand code for statistics and databased for analysis on goals for and against in soccer</td>
</tr>
</tbody>
</table>

*continued on next page*
## Appendix 1 continued

<table>
<thead>
<tr>
<th>Type of technology</th>
<th>Investigator/s</th>
<th>No. matches</th>
<th>Competition Level</th>
<th>Application of the technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computerised notation systems with customised keyboards</td>
<td>Church &amp; Hughes (1987)</td>
<td></td>
<td>1986 Soccer World Cup</td>
<td>Analysed patterns of play with specialised keyboard</td>
</tr>
<tr>
<td></td>
<td>Treadwell (1988)</td>
<td></td>
<td>Rugby Union</td>
<td>Analysed statistics using modified keyboard</td>
</tr>
<tr>
<td></td>
<td>Pollard (1988)</td>
<td>74</td>
<td>1982 Soccer World Cup &amp; Spanish 1st Division</td>
<td>Used the ‘Reep system’ by entering in a shorthand code into customised computer software</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computerised notation systems with customised touch pad/mouse</td>
<td>Hughes &amp; Billingham (1986)</td>
<td>16 matches</td>
<td>1986 Soccer World Cup</td>
<td>BBC concept keyboard and digital touch pad and stylus to record match events and location on the playing area</td>
</tr>
<tr>
<td></td>
<td>Hughes et al. (1988)</td>
<td></td>
<td></td>
<td>Used a touch keyboard to collect match statistics</td>
</tr>
<tr>
<td></td>
<td>Partridge et al. (1993)</td>
<td>52 matches</td>
<td>1990 Soccer World Cup</td>
<td>Used a real time microcomputer with touch pad for collecting match statistics</td>
</tr>
<tr>
<td></td>
<td>Yamanaka et al. (1993)</td>
<td>12 matches</td>
<td>1990 Soccer World Cup</td>
<td>Modified system previously used by (Hughes &amp; Billingham, 1986) to collect match statistics</td>
</tr>
<tr>
<td></td>
<td>Luhtanen et al. (1997)</td>
<td>7 matches</td>
<td>1994 Soccer World Cup</td>
<td>Used computer mouse and on-screen diagram of soccer field to collect statistics on attack, scoring chances, goal shots, goals, time in possession and ball distance</td>
</tr>
<tr>
<td></td>
<td>Yamanaka et al. (1997)</td>
<td>8 matches</td>
<td>1994 Asian Soccer World Cup qualifying matches</td>
<td>Used later version of (Hughes &amp; Billingham, 1986) system to evaluate playing patterns</td>
</tr>
<tr>
<td></td>
<td>Dufour (2005)</td>
<td></td>
<td></td>
<td>BBC concept keyboard and digital touch pad and stylus to record match events and location on the playing area</td>
</tr>
<tr>
<td>Computerised system with customised statistical software</td>
<td>Patrick &amp; McKenna (1988)</td>
<td>1 match</td>
<td>Australian Rules Football</td>
<td>Cabercomp system for collecting match statistics</td>
</tr>
<tr>
<td></td>
<td>McKenna et al. (1988)</td>
<td>4 matches</td>
<td>Australian Rules Football</td>
<td>Cabercomp system for collecting match statistics</td>
</tr>
<tr>
<td></td>
<td>Lanham (1993)</td>
<td>479 matches</td>
<td>English Premier League</td>
<td>Database computer program for statistical analysis</td>
</tr>
<tr>
<td></td>
<td>Bishovets et al. (1993)</td>
<td>52 matches</td>
<td>1990 Soccer World Cup</td>
<td>Used a Rival 386 SX PC to process statistics on technical and tactical moves during world cup matches</td>
</tr>
<tr>
<td></td>
<td>Lawlor (2004)</td>
<td>40 matches</td>
<td>2002 Soccer World Cup</td>
<td>Used sportscode to tabulate the number and time of events in matches including runs, dribbles, crosses, passes and goals</td>
</tr>
<tr>
<td></td>
<td>Grehaigne et al. (2002)</td>
<td>4 matches</td>
<td>1994 Soccer World Cup</td>
<td>Used video recorder with stabilised alimentation and computerised grid to record patterns of play</td>
</tr>
<tr>
<td></td>
<td>Williams et al. (2005)</td>
<td>21 matches</td>
<td>Six nations (n=15) and Tri Nations (n=6) Rugby Union matches</td>
<td>Customised statistical analysis software for real time capture of match statistics</td>
</tr>
<tr>
<td></td>
<td>Dawson et al. (2005)</td>
<td>22 matches</td>
<td>Australian Rules Football League</td>
<td>Prowess statistical analysis software system for collecting real time statistics and post match match analysis</td>
</tr>
</tbody>
</table>
### Appendix 2. A review of the body composition of elite soccer players of various nationalities, leagues and ages.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality Of Players</th>
<th>Playing Level</th>
<th>n</th>
<th>(\bar{X}) Age (sd)</th>
<th>(\bar{X}) Stature (sd)</th>
<th>(\bar{X}) Mass (sd)</th>
<th>(\bar{X}) Body Fat (sd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>Bangsbo (1992)</td>
<td>Denmark</td>
<td>Professional D1</td>
<td>9</td>
<td>23.9 (1.0)</td>
<td>183.0 (1.4)</td>
<td>77.7 (1.9)</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Matkovic et al. (1993)</td>
<td>Croatia</td>
<td>Professional D1</td>
<td>44</td>
<td>26.4 (3.5)</td>
<td>179.1 (5.9)</td>
<td>77.5 (7.1)</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>Mercer et al. (1997)</td>
<td>England</td>
<td>Professional D1</td>
<td>15</td>
<td>24.7 (3.8)</td>
<td>179.0 (8.0)</td>
<td>78.1 (9.2)</td>
<td>16.2 (3.4)</td>
</tr>
<tr>
<td>1997</td>
<td>Dunbar &amp; Power (1997)</td>
<td>England</td>
<td>Professional D1</td>
<td>18</td>
<td>22.5 (3.6)</td>
<td>177.7 (7.6)</td>
<td>12.6 (2.9)</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>Dunbar &amp; Power (1997)</td>
<td>England</td>
<td>Professional D3</td>
<td>14</td>
<td>25.8 (4.7)</td>
<td>73.8 (5.8)</td>
<td>12.7 (3.2)</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>Tiryaki et al. (1997)</td>
<td>Turkey</td>
<td>Professional D1</td>
<td>16</td>
<td>178.8 (3.8)</td>
<td>74.8 (6.6)</td>
<td>7.6 (0.7)</td>
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<tr>
<td>1997</td>
<td>Tiryaki et al. (1997)</td>
<td>Turkey</td>
<td>Professional D2</td>
<td>16</td>
<td>177.7 (3.4)</td>
<td>69.6 (4.1)</td>
<td>7.1 (0.4)</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>Tiryaki et al. (1997)</td>
<td>Turkey</td>
<td>Professional D3</td>
<td>16</td>
<td>178.8 (5.9)</td>
<td>72.7 (6.5)</td>
<td>7.2 (0.5)</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>Casajus (2001)</td>
<td>Spain</td>
<td>Professional D1</td>
<td>15</td>
<td>26.3 (3.2)</td>
<td>180.0 (8.0)</td>
<td>78.5 (6.5)</td>
<td>8.2 (0.9)</td>
</tr>
<tr>
<td>2002</td>
<td>Dowson et al. (2002)</td>
<td>New Zealand</td>
<td>National</td>
<td>21</td>
<td>178.8 (6.8)</td>
<td>78.9 (6.0)</td>
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<td></td>
</tr>
<tr>
<td>2002</td>
<td>Strudwick et al. (2002)</td>
<td>England</td>
<td>Professional D1</td>
<td>19</td>
<td>22.0 (2.0)</td>
<td>177.0 (0.1)</td>
<td>77.9 (8.9)</td>
<td>11.2 (1.8)</td>
</tr>
<tr>
<td>2004</td>
<td>Arnason et al. (2004)</td>
<td>Iceland</td>
<td>Professional PL</td>
<td>90</td>
<td>24.2 (0.2)</td>
<td>181.7 (0.5)</td>
<td>77.0 (0.7)</td>
<td>9.9 (0.5)</td>
</tr>
<tr>
<td>2004</td>
<td>Bloomfield et al. (2004a)</td>
<td>Spain</td>
<td>Professional D1</td>
<td>26.4 (4.4)</td>
<td>181.0 (5.0)</td>
<td>74.3 (5.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>Bloomfield et al. (2004a)</td>
<td>Spain</td>
<td>Professional D1</td>
<td>26.5 (4.0)</td>
<td>180.0 (5.0)</td>
<td>75.0 (5.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>Bloomfield et al. (2004a)</td>
<td>Germany</td>
<td>Professional D1</td>
<td>26.6 (4.4)</td>
<td>183.0 (6.0)</td>
<td>77.5 (6.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>Bloomfield et al. (2004a)</td>
<td>England</td>
<td>Professional D1</td>
<td>26.3 (4.8)</td>
<td>181.0 (6.0)</td>
<td>75.3 (7.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Sampaio &amp; Maçās (2005)</td>
<td>Portugal</td>
<td>Professional D1</td>
<td>19</td>
<td>26.0 (3.0)</td>
<td>177.0 (5.6)</td>
<td>72.7 (5.5)</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Sampaio &amp; Maçās (2005)</td>
<td>Portugal</td>
<td>Professional D2</td>
<td>17</td>
<td>24.0 (2.0)</td>
<td>176.0 (4.4)</td>
<td>70.4 (6.1)</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Aziz et al. (2005b)</td>
<td>Singapore</td>
<td>Professional D1</td>
<td>131</td>
<td>25.3 (4.2)</td>
<td>173.4 (6.7)</td>
<td>69.7 (8.7)</td>
<td>10.8 (2.4)</td>
</tr>
<tr>
<td>2005</td>
<td>Aziz et al. (2005a)</td>
<td>Singapore</td>
<td>Professional D1</td>
<td>41</td>
<td>25.7 (3.9)</td>
<td>174.0 (8.3)</td>
<td>70.6 (10.3)</td>
<td></td>
</tr>
</tbody>
</table>

**Combined Average Scores**

| National | 21 | 178.8 (6.8) | 78.9 (6.0) |
| Professional D1 | 398 | 25.4 (1.3) | 179.3 (2.4) | 75.5 (2.6) |
| Professional D2 | 33 | 24.0 | 176.9 (0.7) | 70.0 (1.4) |
| Professional D3 | 30 | 25.8 | 178.8 | 73.3 (0.5) | 10.0 (1.9) |

D1 = Division One, D2 = Division Two, D3 = Division Three, PL = Professional League, National = National Team
Appendix 3. A review of the VO\textsubscript{2max} scores of elite soccer players of various nationalities, leagues and genders.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality</th>
<th>Playing Level</th>
<th>Gender</th>
<th>VO\textsubscript{2max} (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Rhodes et al. (1986)</td>
<td>Canada</td>
<td>National</td>
<td>male</td>
<td>58.7 (16)</td>
</tr>
<tr>
<td>1988</td>
<td>Faina et al. (1988)</td>
<td>Italy</td>
<td>National</td>
<td>male</td>
<td>63.2 (1)</td>
</tr>
<tr>
<td>1976</td>
<td>Raven et al. (1976)</td>
<td>USA</td>
<td>Professional D1</td>
<td>male</td>
<td>58.4 (18)</td>
</tr>
<tr>
<td>1976</td>
<td>Reilly &amp; Thomas (1976)</td>
<td>England</td>
<td>Professional D1</td>
<td>male</td>
<td>66.0 (40)</td>
</tr>
<tr>
<td>1986</td>
<td>Ekblom (1986)</td>
<td>Sweden</td>
<td>Professional D1</td>
<td>male</td>
<td>61.0</td>
</tr>
<tr>
<td>1988</td>
<td>Apor (1988)</td>
<td>Hungary</td>
<td>Professional D1</td>
<td>male</td>
<td>66.0</td>
</tr>
<tr>
<td>1988</td>
<td>Apor (1988)</td>
<td>Hungary</td>
<td>Professional D1</td>
<td>male</td>
<td>64.3</td>
</tr>
<tr>
<td>1988</td>
<td>Apor (1988)</td>
<td>Hungary</td>
<td>Professional D1</td>
<td>male</td>
<td>63.3</td>
</tr>
<tr>
<td>1988</td>
<td>Faina et al. (1988)</td>
<td>Italy</td>
<td>Professional D1</td>
<td>male</td>
<td>68.9 (27)</td>
</tr>
<tr>
<td>1993</td>
<td>Matkovic et al. (1993)</td>
<td>Croatia</td>
<td>Professional D1</td>
<td>male</td>
<td>52.1 (44)</td>
</tr>
<tr>
<td>1993</td>
<td>Vanfraechem &amp; Tomas (1993)</td>
<td>Belgium</td>
<td>Professional D1</td>
<td>male</td>
<td>58.5 (18)</td>
</tr>
<tr>
<td>1994</td>
<td>Bangso (1994)</td>
<td>Norway</td>
<td>Professional D1</td>
<td>male</td>
<td>60.5 (60)</td>
</tr>
<tr>
<td>1997</td>
<td>Dunbar &amp; Power (1997)</td>
<td>England</td>
<td>Professional D1</td>
<td>male</td>
<td>60.7* (18)</td>
</tr>
<tr>
<td>1997</td>
<td>Mercer et al. (1997)</td>
<td>Turkey</td>
<td>Professional D1</td>
<td>male</td>
<td>62.6* (15)</td>
</tr>
<tr>
<td>1997</td>
<td>Tiryaki et al. (1997)</td>
<td>Turkey</td>
<td>Professional D1</td>
<td>male</td>
<td>51.6* (16)</td>
</tr>
<tr>
<td>1998</td>
<td>Wilsøff et al. (1998)</td>
<td>Norway</td>
<td>Professional D1</td>
<td>male</td>
<td>67.6 (14)</td>
</tr>
<tr>
<td>1998</td>
<td>Wilsøff et al. (1998)</td>
<td>Norway</td>
<td>Professional D1</td>
<td>male</td>
<td>59.9 (15)</td>
</tr>
<tr>
<td>1997</td>
<td>Tiryaki et al. (1997)</td>
<td>Turkey</td>
<td>Professional D2</td>
<td>male</td>
<td>51.1* (16)</td>
</tr>
<tr>
<td>1991</td>
<td>Brewer &amp; Davis (1991)</td>
<td>England</td>
<td>Professional D2</td>
<td>male</td>
<td>59.6 (12)</td>
</tr>
<tr>
<td>1997</td>
<td>Tiryaki et al. (1997)</td>
<td>Turkey</td>
<td>Professional D3</td>
<td>male</td>
<td>51.3* (16)</td>
</tr>
<tr>
<td>1988</td>
<td>Faina et al. (1988)</td>
<td>Italy</td>
<td>Amateur</td>
<td>male</td>
<td>64.1 (17)</td>
</tr>
<tr>
<td>1993</td>
<td>Jankovic et al. (1993)</td>
<td>Croatia</td>
<td>Elite Youth</td>
<td>male</td>
<td>59.9 (47)</td>
</tr>
<tr>
<td>1993</td>
<td>Jones &amp; Helms (1993)</td>
<td>England</td>
<td>Elite Youth</td>
<td>male</td>
<td>60.2 (23)</td>
</tr>
<tr>
<td>2002</td>
<td>Dowson et al. (2002)</td>
<td>New Zealand</td>
<td>National</td>
<td>female</td>
<td>49.1</td>
</tr>
<tr>
<td>1986</td>
<td>Colquhoun &amp; Chad (1986)</td>
<td>Australia</td>
<td>Professional D1</td>
<td>female</td>
<td>47.9</td>
</tr>
<tr>
<td>1993</td>
<td>Jensen &amp; Larsson (1993)</td>
<td>Denmark</td>
<td>Professional D1</td>
<td>female</td>
<td>57.6 (10)</td>
</tr>
<tr>
<td>1997</td>
<td>Tamer et al. (1997)</td>
<td>Turkey</td>
<td>Professional D1</td>
<td>female</td>
<td>43.15* (22)</td>
</tr>
<tr>
<td>1993</td>
<td>Miles et al. (1993)</td>
<td>England</td>
<td>Amateur</td>
<td>female</td>
<td>42.4</td>
</tr>
</tbody>
</table>

* estimated VO\textsubscript{2max} from field-based tests. \( n \) = number of subjects. D1 = division 1, D2 = division 2, D3 = division 3
Appendix 4. Results of studies investigating the blood lactate concentration [HLa] response of elite soccer players during match play

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality</th>
<th>Playing Level</th>
<th>Peak [HLa] First Half (mmol.L(^{-1}))</th>
<th>Peak [HLa] Second Half (mmol.L(^{-1}))</th>
<th>[HLa] ranges (mmol.L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Ekblom (1986)</td>
<td>Swedish</td>
<td>Prof Division 1</td>
<td>9.5</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>Rohde &amp; Espersen (1988)</td>
<td>Danish</td>
<td>Prof Div. 1 &amp; 2</td>
<td>5.1 ± 1.6</td>
<td>3.9 ± 1.6</td>
<td>(2.1-10.3)</td>
</tr>
<tr>
<td>1991</td>
<td>Bangsbo et al. (1991)</td>
<td>Danish</td>
<td>Prof Div. 1 &amp; 2</td>
<td>4.9</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Bangsbo (1994)</td>
<td>Danish</td>
<td>Prof Division 1</td>
<td>4.1</td>
<td>2.7</td>
<td>(1.6-6.0)</td>
</tr>
<tr>
<td>1994</td>
<td>Bangsbo (1994)</td>
<td>Danish</td>
<td>Prof Division 1</td>
<td>6.6</td>
<td>4.0</td>
<td>(2.3-9.3)</td>
</tr>
<tr>
<td>2004</td>
<td>Roi et al. (2004)</td>
<td>Italian</td>
<td>Prof Division 1</td>
<td>6.3 ± 2.4</td>
<td></td>
<td>(2.1-11.3)</td>
</tr>
</tbody>
</table>

Professional Division 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality</th>
<th>Playing Level</th>
<th>Peak [HLa] First Half (mmol.L(^{-1}))</th>
<th>Peak [HLa] Second Half (mmol.L(^{-1}))</th>
<th>[HLa] ranges (mmol.L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Smaros (1980)</td>
<td>Finland</td>
<td>Prof Division 2</td>
<td>4.9 ± 1.9</td>
<td>4.1 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>Ekblom (1986)</td>
<td>Swedish</td>
<td>Prof Division 2</td>
<td>8.0</td>
<td>6.6</td>
<td>(3.0-11.5)</td>
</tr>
</tbody>
</table>

Professional Division 3

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality</th>
<th>Playing Level</th>
<th>Peak [HLa] First Half (mmol.L(^{-1}))</th>
<th>Peak [HLa] Second Half (mmol.L(^{-1}))</th>
<th>[HLa] ranges (mmol.L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Ekblom (1986)</td>
<td>Swedish</td>
<td>Prof Division 3</td>
<td>5.5</td>
<td>4.2</td>
<td>(3.0-12.6)</td>
</tr>
</tbody>
</table>

Professional Division 4

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Nationality</th>
<th>Playing Level</th>
<th>Peak [HLa] First Half (mmol.L(^{-1}))</th>
<th>Peak [HLa] Second Half (mmol.L(^{-1}))</th>
<th>[HLa] ranges (mmol.L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Ekblom (1986)</td>
<td>Swedish</td>
<td>Prof Division 4</td>
<td>4.0</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>Krstrup et al. (2004)</td>
<td>Danish</td>
<td>Prof Division 4</td>
<td>4.3 ± 0.6</td>
<td>4.0 ± 2.5</td>
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</tr>
<tr>
<td>2006</td>
<td>Krstrup et al. (2006)</td>
<td>Danish</td>
<td>Prof Division 4</td>
<td>6.0 ± 0.4</td>
<td>5.0 ± 0.4</td>
<td>(4.2-11.9)</td>
</tr>
</tbody>
</table>

Youth

<table>
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<th>Year</th>
<th>Source</th>
<th>Nationality</th>
<th>Playing Level</th>
<th>Peak [HLa] First Half (mmol.L(^{-1}))</th>
<th>Peak [HLa] Second Half (mmol.L(^{-1}))</th>
<th>[HLa] ranges (mmol.L(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>1998</td>
<td>Rebelo et al. (1998)</td>
<td>Portuguese</td>
<td>Elite Youth</td>
<td>4.2 ± 0.5</td>
<td>3.4 ± 0.4</td>
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</tbody>
</table>

Amateur

<table>
<thead>
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<th>Year</th>
<th>Source</th>
<th>Nationality</th>
<th>Playing Level</th>
<th>Peak [HLa] First Half (mmol.L(^{-1}))</th>
<th>Peak [HLa] Second Half (mmol.L(^{-1}))</th>
<th>[HLa] ranges (mmol.L(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>1988</td>
<td>Gerisch et al. (1988)</td>
<td>German</td>
<td>Amateur</td>
<td>5.6 ± 2.0</td>
<td>4.7 ± 2.2</td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>Gerisch et al. (1988)</td>
<td>German</td>
<td>College</td>
<td>5.9 ± 2.0</td>
<td>4.9 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Smith et al. (1993)</td>
<td>English</td>
<td>College</td>
<td>8.5 ± 2.2</td>
<td></td>
<td>(5.6-11.6)</td>
</tr>
<tr>
<td>1993</td>
<td>Nowacki &amp; Preuhs (1993)</td>
<td>German</td>
<td>Amateur</td>
<td>5.3</td>
<td>5.5</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 5: Elite Coach Questionnaire Results

Elite Coach Questionnaire

The requirements for analysis of physical performance during soccer match play

A questionnaire conducted as part of the thesis entitled “Analysis of the physical performance of soccer players”

Troy Flanagan
PhD Candidate
School of Aerospace, Mechanical and Manufacturing Engineering
RMIT University
Melbourne Australia

Please complete the following questions by either checking the most correct check-box or typing a response in the space provided.

Coach Level: □Prof D1 □Prof D2 □Prof D3 □Elite Youth
League: Australian Youth League/Victorian Institute of Sport

1. Rate how important each of the following characteristics of a soccer player is to successful on-field soccer physical performance?

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No</th>
<th>Low</th>
<th>Med</th>
<th>High</th>
<th>V High</th>
<th>Critical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Player body composition</td>
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<td>Aerobic Power</td>
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<td>Training Status</td>
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</tbody>
</table>
2. What effect do you think the performance environment has on physical performance?

Player position:
“Various player positions will certainly have an effect on physical performance”.

Competition Level:
“If the competition level is poor, physical performance will be effected as it will be if under intense pressure. The competition level must always be graded against physical performance”.

Environmental conditions:
“All, I believe, have an impact. Also the squad that I coach play the majority of games on a synthetic surface, so along with appropriate footwear, this may have an effect”

Tactics:
“No doubt, tactics will affect a player’s performance and may assist or hinder physical performance. That is, will we defend from the front or back off and allow the opposition time and space? Either situation will result in quite different physical work rates and effort required”.

3. Have you used player tracking technology for at least 12 months to measure the on-field activity of players during match play?

“We have used GPS tracking, but are still in the early stages of gathering and compiling information collected on players during a game.”

4. What are the important variables that you are measuring?

“We are measuring how often a player enters speed zones or the speed distribution graphs, distance of sprints, time period between sprints and heart rate. Total distance travelled is not that important”

5. Are there any limitations of the player tracking technology that you are using?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Yes</th>
<th>No</th>
<th>N/A</th>
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<tbody>
<tr>
<td>Sample rate</td>
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<td>Data storage capacity</td>
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<td>Location on the body</td>
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</tbody>
</table>
Elite Coach Questionnaire

The requirements for analysis of physical performance during soccer match play

A questionnaire conducted as part of the thesis entitled “Analysis of the physical performance of soccer players”

Troy Flanagan
PhD Candidate
School of Aerospace, Mechanical and Manufacturing Engineering
RMIT University
Melbourne Australia

Please complete the following questions by either checking the most correct check-box or typing a response in the space provided.

Coach Level:  ✔Prof D1  □Prof D2  □Prof D3  □Elite Youth
League: Australian A League – Melbourne Victory Football Club

1. Rate how important each of the following characteristics of a soccer player is to successful on-field soccer physical performance?

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No</th>
<th>Low</th>
<th>Med</th>
<th>High</th>
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</tbody>
</table>
2. What effect do you think the performance environment has on physical performance?

Player position:
“Each player is considered individually regarding his physical performance. The physical work rate of each player is also considered in relation to the team performance and strategy. A defensive midfielder, for example, may have less physiological demands than an attacking midfielder”.

Competition Level:
“Elite level performers are susceptible to change in environment, in particular, the standard of competition. Different levels of competition causes different levels of stress or psychological pressure. Higher standard players are fitter, however, and can cope with additional environment stress such as high temperatures, humidity or altitude”.

Environmental conditions:
“In my observations, defenders are often affected by the state of the pitch and wind. Midfielders are often more affected by heat, humidity, wind and the state of the pitch. Strikers are more affected by the wind, heat and the state of the pitch.”

Tactics:
“Factors such as knowledge of the opposition, tactics that are going to be played including set plays and the environmental conditions etc will impact on team strategy. The team will be structured in a way to maximise our strengths and minimise the oppositions. For these reasons, applying different team tactics will affect the on-field work rate of players during a match.”

3. Have you used player tracking technology for at least 12 months to measure the on-field activity of players during match play?

“Yes, we have used GPS tracking technology.”

4. What are the important variables that you are measuring?

“We have measured speed, acceleration, distance and where the player moves.”

5. Are there any limitations of the player tracking technology that you are using?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Yes</th>
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<tr>
<td>Sample rate</td>
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Elite Coach Questionnaire

The requirements for analysis of physical performance during soccer match play

A questionnaire conducted as part of the thesis entitled “Analysis of the physical performance of soccer players”

Troy Flanagan
PhD Candidate
School of Aerospace, Mechanical and Manufacturing Engineering
RMIT University
Melbourne Australia

Please complete the following questions by either checking the most correct check-box or typing a response in the space provided.

<table>
<thead>
<tr>
<th>Coach Level:</th>
<th>☑Prof D1 ☐Prof D2 ☐Prof D3 ☐Elite Youth</th>
</tr>
</thead>
<tbody>
<tr>
<td>League:</td>
<td>Australian A League – Melbourne Victory Football Club</td>
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</table>

1. Rate how important each of the following characteristics of a soccer player is to successful on-field soccer physical performance?

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<th>Characteristic</th>
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</tbody>
</table>
2. What effect do you think the performance environment has on physical performance?

Player position:
“Midfielders run the most during matches due to their tactical duty during a match. Defenders and strikers run less distance. Each playing position has a slightly different role, requiring different types of runs and tactical role against the opposition. This causes each player to run in different areas of the pitch and do different amounts of work during a match. Therefore, playing position is an important factor to consider when analysing the performance of players.”

Competition Level:
“Elite performers are more affected than lower grade competitors by the quality of the playing environment”.

Environmental conditions:
“Players who require accuracy in fine motor skills require an excellent playing surface. Extreme weather affects players who run the greatest distances such as midfielders who run between 10-15 kilometres.”

Tactics:
“Prior knowledge of the match performance conditions and environment would determine team strategy. The strategy imposed on the game determines where a player runs and how much running is required”.

3. Have you used player tracking technology for at least 12 months to measure the on-field activity of players during match play?

“Yes, GPS tracking for football player movement patterns”.

4. What are the important variables that you are measuring?

“Speed of movement, distance covered, areas of the field that they are most frequently covering”.

5. Are there any limitations of the player tracking technology that you are using?

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample rate</td>
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<td>Location on the body</td>
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</table>
Appendix 7: Pitch, roll and heading data for the ankle during a kick (drive), one-touch pass and slide tackle.

(i) Slide tackle

(ii) Kick (drive) of a ball

(iii) One-touch pass
Appendix 8: Schematic diagrams of magnetometer, accelerometer and gyroscope sensors contained within the Magnetic and Inertial Navigation (MAIN) system prototype.

A schematic diagram of the magnetometers (HMC1023, Honeywell, USA) used in the Magnetic and Inertial Navigation (MAIN) sensor system. Figure adapted from Honeywell (2004).

A schematic diagram of the triaxial accelerometer (ADXL210E, Analog Devices, USA) the Magnetic and Inertial Navigation (MAIN) sensor system. Figure adapted from Analog Devices (2002).
A schematic diagram of the rate gyroscopes (ADXRS300, Analog Devices, USA) used in the Magnetic and Inertial Navigation (MAIN) sensor system. Figure adapted from Analog (2004).
Appendix 9: Detailed Schematic of MAIN Sensor System Power Supply

This schematic was designed in collaboration with Kendall Hook.
Appendix 10: Detailed Schematic of MAIN Sensor and Microcontroller

This schematic was designed in collaboration with Kendall Hook
Appendix 11: Software Code for the MAIN Sensor System Hardware

This appendix contains software written in C programming language for the MAIN sensor system. The following software components are included:

(i) VEMAIN.c
(ii) VEMAIN.h
(iii) ADC.c
(iv) ADC.h
(v) CRC16.c
(vi) CRC16.h
(vii) DFLASH.c
(viii) DFLASH.h
(ix) MISC.c
(x) MISC.h
(xi) USB.c
(xii) USB.h
(xiii) UTILITIES.c
(xiv) UTILITIES.h

This software was written in collaboration with Kendall Hook.

(i) "VE MAIN.c"

//*****************************************
//           MAIN SENSOR SYSTEM
//*****************************************
#include "msp430x14x.h"
#include "VEmain.h"
#include "Misc.h"
#include "ADC.h"
#include "USB.h"
#include "acceleration_timer_b.h"
#include "Dflash.h"
#include "string.h"
#include "utilities.h"
#include "intwri.c"
#include "reed_solomon.h"
#include "Bootloader.h"
define TIMEOUTVALUE 10000
#define bool unsigned char

unsigned char BigBuff_hi[1058];
static unsigned int VE_state,
local_current_page;
static bool USBstreamOn = false;
static bool RFstreamOn =false;
unsigned char hex_buff[2];
unsigned char sample_rate;
unsigned int stream_data[10];
static unsigned int local_current_page;
unsigned int page_data_count;

//*****************************************
//           MAIN PROGRAM
//*****************************************

void main(void)
{
  int i,j;
  static unsigned int bytes;
  WDTCTL = WDTPW + WDTHOLD;
  init();
  _EINT();
  X2_on();
  VE_state = USB_comms;
dflash_powerdown();
P3SEL ^= ~P3_DLCK;
P3DIR |= P3_DLCK;

  FlushUARTRx();
  for (; ;)
  {
    test_for_USB_attached();
    switch (VE_state)
    {
    //////////////////////////////////////////////////////
    case recording:
    X2_on();
sensor_power_on();
setup_adc();
setup_adc_timer();
init_dflash();
in_recording();
local_current_page = 0;
do
  {
    local_current_page =
    get_local_current_page();
    while ((P3IN & P3_DIO_OUT)!=0);
    xyzaccelerometer_timerB_off();
    stop_adc();
    VE_state = USB_comms;
sensor_power_off();
dflash_powerdown();
write_flash_int(local_current_page
break;
    //////////////////////////////////////////////////////
    case USB_comms:
    do
      {
    USB_ReadByte();
    //////////////////////////////////////////////////////
    if(Is_UARTRx("VELast"))
    {
    write_string_UART("VELast");
FlushUARTRx();
    delay1S();
    local_current_page = 0;
    do
      {
    init_dflash();
main_memory_page_to_buffer2_transfer(locac
l__current_page);
    read_dflash_buffer2_hi();
    bytes=0;
    while (bytes<1034)
    {
    //XMAG
    i = (int)get_BigBuff_hi(bytes);
    bytes++; //next byte
    j = (int)get_BigBuff_hi(bytes);
    i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);
bytes++; //YMAG
    i = (int)get_BigBuff_hi(bytes);
    bytes++; //next byte
    j = (int)get_BigBuff_hi(bytes);
    i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);
bytes++; //
//ZMAG
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//XGYRO
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//YGYRO
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//ZGYRO
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//XT1
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//YT1
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//ZT1
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//XYT2
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

//ZT2
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%x",i);
TransmitUARTByte(0x20);

*/

//x_accel
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%d",i);
TransmitUARTByte(0x20);

//y_accel
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%d",i);
TransmitUARTByte(0x20);

//z_accel
i = (int)get_BigBuff_hi(bytes);
bytes++ ;   //next byte
j = (int)get_BigBuff_hi(bytes);
i = (i<<8) + j;
USBprintf("%d",i);
TransmitUARTByte(0x20);

//XGYROTEMP
j = (int)get_BigBuff_hi(508);
i = (int)get_BigBuff_hi(507);
i += (j<<8);
USBprintf("%d",i);
TransmitUARTByte(0x20);

//YGYROTEMP
j = (int)get_BigBuff_hi(510);
i = (int)get_BigBuff_hi(509);
i += (j<<8);
USBprintf("%d",i);
TransmitUARTByte(0x20);

//ZGYROTEMP
j = (int)get_BigBuff_hi(512);
i = (int)get_BigBuff_hi(511);
i += (j<<8);
USBprintf("%d",i);
TransmitUARTByte(0x20);

//Battery_Voltage
j = (int)get_BigBuff_hi(514);
i = (int)get_BigBuff_hi(513);
i += (j<<8);
USBprintf("%d",i);

local_current_page++;}
while (local_current_page <= (read_flash_int()-2));
FlushUARTRx();
}
if(Is_UARTRx("VELast??"))
{
write_string_UART("VELast");
FlushUARTRx();
delay1S();
local_current_page = 1;
if ((bool)(read_flash_int() == 0xffff))
do
    { init_dflash();

    main_memory_page_to_buffer2_transfer(local_current_page);
    init_dflash();
    transfer_dflash_buffer2_to_USB();
    local_current_page++;
    while (local_current_page <= (read_flash_int()-2));
}

if(Is_UARTRx("VE"))
    { write_string_UART("VE1000000001VE?");
      FlushUARTRx();
    }

if(Is_UARTRx("VEDump"))
    { write_string_UART("VEDump");
      FlushUARTRx();
      delay15();
      dump_flash_to_usb_8mb();
    }

/*
if(Is_UARTRx("VEProgram"))
    { write_string_UART("VEProgram");
      FlushUARTRx();
    }

flashburn();
}/*
if(Is_UARTRx("VEAcquire"))
{

/*
hex_buff[0] = ReceiveUARTByte();
hex_buff[1] = ReceiveUARTByte();
recording_speed = hex2bin(hex_buff);
if (recording_speed == 200) sample_rate = ID_0; //200 Hz divider set
if (recording_speed == 100) sample_rate = ID_1; //100 Hz
if (recording_speed == 50) sample_rate = ID_2; //50 Hz
if (recording_speed == 25) sample_rate = ID_3; //25 Hz
hex_buff[0] = ReceiveUARTByte();
hex_buff[1] = ReceiveUARTByte();
dummy = hex2bin(hex_buff);
hex_buff[0] = ReceiveUARTByte();
hex_buff[1] = ReceiveUARTByte();
dummy = (dummy<<8);
dummy += hex2bin(hex_buff);
page_data_count = dummy;
*/

/*
sample_rate = ID_1; //100 Hz
page_data_count = 8190;
FlushUARTRx();
write_string_UART("VEAcquire");
VE_state = recording;
break;
*/

P3SEL &= ~P3_DLCK;
P3DIR |= P3_DLCK;
P3OUT &= ~P3_DLCK;
P3OUT |= P3_DLCK;
P3SEL &= ~P3_DIO_OUT;
P3DIR |= P3_DIO_OUT;
P3OUT &= ~P3_DIO_OUT;
P3DIR |= P3_DIO_OUT;
}

if ((P3IN & P3_DIO_OUT)!=0)
    { delay3mS();
      sample_rate = ID_1; //100 Hz
      erase_info_flash();
      recording_session
      VE_state = recording;
      break;
    }

if(Is_UARTRx("VEUSBstream"))
    { sample_rate = ID_1; //100 Hz
      USBstreamOn = true;
      FlushUARTRx();
      write_string_UART("VEUSBstream");
      VE_state = USBstream;
      break;
    }

if(Is_UARTRx("VEStop"))
    { FlushUARTRx();
      write_string_UART("VEStop");
      USBstreamOn = false;
      RFstreamOn = false;
      VE_state = USB_comms;
    }

if(Is_UARTRx("VEEraseFlash"))
    { FlushUARTRx();
      write_string_UART("VEEraseFlash");
      erase_info_flash();
      write_string_UART("Flash Erased");
      VE_state = USB_comms;
    }

if(Is_UARTRx("VESleep"))
    { FlushUARTRx();
      write_string_UART("VESleep");
      VE_state = low_power;
    }

if(Is_UARTRx("VEMagSet"))
    { FlushUARTRx();
      write_string_UART("VEMagSet");
      sensor_power_on();
      set_mag();
    }

if(Is_UARTRx("VEMagReset"))
    { FlushUARTRx();
      write_string_UART("VEMagReset");
      sensor_power_on();
      reset_mag();
    }

while (VE_state == USB_comms);
break;
}
}

set_USB_comms_state(void)
{
    VE_state = USB_comms;
}

bool test_for_USB_attached(void)
{
    bool usb_status;
    if (P2IN & P2_USB_INT)
    {
        power_1_on(); //to get power to the 245
        transceiver chip
        P2OUT |=P2_245_OE;
        usb_status = true;
    }
if ((P2IN & P2_USB_INT)==0) {
P2DIR &=~P2_245_OE;
P3OUT &=~P3_USB_RD_HASH;
P3OUT &=~P3_USB_WR;
if (VE_state != recording) {
power_1_off();
usb_status = false;
} return usb_status;
}

void SetADCstreamReady(void) {
ADCstreamReady = true;
}

bool is_USBstreamOn(void) {
return USBstreamOn;
}

bool is_RFstreamOn(void) {
return RFstreamOn;
}

(ii) VE MAIN.h
#define Ui1 0x33
/* First byte of unique identifier */
#define Ui2 0xCC
/* Second byte of unique identifier */
#define Ui3 0xbb
/* Third byte of unique identifier */
#define HEADER_SIZE 4
/* 4 bytes header */
#define TX_BUFFER_SIZE 128
/* Size (in bytes) of transmit buffer */
#define RX_BUFFER_SIZE 128
/* Size (in bytes) of receive ring-buffer */
#define PREAMBLE_LENGTH 4
/* Number of bytes of preamble to send */
#define PREAMBLE_REQ 4
/* Number of bits required in addition to */
/* the initial 8 bits for the preamble to */
/* be accepted */

//define FALSE 0
//define TRUE (!FALSE)
#define false 0x00
#define true !false
#define bool unsigned char

#define P1_FLASH_D0   0x01
#define P1_FLASH_D1   0x02
#define P1_FLASH_D2   0x04
#define P1_FLASH_D3   0x08
#define P1_FLASH_D4   0x10
#define P1_FLASH_D5   0x20
#define P1_FLASH_D6   0x40
#define P1_FLASH_D7   0x80
#define P2_FLASH_RSTLOW     0x01
#define P2_FLASH_SCKCLK     0x02
#define P2_FLASH_CSLow      0x04
#define P2_FLASH_Rdy_BsLow   0x08
#define P2_USB_RXF_Hash     0x10
#define P2_USB_INT         0x20
#define P2_USB_TXE_Hash    0x40
#define P2_245_OE         0x80
#define P3_MAG_SET        0x01
#define P3_Dio_Out        0x02
#define P3_Dio_In         0x04
#define P1_Dlcr           0x08
#define P3_Ensv           0x10
#define P3_Mag_Reset      0x20
#define P3_USB_wr         0x40
#define P3_USB_rd_hash    0x80
#define P4_En_Sw_Bat_1    0x01
#define P4_Yacc1          0x02
#define P4_Yacc2          0x04
#define P4_Yacc3          0x08
#define P4_Zacc4          0x10
#define P4_Zacc5          0x20
#define P4_EN_3V_Ref      0x40
#define P4_EN_AVcc        0x80
#define P5_Pale           0x01
#define P5_Pdata_In       0x02
#define P5_Pdata_Out      0x04
#define P5_Pclk           0x08
#define P5_245_Dir        0x10
#define P5_3V_Rp_Low      0x20
#define P5_EN_3Vref_2     0x40
#define P5_EN_Bat_2       0x80
#define P6_Xmag           0x01
#define P6_Ymag           0x02
#define P6_Zmag           0x04
#define P6_Ygryo          0x08
#define P6_Zgryo          0x10
#define P6_Xgyrotemp      0x40
#define P6_Ygyrotemp      0x80
#define low_power BIT0 //
#define recording BIT1 //
#define USB_comms BIT2 //
#define RF_comms BIT3 //
#define USBstream BIT4 //
void set_USB_comms_state(void);
bool test_for_USB_attached(void);
void GetSetUSBstreamReady(void);
bool is_USBstreamOn(void);
bool is_RFstreamOn(void);

(iii) AccelerationTimer_b.c
#include "msp430x14x.h"
#include "math.h"
#include "acceleration_timer_b.h"
#include "misc.h"
#include "VEmain.h"
#include "ADC.h"
#define P1_FLASH_D0   0x01
#define P1_FLASH_D1   0x02
#define P1_FLASH_D2   0x04
#define P1_FLASH_D3   0x08
#define P1_FLASH_D4   0x10
#define P1_FLASH_D5   0x20
#define P1_FLASH_D6   0x40
#define P1_FLASH_D7   0x80
#define P2_FLASH_RSTLOW     0x01
#define P2_FLASH_SCKCLK     0x02
#define P2_FLASH_CSLow      0x04
#define P2_FLASH_Rdy_BsLow   0x08
#define P2_USB_RXF_Hash     0x10
#define P2_USB_INT         0x20
#define P2_USB_TXE_Hash    0x40
#define P2_245_OE         0x80
#define P3_MAG_SET        0x01
#define P3_Dio_Out        0x02
#define P3_Dio_In         0x04
#define P1_Dlcr           0x08
#define P3_Ensv           0x10
#define P3_Mag_Reset      0x20
#define P3_USB_wr         0x40
#define P3_USB_rd_hash    0x80
#define P4_En_Sw_Bat_1    0x01
#define P4_Yacc1          0x02
#define P4_Yacc2          0x04
#define P4_Yacc3          0x08
#define P4_Zacc4          0x10
#define P4_Zacc5          0x20
#define P4_EN_3V_Ref      0x40
#define P4_EN_AVcc        0x80
#define P5_Pale           0x01
#define P5_Pdata_In       0x02
#define P5_Pdata_Out      0x04
#define P5_Pclk           0x08
#define P5_245_Dir        0x10
#define P5_3V_Rp_Low      0x20
#define P5_EN_3Vref_2     0x40
#define P5_EN_Bat_2       0x80
#define P6_Xmag           0x01
#define P6_Ymag           0x02
#define P6_Zmag           0x04
#define P6_Ygryo          0x08
#define P6_Zgryo          0x10
#define P6_Xgyrotemp      0x40
#define P6_Ygyrotemp      0x80
#define low_power BIT0 //
#define recording BIT1 //
#define USB_comms BIT2 //
#define RF_comms BIT3 //
#define USBstream BIT4 //
void set_USB_comms_state(void);
bool test_for_USB_attached(void);
void GetSetUSBstreamReady(void);
bool is_USBstreamOn(void);
bool is_RFstreamOn(void);

(unsigned int get_last_XT1(void) {
return xt1;
}
(unsigned int get_last_YT1(void) {
return yt1;
}
(unsigned int get_last_ZT1(void) {
return zt1;
}
(unsigned int get_last_ZT2(void) {
return zt2;
}
(iii) AccelerationTimer_b.h

```c
#define bool unsigned char

void xyzaccelerometer_timerB_on(void);
unsigned int get_x_accel(void);
unsigned int get_y_accel(void);
unsigned int get_z_accel(void);
void xyzaccelerometer_timerB_off(void);

(void)
```

(iii) ADC.c

```c
#include "msp430x14x.h"
#include "ADC.h"
#include "VEmain.h"
#include "acceleration_timer_b.h"
#include "Dflash.h"
#include "USB.h"
#include "reed_solomon.h"

static unsigned int A0;
static unsigned int A1;
static unsigned int A2;
static unsigned int A3;
static unsigned int A4;
static unsigned int A5;
static unsigned int A6;
static unsigned int A7;
static unsigned int A8;
static unsigned int A9;
static unsigned int adc_count;
extern unsigned char sample_rate;
```
static unsigned int count_ZGYROTEMP;
static unsigned int count_Battery_Voltage;
static unsigned int stream_data[10];
static unsigned int stream_count;
static unsigned char adc_record[30];
static bool time_to_pack_flag=false;
static bool timer_A_packing = false;
static unsigned int testcount=0;

void sendUSBword(unsigned int data)
{
    unsigned char hi_byte,lo_byte;
    hi_byte=(unsigned char)data;
    while (P2IN & P2_USB_TXE_HASH);
    P2OUT |=P2_245_OE;
    P5DIR |=P5_245_DIR; //output A-->B
    P5OUT |=P5_245_DIR; //set as out
    P1DIR = 0xff; //out
    P1OUT = hi_byte;
    P2OUT &=~P2_245_OE;
    P3OUT |= P3_USB_WR;
    P3OUT &= ~P3_USB_WR;
    while (P2IN & P2_USB_TXE_HASH);
    P1OUT = 0xFF; //out
    P1OUT = hi_byte;
    P2OUT |=P2_245_OE;
    P3OUT |= P3_USB_WR;
    P3OUT &= ~P3_USB_WR;
    while (P2IN & P2_USB_TXE_HASH);
    P1OUT = lo_byte;
    P2OUT &=~P2_245_OE;
    P3OUT |= P3_USB_WR;
    P3OUT &=~P3_USB_WR;
    while (P2IN & P2_USB_TXE_HASH);
    P1DIR = 0x00;
    P2OUT |=P2_245_OE;
    P5DIR |=P5_245_DIR; //output A-->B
    P5OUT |=P5_245_DIR; //set as out
    P1DIR = 0xff; //out
    P1OUT = hi_byte;
    P2OUT = P2_245_OE;
    P3OUT |= P3_USB_WR;
    P3OUT &= ~P3_USB_WR;
}

void stream_ADC_data_to_USB(void)
{
    TransmitUARTByte(1); //SOH
    sendUSBword(stream_count++);
    sendUSBword(stream_data[0]);
    sendUSBword(stream_data[1]);
    sendUSBword(stream_data[2]);
    sendUSBword(stream_data[3]);
    sendUSBword(stream_data[4]);
    sendUSBword(stream_data[5]);
    sendUSBword(stream_data[6]);
    sendUSBword(stream_data[7]);
    sendUSBword(stream_data[8]);
    TransmitUARTByte(4); //EOT
}

void clear_stream_count(void)
{
    stream_count=0;
}

unsigned int get_XMAG(void)
{
    testcount++;
    return testcount;
    //return (unsigned int)(A0/adc_count);
}

unsigned int get_YMAG(void)
{
    return (unsigned int)(A1/adc_count);
}

unsigned int get_ZMAG(void)
{
    return (unsigned int)(A2/adc_count);
}

unsigned int get_XGYRO(void)
{
    return (unsigned int)(A3/adc_count);
}

unsigned int get_YGYRO(void)
{
    return (unsigned int)(A4/adc_count);
}

unsigned int get_ZGYRO(void)
{
    return (unsigned int)(A5/adc_count);
}

unsigned int get_Battery_Voltage(void)
{
    return (unsigned int)(A9/adc_count);
}

unsigned int X_GYRO_AV(void)
{
    return (unsigned int)
            (total_XGYROTEMP/count_XGYROTEMP);
}

unsigned int Y_GYRO_AV(void)
{
    return (unsigned int)
            (total_YGYROTEMP/count_YGYROTEMP);
}

unsigned int Z_GYRO_AV(void)
{
    return (unsigned int)
            (total_ZGYROTEMP/count_ZGYROTEMP);
}

unsigned int BAT_VOLTS_AV(void)
{
    return (unsigned int)
            (total_Battery_Voltage/count_Battery_Voltage);
}

void reset_long_count(void)
{
    total_XGYROTEMP = 0;
    total_YGYROTEMP = 0;
    total_ZGYROTEMP = 0;
    count_XGYROTEMP = 0;
    count_YGYROTEMP = 0;
    count_ZGYROTEMP = 0;
    count_Battery_Voltage = 0;
}

void reset_adc(void)
{
    adc_count = 0; //init count
    A0 = 0;
    A1 = 0;
    A2 = 0;
    A3 = 0;
    A4 = 0;
    A5 = 0;
    A6 = 0;
    A7 = 0;
    A8 = 0;
    A9 = 0;
}

void stop_adc(void)
{
    ADC12CTL0 = 0;
    conversion
    TACTL &=~MC1;
}

void start_adc(void)
{
    ADC12CTL0 |= ADC12SC;
}

void setup_adc(void)
{
    //main_to_save_data = false;
    time_to_pack_flag = false;
    adc_count = 0; //init count
    A0 = 0;
    A1 = 0;
A2 = 0;
A3 = 0;
A4 = 0;
A5 = 0;
A6 = 0;
A7 = 0;
A8 = 0;
A9 = 0;
P6SEL = 0xFF; // Enable A/D channel
inputs
P6DIR = 0x00;   //6 seems best so far
ADC12CTL0 = ADC12ON+MSC+SHT0_15; // Turn on ADC12, extend sampling time+
// to avoid overflow of results
ADC12CTL1 = SHP+CONSEQ_3; // use timer TA1, repeat sequence once
ADC12MCTL0 = INCH_0; // ref+=AVcc, channel = A0
ADC12MCTL1 = INCH_1; // ref+=AVcc, channel = A1
ADC12MCTL2 = INCH_2; // ref+=AVcc, channel = A2
ADC12MCTL3 = INCH_3; // ref+=AVcc, channel = A3
ADC12MCTL4 = INCH_4; // ref+=AVcc, channel = A4
ADC12MCTL5 = INCH_5; // ref+=AVcc, channel = A5
ADC12MCTL6 = INCH_6; // ref+=AVcc, channel = A6
ADC12MCTL7 = INCH_7; // ref+=AVcc, channel = A7
ADC12MCTL8 = INCH_8; // ref+=AVcc, channel = A8
ADC12MCTL9 = INCH_9+EOS; //ref+=AVcc, channel = A9
ADC12IE = 0x08; // Enable ADC12IFG.3
ADC12CTL0 |= ENC; // Enable conversions
ADC12CTL0 |= ADC12SC; // Start conversion
}

void setup_adc_timer(void)
{

}

PRAGMA vector=ADC_VECTOR
__interrupt void adc_isr(void)
{
if (timer_A_packing==false)
{
A0 += ADC12MEM0;
A1 += ADC12MEM1;
A2 += ADC12MEM2;
A3 += ADC12MEM3;
A4 += ADC12MEM4;
A5 += ADC12MEM5;
A6 += ADC12MEM6;
A7 += ADC12MEM7;
A8 += ADC12MEM8;
A9 += ADC12MEM9;
adc_count++;
}
}

//*****************************************
void pack_adc_record(void)
{
unsigned int i;
i = get_XMAG();
adc_record[0] = 0x30;
adc_record[1] = 0x30;
i = get_YMAG();
adc_record[2] = 0x31;
adc_record[3] = 0x31;
i = get_ZGYRO();
adc_record[4] = 0x32;
adc_record[5] = 0x32;
i = get_ZGYRO();
adc_record[6] = 0x33;
adc_record[7] = 0x33;
i = get_ZGYRO();
//*****************************************************
//#pragma vector=TIMER1_VECTOR
__interrupt void RX_01(void) {
    TACCTL1 &= ~TAIFG;
    TACCR1 +=40000;
    timer_A_packing = true;
    pack_adc_record();
    timer_A_packing = false;
    write_record(adc_record);
}

(iv)  adc.h
#define bool unsigned char
void setup_adc(void);
unsigned int get_XMAG(void);
unsigned int get_YMAG(void);
unsigned int get_ZMAG(void);
unsigned int get_XGYRO(void);
unsigned int get_YGYRO(void);
unsigned int get_ZGYRO(void);
unsigned int get_XGYROTEMP(void);
unsigned int get_YGYROTEMP(void);
unsigned int get_ZGYROTEMP(void);
unsigned int get_Battery_Voltage(void);
void reset_adc(void);
void stop_adc(void);
void start_adc(void);
void setup_adc_timer(void);
unsigned int BAT_VOLTS_AV(void);
void reset_long_count(void);
void stream_ADC_data_to_USB(void);
void sendUSBword(unsigned int data);
void clear_stream_count(void);
void pack_adc_record(void);

(v)  CRC16.c
#include "crc16.h"
/* CRC16 implementation according to CCITT
standards */

static const unsigned short crc16tab[256] =
    {
        0x0000, 0x1021, 0x2042, 0x3063, 0x4084, 0x50a5, 0x60c6, 0x70e7,
        0x8108, 0x9129, 0xa14a, 0xb16b, 0xc18c, 0xd1ad, 0xe1ce, 0xf1ef,
        0x3273, 0x2252, 0x52b5, 0x4294, 0x72f7, 0x62d6, 0x9339, 0x8318,
        0xb37b, 0xa35a, 0xd31c, 0xc39d, 0xf35e, 0xe3de, 0x1411, 0x0490,
        0x34f3, 0x24d2, 0x5435, 0x4414, 0x7476, 0x6455, 0x9519, 0x8538,
        0xb57b, 0xa55a, 0xd53d, 0xc51c, 0xf57f, 0xe55e, 0x2612, 0x1691,
        0x46f4, 0x36d3, 0x6656, 0x5635, 0x8799, 0x9778, 0xe7f7, 0xf7d8,
        0x0730, 0x17b1, 0x47d4, 0x5755, 0x67b6, 0x7797, 0x9839, 0x8818,
        0xe8f9, 0xf8df, 0xc93c, 0xb91d, 0x8955, 0x7974, 0x49d3, 0x39f2,
        0x5a90, 0x6a79, 0x1a12, 0x0a91, 0xfacb, 0xecf5, 0xdb3d, 0xcb1c,
        0xaeb9, 0x9e8d, 0xeef6, 0x3ec2, 0x2e43, 0x7ed5, 0x6ec4, 0x5ec5,
        0x1ef1, 0x0ed0, 0xe80e, 0xf82f, 0xc861, 0xb842, 0x8883, 0x98a4,
        0x7948, 0x6969, 0x39f2, 0x2971, 0x5ae4, 0x4a65, 0x0a20, 0x1a41,
        0xeaf5, 0xfac6, 0xcad1, 0xdb82, 0xbab3, 0x9b54, 0x8bf5, 0x7be6,
        0x6bf7, 0x5be8, 0x1bf1, 0x0b90, 0xfca4, 0xec85, 0xdb66, 0xcba7,
        0xbaf8, 0x9ae9, 0x8af0, 0x7ae1, 0x6a82, 0x5ab5, 0x4a64, 0x3a43,
        0x2a22, 0x1a01, 0xe94e, 0xf96f, 0xc908, 0xb929, 0x896a, 0x9949,
        0x798b, 0x69a2, 0x59c5, 0x49e4, 0x3a83, 0x2a62, 0x1a81, 0x0a00,
        0xfdbf, 0xecb6, 0xdb97, 0xcba8, 0xbaf9, 0x9a8a, 0x8a69, 0x7a48,
        0x6a27, 0x5a46, 0x4a65, 0x3a83, 0x2a62, 0x1a81, 0x0a00,
    };

unsigned short crc16_ccitt(const void *buf, int len)
{
    register int counter;
    register unsigned short crc = 0;
    for( counter = 0; counter < len; counter++)
        crc = (crc<<8) ^ crc16tab[((crc>>8) ^ *(char *)buf)++&0x00FF];
    return crc;
}

(vi)  CRC16.h
#ifndef _CRC16_H_
#define _CRC16_H_
unsigned short crc16_ccitt(const void *buf, int len);
#endif /* _CRC16_H_ */

(vii) DFLASH.c
#include <msp430x14x.h>
#include "Dflash.h"
#include "VEmain.h"
#include "string.h"
#include "adc.h"
#include "reed_solomon.h"

FLASH definitions
#define false 0x00
#define true !false
#define bool unsigned char
#define pagesize 1056
#define pages_per_device 8192

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extern unsigned int page_data_count,
start_page, stop_page;
static unsigned int current_recording_page = 0;
static unsigned int current_recording_page_data_pntr = 0;
static unsigned char BigBuff_hi[1058];
//extra + 8 bytes Temp and Volts
static unsigned int BigBuff_Pos_hi = 0;
//the position
static bool flash_high_ready = false,
flash_low_ready = true, flash_open = false;
bool is_flash_low_ready_for_burn(void)
{
return flash_low_ready;
}
bool is_flash_high_ready_for_burn(void)
{
return flash_high_ready;
}
//*****************************************
// init_dflash
//*****************************************
void init_dflash(void)
{
P2OUT |=P2_245_OE; //set 245 back to HiZ
P2SEL &=~P2_FLASH_RDY_BSYLOW;
P2DIR &=~P2_FLASH_RDY_BSYLOW;
//Set up Busy Ready as an input
P2SEL &=~P2_FLASH_RSTLOW;
P2DIR |=P2_FLASH_RSTLOW;
P2OUT &=~P2_FLASH_RSTLOW;
//RS low
P2OUT |=P2_FLASH_RSTLOW;
//RS high ready for action
P2SEL &=~P2_FLASH_RSTLOW;
P2DIR |=P2_FLASH_RSTLOW;
P2OUT &=~P2_FLASH_RSTLOW;
//CS low
P2OUT |=P2_FLASH_RSTLOW;
//CS high so device is off for lowest
power
BigBuff_Pos_hi=0;
P2SEL = 0x00;
//set as port
P1DIR = 0xff;
P2OUT |=P2_245_OE; //set 245 back to HiZ
}
//*****************************************
// erase a page
//*****************************************
void page_erase(unsigned int page)
{
while (~P2IN&P2_FLASH_RDY_BSYLOW);
//loop while dflash busy is low
P2OUT &=~P2_FLASH_SCKCLK;
//Sck-Clk low One clock of data
P1OUT = ((unsigned char)(page>>5));
//Hi 8 bits of 13 bit page address
P2OUT |=P2_FLASH_SCKCLK;
//Sclk high
P2OUT &=~P2_FLASH_SCKCLK;
//Sck-Clk low One clock of data
P1OUT = ((unsigned char)(page<<3));
//Lo 5 bits of page address shifted left
P2OUT |=P2_FLASH_SCKCLK;
//Sclk high
P2OUT &=~P2_FLASH_SCKCLK;
}
//*****************************************
// buffer_writel_and_main_memory_// transfer_with_erase
//*****************************************
void hi_buffer_write1_and_transfer(unsigned
int page,unsigned char* databuffer)
{
unsigned int pos;
P2OUT |=P2_245_OE;
P2OUT &=~P2_FLASH_CSLOW;
P1DIR = 0xff;
P1OUT = 0x84;
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P1OUT = 0;
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P1OUT = 0x02;
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P1OUT = 0x10;
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
for (pos=0;pos<514;pos++)
{
P1OUT = (databuffer[pos]);
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P1OUT = ((unsigned char)(page>>5));
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P1OUT = ((unsigned char)(page<<3));
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P1OUT = 0;
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P2OUT |=P2_FLASH_CSLOW;  //CS high
}
//*****************************************
// main_memory_page_// to_buffer2_transfer
//*****************************************
void main_memory_page_to_buffer2_transfer
(unsigned int page)
{
P2OUT |=P2_245_OE;
P2OUT &=~P2_FLASH_SCKCLK;
P1OUT = 0x83;
P2OUT |=P2_FLASH_SCKCLK;
P2OUT &=~P2_FLASH_SCKCLK;
P2OUT |=P2_FLASH_CSLOW;  //CS high
}

while (~P2IN&P2_FLASH_RDY_BSYLOW);
//loop while dflash busy is low

void read_dflash_buffer2(void)
{
    unsigned int pos;
    P2OUT |=P2_245_OE;
    P2OUT &=~P2_FLASH_SCKCLK;
    P2OUT &=~P2_FLASH_CSLOW;
    P1DIR = 0xff;
    P1OUT = 0x56;
    P2OUT |=P2_FLASH_SCKCLK;
    P2OUT &=~P2_FLASH_SCKCLK;
    P1OUT = 0x00; //all bits in
    P2OUT |=P2_FLASH_SCKCLK;
    P2OUT &=~P2_FLASH_SCKCLK;
    P1OUT = 0x00; //all bits in
    P2OUT |=P2_FLASH_SCKCLK;
    P2OUT &=~P2_FLASH_SCKCLK;
    P1OUT = 0x00; //all bits in
    P2OUT |=P2_FLASH_SCKCLK;
    P2OUT &=~P2_FLASH_SCKCLK;
    P1OUT = 0x00; //all bits in
    P2OUT |=P2_FLASH_SCKCLK;
    P2OUT &=~P2_FLASH_SCKCLK;
    for (pos=0;pos<1056;pos++)
    {
        P2OUT |=P2_FLASH_SCKCLK;
        P2OUT &=~P2_FLASH_SCKCLK;
        BigBuff_hi[pos]=P1IN;
    }
    P2OUT |=P2_FLASH_CSLOW;
    //CS high so device is off for lowest power
    P2OUT |=P2_FLASH_RSTLOW;
    //RS high as per page 13 on datasheet

    unsigned int
    get_current_recording_page(void)
    {
        return current_recording_page;
    }
    void init_recording(void)
    {
        BigBuff_Pos_hi=0;
    }
    void CopyBigBuff15_hi(unsigned char* buff)
    {
        unsigned int pos,dummy;
        for
        {
            pos=0;pos<22;pos++)
            BigBuff_hi[BigBuff_Pos_hi+pos]=buff[pos];
            BigBuff_Pos_hi += 22;
            if (BigBuff_Pos_hi>=1034)
            {
                dummy = X_GYRO_AV();
                BigBuff_hi[507] = (unsigned char)dummy;
                BigBuff_hi[508] = (unsigned char)
                (dummy>>8);
                dummy = Y_GYRO_AV();
                BigBuff_hi[509] = (unsigned char)dummy;
                BigBuff_hi[510] = (unsigned char)
                (dummy>>8);
                dummy = Z_GYRO_AV();
                BigBuff_hi[511] = (unsigned char)dummy;
                BigBuff_hi[512] = (unsigned char)
                (dummy>>8);
                dummy = BAT_VOLTS_AV();
                BigBuff_hi[513] = (unsigned char)dummy;
                BigBuff_hi[514] = (unsigned char)
                (dummy>>8);
                reset_long_count();
                BigBuff_Pos_hi = 0;
                flash_high_ready = true;
            }
            unsigned int burn_flash_hi(void)
            {
                hi_buffer_write1_and_transfer(current_recording_page, BigBuff_hi);
                flash_high_ready = false;
                current_recording_page++;
            }
            void dump_flash_to_usb_8mb(void)
            {
                unsigned long i;
                P2DIR |=P2_245_OE;
                while (~P2IN&P2_FLASH_RDY_BSYLOW);
                P2OUT &=~P2_FLASH_SCKCLK;
                P2OUT &=~P2_FLASH_CSLOW;
                P1DIR = 0xff;
                P1OUT = 0x68;
                for buffer2
                P2OUT |=P2_FLASH_SCKCLK;
                P2OUT &=~P2_FLASH_CSLOW;
                P1OUT = 0x00;
                P2OUT |=P2_FLASH_SCKCLK;
                P2OUT &=~P2_FLASH_CSLOW;
                P1OUT = 0x00;
                P2OUT |=P2_FLASH_SCKCLK;
                P2OUT &=~P2_FLASH_CSLOW;
                P1OUT = 0x00;
                P2OUT |=P2_FLASH_SCKCLK;
                P2OUT &=~P2_FLASH_CSLOW;
                P1OUT = 0x00;
                P2OUT |=P2_FLASH_SCKCLK;
                P2OUT &=~P2_FLASH_CSLOW;
                P1OUT = 0x00;
                P2OUT |=P2_FLASH_SCKCLK;
                P2OUT &=~P2_FLASH_CSLOW;
                P1OUT = 0x00;
            }
        }
    }
}
P2OUT |= P2_FLASH_SCKCLK;
P2OUT &=~ P2_FLASH_SCKCLK;
clock60bytes();
P1DIR = 0x00;
P5DIR |= P5_245_DIR;
P5OUT |= P5_245_DIR;
P2OUT &=~ P2_245_OE;
for (i=0; i<8650752; i++)
{
    while (P2IN & P2_USB_TXE_HASH)
    P2OUT |= P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P3OUT |= P3_USB_WR; // high then low
    P3OUT &=~ P3_USB_WR;
    P2OUT |= P2_FLASH_CSLOW; // CS High
    P2OUT &=~ P2_FLASH_SCKCLK;
}

void clock60bytes(void)
{
    unsigned int p;
    for (p=0; p<60; p++)
    {
        P2OUT |= P2_FLASH_SCKCLK;
        P2OUT &=~ P2_FLASH_SCKCLK;
        P1OUT = 0x83;
    }
}

// ********* Dflash TESTING
ROUTINES*********

void Test_Dflash(void)
{
    unsigned int i = 0;
    unsigned char j = 0x30;
    for (i=0; i<8192; i++)
    {
        fillpage(i, j);
        j++;
        if (j>=0x3a)
            j=0x30;
    }
}

//************************************************

void fillpage(unsigned int page, unsigned char ch)
{
    unsigned int pos;
    P1OUT = 0x84;
    P2OUT |= P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P1OUT = 0;
    P2OUT |= P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_SCKCLK;
    for (pos=0; pos<1056; pos++)
    {
        P1OUT = ch;
        P2OUT |= P2_FLASH_SCKCLK;
        P2OUT &=~ P2_FLASH_SCKCLK;
    }
}

//************************************************

void transfer_dflash_buffer2_to_USB(void)
{
    unsigned int pos;
    P2DIR |= P2_245_OE;
    P2OUT |= P2_245_OE;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_CSLOW;
    P1DIR = 0xff;
    P1OUT = 0x56;
    P2OUT |= P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P1OUT = ((unsigned char)(page>>5));
    P2OUT |= P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P1OUT = ((unsigned char)(page<<3));
    P2OUT |= P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P1OUT = 0;
    P2OUT |= P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P1OUT = 0;
    P5DIR |= P5_245_DIR;
    P5OUT |= P5_245_DIR;
    P2OUT &=~ P2_245_OE;
    for (pos=0; pos<908; pos++)
    {
        P2OUT |= P2_FLASH_SCKCLK;
        P2OUT &=~ P2_FLASH_SCKCLK;
        P3OUT |= P3_USB_WR;
        P3OUT &=~ P3_USB_WR;
    }
    P2OUT |= P2_FLASH_CSLOW;
    while (~P2IN & P2_FLASH_RDY_BSYLOW);
}

unsigned char get_BigBuff_hi(unsigned int bytes)
{
    return BigBuff_hi[bytes];
}

//************************************************

void write_record(unsigned char* buff)
{
    unsigned char pos;
    P2OUT &=~ P2_FLASH_SCKCLK;
    P2OUT &=~ P2_FLASH_CSLOW;
    if ((current_recording_page&0x0001) == 0)
    {
        P1OUT = 0x84;
    }
    if ((current_recording_page&0x0001) == 1)
    {
        P1OUT = 0x87;
    }
    if ((current_recording_page&0x0001) == 1)
    {
        P1OUT = 0x87;
    }
}
unsigned char get_BigBuff_hi(unsigned int);
void write_record(unsigned char* buff);
unsigned int
get_local_current_page(void);

(ix) MISC.c

/**********************************************************
/* Misc.c
/**********************************************************
#include "msp430x14x.h"
#include "Misc.h"
#include "VEmain.h"

void erase_info_flash(void)
{
    unsigned int *Flash_ptr;
    Flash_ptr = (unsigned int *) 0x1000;
    _DINT();
    WDTCTL = WDTPW + WDTHOLD;
    DCO_750kHz();
    FCTL2 = FWKEY+FSSEL1+FN0;
    FCTL3 = FWKEY;
    FCTL1 = FWKEY + ERASE
*Flash_ptr = 0;
FCTL3 = FWKEY+LOCK;
_EINT();
}

void write_flash_int(unsigned int page)
{
    unsigned int *Flash_ptr;
    Flash_ptr = (unsigned int *) 0x1000;
    _DINT();
    WDTCTL = WDTPW + WDTHOLD;
    DCO_750kHz();
    FCTL2 = FWKEY+FSSEL1+FN0;
    FCTL3 = FWKEY;
    FCTL1 = FWKEY + WRT;
*Flash_ptr = page;
FCTL3 = FWKEY+LOCK;
_EINT();
}

unsigned int get_local_current_page(void)
{
    return current_recording_page;
}

(viii) DFLASH.h

#define bool unsigned char
void init_dflash(void);
void hi_buffer1_write_and_transfer(unsigned int page,unsigned char* databuffer);
void lo_buffer_write1(unsigned char* databuffer);
void main_memory_page_to_buffer2_transfer(unsigned int page);
void dump_flash_to_usb_8mb(void);
void fillpage(unsigned int page, unsigned char ch);
unsigned int CopyBigBuff15(unsigned char* buff);
void init_recording(void);
unsigned int get_current_recording_page(void);
void page_erase(unsigned int page);
void clock60bytes(void);
unsigned int burn_flash_hi(void);
bool is_flash_low_ready_for_burn(void);
bool is_flash_high_ready_for_burn(void);
void read_dflash_buffer2_hi(void);
void read_dflash_buffer2(void);
void dflash_powerdown(void);
unsigned int read_flash_int(void);
void usleep(unsigned int millisec);
void delay1mS(void);
void delay_TX(void);
void delay10uS(void);
unsigned char get_BigBuff_hi(unsigned int);
void write_record(unsigned char* buff);
unsigned int
get_local_current_page(void);

(ix) MISC.c

/**********************************************************
/* Misc.c
/**********************************************************
#include "msp430x14x.h"
#include "Misc.h"
#include "VEmain.h"

void erase_info_flash(void)
{
    unsigned int *Flash_ptr;
    Flash_ptr = (unsigned int *) 0x1000;
    _DINT();
    WDTCTL = WDTPW + WDTHOLD;
    DCO_750kHz();
    FCTL2 = FWKEY+FSSEL1+FN0;
    FCTL3 = FWKEY;
    FCTL1 = FWKEY + ERASE
*Flash_ptr = 0;
FCTL3 = FWKEY+LOCK;
_EINT();
}

void write_flash_int(unsigned int page)
{
    unsigned int *Flash_ptr;
    Flash_ptr = (unsigned int *) 0x1000;
    _DINT();
    WDTCTL = WDTPW + WDTHOLD;
    DCO_750kHz();
    FCTL2 = FWKEY+FSSEL1+FN0;
    FCTL3 = FWKEY;
    FCTL1 = FWKEY + WRT;
*Flash_ptr = page;
FCTL3 = FWKEY+LOCK;
_EINT();
}

unsigned int get_local_current_page(void)
{
    return current_recording_page;
}

(viii) DFLASH.h

#define bool unsigned char
void init_dflash(void);
void hi_buffer1_write_and_transfer(unsigned int page,unsigned char* databuffer);
void lo_buffer_write1(unsigned char* databuffer);
void main_memory_page_to_buffer2_transfer(unsigned int page);
void dump_flash_to_usb_8mb(void);
void fillpage(unsigned int page, unsigned char ch);
unsigned int CopyBigBuff15(unsigned char* buff);
void init_recording(void);
unsigned int get_current_recording_page(void);
void page_erase(unsigned int page);
void clock60bytes(void);
unsigned int burn_flash_hi(void);
bool is_flash_low_ready_for_burn(void);
bool is_flash_high_ready_for_burn(void);
void read_dflash_buffer2_hi(void);
unsigned char get_BigBuff_hi(unsigned int);
void write_record(unsigned char* buff);
unsigned int
get_local_current_page(void);

(ix) MISC.c

/**********************************************************
/* Misc.c
/**********************************************************
#include "msp430x14x.h"
#include "Misc.h"
#include "VEmain.h"

void erase_info_flash(void)
{
    unsigned int *Flash_ptr;
    Flash_ptr = (unsigned int *) 0x1000;
    _DINT();
    WDTCTL = WDTPW + WDTHOLD;
    DCO_750kHz();
    FCTL2 = FWKEY+FSSEL1+FN0;
    FCTL3 = FWKEY;
    FCTL1 = FWKEY + ERASE
*Flash_ptr = 0;
FCTL3 = FWKEY+LOCK;
_EINT();
}

void write_flash_int(unsigned int page)
{
    unsigned int *Flash_ptr;
    Flash_ptr = (unsigned int *) 0x1000;
    _DINT();
    WDTCTL = WDTPW + WDTHOLD;
    DCO_750kHz();
    FCTL2 = FWKEY+FSSEL1+FN0;
    FCTL3 = FWKEY;
    FCTL1 = FWKEY + WRT;
*Flash_ptr = page;
FCTL3 = FWKEY+LOCK;
_EINT();
}

unsigned int get_local_current_page(void)
{
    return current_recording_page;
}

(viii) DFLASH.h

#define bool unsigned char
void init_dflash(void);
void hi_buffer1_write_and_transfer(unsigned int page,unsigned char* databuffer);
void lo_buffer_write1(unsigned char* databuffer);
void main_memory_page_to_buffer2_transfer(unsigned int page);
void dump_flash_to_usb_8mb(void);
void fillpage(unsigned int page, unsigned char ch);
unsigned int CopyBigBuff15(unsigned char* buff);
void init_recording(void);
unsigned int get_current_recording_page(void);
void page_erase(unsigned int page);
void clock60bytes(void);
unsigned int burn_flash_hi(void);
bool is_flash_low_ready_for_burn(void);
bool is_flash_high_ready_for_burn(void);
void read_dflash_buffer2_hi(void);
unsigned char get_BigBuff_hi(unsigned int);
void write_record(unsigned char* buff);
unsigned int
get_local_current_page(void);
void delay100uS(void) {
    unsigned int i;
    for (i = 0x00c0; i > 0; i--);
}

void delay250uS(void) {
    unsigned int i;
    for (i = 0x00f0; i > 0; i--);
}

void delay3mS(void) {
    unsigned int i;
    for (i = 0x0990; i > 0; i--);
}

void delay1S(void) {
    unsigned int i,j;
    for (j = 0x001f; j > 0; j--)
    {
        for (i = 0xffff; i > 0; i--);
    }
}

void DCDC_power_on(void) {
    P3OUT |= P3_EN5V;
}

void DCDC_power_off(void) {
    P3OUT &= ~P3_EN5V;
}

void ref_on(void) {
    P4OUT |= P4_EN_3V_REF;
}

void ref_off(void) {
    P4OUT &= ~P4_EN_3V_REF;
}

void power_1_on(void) {
    P4OUT |= P4_EN_SW_BAT_1;
}

void power_1_off(void) {
    P4OUT &= ~P4_EN_SW_BAT_1;
}

void power_2_on(void) {
    P5OUT |= P5_EN_3VREF_2;
}

void power_2_off(void) {
    P5OUT &= ~P5_EN_3VREF_2;
}

void power_3_on(void) {
    P5OUT |= P5_EN_BAT_2;
}

void power_3_off(void) {
    P5OUT &= ~P5_EN_BAT_2;
}

void power_4_on(void) {
    P4OUT |= P4_EN_AVCC;
}

void power_4_off(void) {
    P4OUT &= ~P4_EN_AVCC;
}

void rf_power_on(void) {
    P5OUT |= P5_3V_RF_LOW;
}

void rf_power_off(void) {
    P5OUT |= P5_3V_RF_LOW;
}

void X1_on(void) {
    unsigned int i;
    BCSCTL1 |= XTS;
    // ACLK = LFXT1 = HF XTAL
    do
    {
        IFG1 &= ~OFIFG;
        for (i = 0xFF; i > 0; i--);
    }
    while ((IFG1 & OFIFG) != 0);
    BCSCTL2 |= SELM1+SELM0;  // MCLK = LFXT1 (safe)
}

void X1_off(void) {
}

void X2_on(void) {
    BCSCTL1 &=~XT2OFF
    do
    {
        unsigned char i;
        IFG1 &= ~OFIFG;
        for (i = 0xFF; i > 0; i--);
    }
    while ((IFG1 & OFIFG) == OFIFG);
    BCSCTL2 |= SELM0;
}

void X2_off(void) {
}

void DCO_max(void) {
    DCOCTL=0xFF;
    BCSCTL1=XT2OFF+RSEL0+RSEL1+RSEL2;
    BCSCTL2=SELM0;
}

void DCO_750kHz(void) {
    DCOCTL=DC0+DCO1;
    BCSCTL1=RSEL2;
    BCSCTL2=0;
}

void set_mag(void) {
    delay1S();
    P3OUT |= P3_MAG_SET;
    delay3mS();
    P3OUT &= ~P3_MAG_SET;
}

void reset_mag(void) {
    delay1S();
    P3OUT |= P3_MAG_RESET;
    delay3mS();
    P3OUT &= ~P3_MAG_RESET;
}

void sensor_power_on(void) {
    power_1_on();
    ref_on();
    DCDC_power_on();
    power_3_on();
    delay3mS();
    power_2_on();
    power_4_on();
    //set_mag();
}

void sensor_power_off(void) {
    power_2_off();
    delay3mS();
    power_3_off();
    DCDC_power_off();
    power_4_off();
    ref_off();
}

void rf_power_on(void) {
    P5OUT |= P5_3V_RF_LOW;
}

void rf_power_off(void) {
    P5OUT |= P5_3V_RF_LOW;
}

void x1_on(void) {
    unsigned int i;
    BCSCTL1 = XTS;
    // ACLK = LFXT1 = HF XTAL
    do
    {
        IFG1 &= ~OFIFG;
        for (i = 0xFF; i > 0; i--);
    }
    while ((IFG1 & OFIFG) != 0);
    BCSCTL2 = SELM1+SELM0;  // MCLK = LFXT1 (safe)
}

void x1_off(void) {
}

void x2_on(void) {
    BCSCTL1 &=~XT2OFF
    do
    {
        unsigned char i;
        IFG1 &= ~OFIFG;
        for (i = 0xFF; i > 0; i--);
    }
    while ((IFG1 & OFIFG) == OFIFG);
    BCSCTL2 &=~SELM0;
}

void x2_off(void) {
}

void dco_max(void) {
    DCOCTL=0xFF;
    BCSCTL1=XT2OFF+RSEL0+RSEL1+RSEL2;
    BCSCTL2=SELM0;
}

void dco_750kHz(void) {
    DCOCTL=DC0+DCO1;
    BCSCTL1=RSEL2;
    BCSCTL2=0;
}

void set_mag(void) {
    delay1S();
    P3OUT |= P3_MAG_SET;
    delay3mS();
    P3OUT &= ~P3_MAG_SET;
}

void reset_mag(void) {
    delay1S();
    P3OUT |= P3_MAG_RESET;
    delay3mS();
    P3OUT &= ~P3_MAG_RESET;
}

void sensor_power_on(void) {
    power_1_on();
    ref_on();
    DCDC_power_on();
    power_3_on();
    delay3mS();
    power_2_on();
    power_4_on();
    //set_mag();
}

void sensor_power_off(void) {
    power_2_off();
    delay3mS();
    power_3_off();
    DCDC_power_off();
    power_4_off();
    ref_off();
}
// Initialise
//*****************************************

void init(void)
{
    X2_on();
    P1SEL = 0x00;
    P1DIR = 0x00;
    P2SEL = ~P2_FLASH_RSTLOW;
    P2DIR |= P2_FLASH_RSTLOW;
    P2OUT |= P2_FLASH_RSTLOW;
    P2SEL &= ~P2_FLASH_SCKCLK;
    P2DIR |= P2_FLASH_SCKCLK;
    P2OUT |= P2_FLASH_SCKCLK;
    P2SEL &= ~P2_FLASH_CSLOW;
    P2DIR |= P2_FLASH_CSLOW;
    P2OUT |= P2_FLASH_CSLOW;
    P2SEL &= ~P2_USB_RXF_HASH;
    P2DIR &= ~P2_USB_RXF_HASH;
    P2SEL &= ~P2_USB_INT;
    P2DIR &= ~P2_USB_INT;
    P2SEL &= ~P2_USB_TXE_HASH;
    P2DIR &= ~P2_USB_TXE_HASH;
    P2SEL &= ~P2_245_OE;
    P2DIR |= P2_245_OE;
    P3SEL &= ~P3_MAG_SET;
    P3DIR |= P3_MAG_SET;
    P3OUT |= P3_MAG_SET;
    P3SEL &= ~P3_DIO_OUT;
    P3DIR &= ~P3_DIO_OUT;
    P3SEL &= ~P3_DIO_IN;
    P3DIR &= ~P3_DIO_IN;
    P3SEL &= ~P3_DLCK;
    P3DIR |= P3_DLCK;
    P3OUT &= ~P3_DLCK;
    P3SEL &= ~P3_EN5V;
    P3DIR |= P3_EN5V;
    P3OUT &= ~P3_EN5V;
    P3SEL &= ~P3_MAG_RESET;
    P3DIR |= P3_MAG_RESET;
    P3OUT |= P3_MAG_RESET;
    P3SEL &= ~P3_USB_WR;
    P3DIR |= P3_USB_WR;
    P3OUT &= ~P3_USB_WR;
    P3SEL &= ~P3_USB_RD_HASH;
    P3DIR |= P3_USB_RD_HASH;
    P3OUT &= ~P3_USB_RD_HASH;
    P4SEL &= ~P4_EN_SW_BAT_1;
    P4DIR |= P4_EN_SW_BAT_1;
    P4OUT &= ~P4_EN_SW_BAT_1;
    P4SEL &= ~P4_XACC1;
    P4DIR |= P4_XACC1;
    P4SEL &= ~P4_YACC2;
    P4DIR |= P4_YACC2;
    P4SEL &= ~P4_YACC3;
    P4DIR |= P4_YACC3;
    P4SEL &= ~P4_ZACC1;
    P4DIR |= P4_ZACC1;
    P4SEL &= ~P4_ZACC4;
    P4DIR |= P4_ZACC4;
    P4SEL &= ~P4_ZACC5;
    P4DIR |= P4_ZACC5;
    P4SEL &= ~P4_AVCC;
    P4DIR |= P4_AVCC;
    P4SEL &= ~P4_EN_AVCC;
    P4DIR |= P4_EN_AVCC;
    P5SEL &= ~P5_PALE;
    P5DIR |= P5_PALE;
    P5OUT |= P5_PALE;
    P5SEL &= ~P5_PDATA_IN;
    P5DIR |= P5_PDATA_IN;
    P5OUT &= ~P5_PDATA_IN;
    P5SEL &= ~P5_PDATA_OUT;
    P5DIR |= P5_PDATA_OUT;
    P5SEL &= ~P5_USB_WR;
    P5DIR |= P5_USB_WR;
    P5OUT &= ~P5_USB_WR;
    P5SEL &= ~P5_USB_RD_HASH;
    P5DIR |= P5_USB_RD_HASH;
    P5OUT &= ~P5_USB_RD_HASH;
}

(x) MISC.h
#define false 0x00
#define true !false
/*
 unsigned int read_flash_int(void);
 void write_flash_int(unsigned int);
 void erase_info_flash(void);
 void DCO_750kHz(void);
 void delay10us(void);
 void delay250us(void);
 void delay3ms(void);
 void DCDC_power_on(void);
 void DCDC_power_off(void);
 void ref_on(void);
 void ref_off(void);
 void power_1_on(void);
 void power_1_off(void);
 void power_2_on(void);
 void power_2_off(void);
 void power_3_on(void);
 void power_3_off(void);
 void power_4_on(void);
 void power_4_off(void);
 void rf_power_on(void);
 void rf_power_off(void);
 void X1_on(void);
 void X1_off(void);
 void X2_on(void);
 void X2_off(void);
 void DCO_max(void);
 void set_mag(void);
 void reset_mag(void);
 void sensor_power_on(void);
 void sensor_power_off(void);
 void delayms(void);
 void usleep(unsigned int millisecond);
 void delay100us(void);
 void delay10s(void);
 void delay1s(void);
 void init(void);
*/

(xi) USB.c
#include "msp430x14x.h"
#include "USB.h"
#include "VEmain.h"
#include "Misc.h"
#include "acceleration_timer_b.h"
#include <stdio.h>
#include <stdarg.h>
#include <stdlib.h>
#include <string.h>
#include "utilities.h"
/*
#define bool unsigned char
#define DLV 1S 1000
#define MAXRETRANS 25
#define SOH 0x01
#define STX 0x02
#define EOT 0x03
#define ACK 0x06
#define NAK 0x15
#define CAN 0x18
*/
#define CTRLZ 0x1A
#define UART_RX_BUFFER_SIZE 64 /* 1,2,4,8,16,32,64,128 or 256 bytes */
#define UART_RX_BUFFER_MASK ( UART_RX_BUFFER_SIZE - 1 )
#define UART_TX_BUFFER_SIZE 8 /* 1,2,4,8,16,32,64,128 or 256 bytes */
#define UART_TX_BUFFER_MASK ( UART_TX_BUFFER_SIZE - 1 )

unsigned char UART_RxBuf[UART_RX_BUFFER_SIZE];
unsigned char UART_RxHead;
unsigned char UART_RxTail;
unsigned char UART_TxBuf[UART_TX_BUFFER_SIZE];
unsigned char UART_TxHead;
unsigned char UART_TxTail;

#if ( UART_RX_BUFFER_SIZE & UART_RX_BUFFER_MASK )
#error RX buffer size is not a power of 2
#endif

/*+++++++++++++++++++++++++++++++++++++++*/
/* PUBLIC FUNCTIONS (Read and write functions) */
/*+++++++++++++++++++++++++++++++++++++++*/

void init_usb(void)
{
  P2SEL &=~P2_USB_INT;
P2DIR &=~P2_USB_INT;
P2IES &=~P2_USB_INT;
P2IE |=P2_USB_INT;
}

bool USB_ReadByte(void)
{
  unsigned char data;
  unsigned char tmphead;
  if ((P2IN & P2_USB_RXF_HASH)==0)
  {
    P1DIR = 0;
P5DIR |=P5_245_DIR;
P5OUT &=~P5_245_DIR;
P1OUT = data;
P2OUT &=~P2_245_OE;
P2OUT |=P2_245_OE; //set back to HiZ
    tmphead = ( UART_RxHead + 1 ) & UART_RX_BUFFER_MASK;
    UART_RxHead = tmphead;
    if ( tmphead == UART_RxTail )
    {}
    UART_RxBuf[tmphead] = data;
    return true;
  }
  return false;
}

unsigned char ReceiveUARTByte( void )
{
  unsigned char tmphead;
  if ( ((P2IN & P2_USB_RXFHASH)==0) )
  {
    P1DIR = 0;
P5DIR |=P5_245_DIR;
P5OUT &=~P5_245_DIR;
P2DIR |=P2_USB_INT;
P5OUT |=P5_USB_DIR;
  }
  return false;
}

unsigned char USB_ReadByte(void)
{
  USB_ReadByte();
  while ( (UART_RxHead == UART_RxTail) )
  {
    tmptail = ( UART_RxTail + 1 ) & UART_RX_BUFFER_MASK; /* calculate buffer index */
    UART_RxTail = tmptail;
    TransmitUARTByte(asc2hex(d>>4));
    TransmitUARTByte(asc2hex(d&0x0F));
  }
  return false;
}

bool char Available( void )
{
  if (UART_RxHead==UART_RxTail)
    return(FALSE);
  else return(TRUE);
}

void void FlushUARTrx(void)
{
  UART_RxHead = 0;
  UART_RxTail = 0;
}

void sendhexUART(unsigned char d)
{
  TransmitUARTByte(asc2hex(d>>4));
  TransmitUARTByte(asc2hex(d&0x0F));
}

bool Is_UARTRx(char *code)
{
  unsigned char pos,t;
  if (UART_RxTail==UART_RxHead)
    return(FALSE);
  t=UART_RxTail; //get buffer tail
  pos=0; //start of string
  do
  {
    t=(t + 1 ) & UART_RX_BUFFER_MASK;
    if (UART_RxBuf[t]==*code) pos++;
    else pos=0;
  }while ((code[pos]!=0)&&(t!=UART_RxHead));
  if (code[pos]==0)
  {
    UART_RxTail=t;
    return (TRUE);
  }
  else return(FALSE);
}

void write_string_UART(char *str)
{
  unsigned char pos;
  for (pos=0;str[pos]!=0;pos++)
    TransmitUARTByte(str[pos]);
}

bool CharAvailable( void )
{
  if (UART_RxHead==UART_RxTail)
    return(FALSE);
  else return(TRUE);
}

#pragma vector=PORT2_INTERRUPT_VECTOR
int USB_Power_Detection(void)
{
  if (P2IN & P2_USB_INT)
  {
    power_1_on();
  }
}

void USB_ReadByte(void)
{
  USB_ReadByte();
  while ( (UART_RxHead == UART_RxTail) )
  {
    tmptail = ( UART_RxTail + 1 ) & UART_RX_BUFFER_MASK; /* calculate buffer index */
    UART_RxTail = tmptail;
    return UART_RxBuf[tmptail];
  }
}
(xii) USB.h

#define FALSE 0
#define TRUE (!FALSE)
#define false 0x00
#define true !false
#define bool unsigned char

unsigned char ReceiveUARTByte( void );
void TransmitUARTByte( unsigned char data );
unsigned char DataInUARTReceiveBuffer( void );
bool UARTCharAvailable( void );
void FlushUARTRx( void );
bool Is_UARTRx(char *code);
void write_string_UART(char *str);
void sendhexUART(unsigned char dat);
unsigned char ReceiveUARTByte( void );
bool USB_ReadByte( void );
void init_usb( void );
bool CharAvailable( void );
int USBprintf(const char *format, ...);

(xiii) UTILITIES.c

// UTILITY ROUTINES
#include <stdlib.h>
#include <stdio.h>
#include <stdarg.h>
#include <string.h>
#include "utilities.h"
#include "VEmain.h"
#define bool unsigned char

char numstr[17];
unsigned char byte_hexstr[3];
unsigned char button_flag=0;

void set_bit(volatile unsigned char* port,unsigned char bit)
{
    *port |= (1<<bit);
}
void clear_bit(volatile unsigned char* port,unsigned char bit)
{
    *port &= ~(1<<bit);
}
void invert_bit(volatile unsigned char* port,unsigned char bit)
{
    *port ^=(1<<bit);
}
bool bit_pattern(volatile unsigned char* port,unsigned char pattern)
{
    if (*port==pattern) return (true);
    else return (false);
}
bool bit_state(volatile unsigned char* port,unsigned char bit)
{
    return((*port>>bit) & 1);
}
unsigned char Hi_Byte(unsigned int dat)
{
    return((char)dat>>8);
}
unsigned char Lo_Byte(unsigned int dat)
{
    return((char)dat);
}
unsigned char* int2str(unsigned int i)
{
    itoa(numstr,i,10);
    return (unsigned char*)(&numstr[0]);
}

unsigned char* myltoa(unsigned long x)
{
    unsigned long d=1000000000,y;
    unsigned char m;
    char i;
    y=x;
    for (i=0;i<10;i++)
    {
        m=(unsigned char)(y/d);
        numstr[i]=m+48;
        y=y-(m*d);
        d=(unsigned long) d/10;
    }
    numstr[i]=0;
    i=0;
    while(numstr[i]=='0') i++;
    return (unsigned char*)(&numstr[i]);
}

unsigned char* byte2hex_str(unsigned char dat)
{
    unsigned char* p;
    byte_hexstr[0]=asc2hex(dat>>4);
    byte_hexstr[1]=asc2hex(dat&0x0F);
    byte_hexstr[2]=0;
    p = &byte_hexstr[0];
    return(p);
}

//=========================================
void itoa(char *buf, unsigned int i, int base)
{
    char* s;
    #define LEN10
    int rem;
    char rev[LEN10];
    if (i == 0)
        s = "0";
    else
    {
        rev[LEN] = 0;
        s = &rev[LEN];
        while (i)
        {
            rem = i % base;
            if (rem < 10)
                *--s = rem + '0';
            else if (base == 16)
                *--s = "abcdef"[rem - 10];
            i /= base;
        }
        strcpy(buf, s);
    }
    //*****************************************

unsigned int hex2bin(unsigned char* p)
//p= most sig nibble
{
    if (*p >= 0x41) *p -= 0x37; else *p -= 0x30;
    p++;
    if (*p >= 0x41) *p -= 0x37; else *p -= 0x30;
    return (((unsigned int) *(p-1)<<4) + *p);
}

(xiv) UTILITIES.h

#define bool unsigned char
bool bit_state(volatile unsigned char* port, unsigned char bit);
bool bit_pattern(volatile unsigned char* port, unsigned char pattern);
void set_bit(volatile unsigned char* port, unsigned char bit);
void clear_bit(volatile unsigned char* port, unsigned char bit);
void invert_bit(volatile unsigned char* port, unsigned char bit);
unsigned char* int2str(unsigned int i);
unsigned char* myltoa(unsigned long x);
unsigned char asc2hex(unsigned char nib);
unsigned char* byte2hex_str(unsigned char dat);
unsigned char Hi_Byte(unsigned int dat);
void itoa(char *buf, unsigned int i, int base);
unsigned int hex2bin(unsigned char* p);
CHAPTER 7

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