PHYSICAL PERFORMANCE IN PROFESSIONAL SOCCER MATCH-PLAY: FACTORS AFFECTING, CHARACTERISTICS AND CONSEQUENCES FOR TRAINING AND PREPARATION

BY

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STUDENT DECLARATION

I declare that while registered as a candidate for the research degree, I have not been a registered candidate or enrolled student for another award of the University or other academic or professional institution.

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ABSTRACT

This thesis presents, discusses and critically evaluates the content and contribution of a selection of research papers published in international peer-reviewed sports science journals. Collectively, these works make a novel contribution to the field of motion analysis of physical performance in official professional soccer competition. Rather than being the result of an initial grand working plan, the programme of research represents the evolution and expression of the author's work over a period of 4 years in a professional soccer club. The research was partly shaped by the author's concomitant experience of the industry and academia but mainly driven by emerging and evolving needs-analyses identified within his work. A total of 1 review (presented in the thesis as an introduction to the field of study) and 9 original peer-reviewed articles are included. This thesis introduces and critically comments on papers within two main streams of work investigating competitive physical performance in the author's own professional soccer team: a) general characteristics and position-specific demands of play, and; b) factors potentially affecting performance. The original research papers are presented in a conceptual sequence within the two themes, rather than a strictly chronological order so as to demonstrate the coherence and synergy within the two collections. The thesis provides critical reflection on the overall contribution to the current body of scientific knowledge and the collective impact of the papers that has been achieved. Limitations in study designs encountered over the course of the work are discussed as are current and future themes for research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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The scientific articles presented in this thesis represent several years of applied research in a professional soccer club setting. I would like to thank all my co-authors for all their valuable help and in particular, I am greatly indebted to the late Professor Tom Reilly. I will always be grateful for his hugely inspirational and insightful knowledge.

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CHAPTER 1 PREFACE TO THE PHD VIA COMPLETED WORK

1.1 Introduction

Performance in soccer (Association Football) is a construct requiring a myriad of skills but is highly dependent upon a subtle blend of players' physical, tactical, technical and socio-psychological abilities (Stølen, Chamari, Castagna, & Wisløff, 2005). At elite levels, the quest for success continuously leads practitioners, researchers and sports scientists to explore different means to evaluate and improve these main areas of performance, both singly and, more impactfully, in combination. As one of these indices, match analysis provides a factual record of game events underpinning both individual and team performance in competition. Moreover, match analysis provides a means of evaluating both the outcome and process of performance through quantification of the many characteristics of team play and the demands specific to individual playing positions (Carling, Williams, & Reilly, 2005). It is, in part, the basis for making informed judgements on performance and the provision of feedback, provided that data collection processes employ methods that are accurate, objective and reliable. Information gleaned from analyses of competition is used to guide decision-making as part of the coaching process and can help determine effective strategies for optimising the technical, tactical and physical skills specific to soccer.

In professional soccer internationally, the foundations for contemporary practice and competition are no longer based solely on simple personal views of how well players perform, or on traditional subjective analytical methods passed from one generation of coach to another. Over recent years, a more comprehensive approach to coaching through science is providing the applied practitioner and player with greater control, preparation, accountability and, most importantly, measurable progress (Meyers, 2006). Of course, the translation of knowledge and expertise gleaned from data derived from match analysis into a form that is usable and applicable in training and competition is paramount if it is to have a meaningful impact on performance. Yet, it is only in the last decade or so, however, that formal match analysis has gained widespread acceptance among soccer practitioners at professional standards of play (James, 2006). Reflecting this evolution, most professional clubs now formally employ match analysis in one form of other. A greater understanding by contemporary practitioners of the potential benefits of science and analytic processes has aided in bridging the gap between research and practice. In turn, this has led to the development of more evidence-based practice frameworks for optimising training and match preparation.

Within any evidence-based framework for professional sports performance, knowledge of the physical requirements of play is necessary to aid in the design and application of adequate fitness training strategies in preparation for contemporary competition (Bradley et al., 2009b). Indeed, research in male professional soccer has shown that the physical characteristics of players (Nevill, Holder, & Watts, 2009) and the fitness demands in official competition have substantially evolved over recent decades (Cazorla, Zazoui, Boussaidi, Zahi & Duclos, 2009; Strudwick & Reilly, 2001). The main purpose of any contemporary strength and conditioning process is thus to equip players with the optimal blend of fitness-related skills to respond to the ever-evolving demands of elite soccer competition. These demands refer to a wide range of characteristics that are essential in assisting players in competing for possession of the ball, reacting quickly and optimally to continually changing game situations, and maintaining high performance levels throughout the entire duration of games and across the competitive season (Reilly, 2007). Accordingly, a thorough understanding of the athletic requirements specific to match-play and factors potentially affecting competitive performance can ensure that objective and realistic decisions are taken for structuring the physical conditioning elements of training programmes.

Generally speaking, the framework structure of any physical conditioning regimen should ensure that an appropriate and complementary combination of fitness components is provided to cope with the particular requirements of play. Indeed, the physical development framework in soccer refers to the various elements underpinning the conditioning programme: developing work capacity and endurance, speed, strength, power and recovery (Svensson & Drust, 2005). A challenge for conditioners is to provide a systematic approach to integrate, develop, and fine-tune this multitude of physical qualities. Accordingly, a primary step underpinning the conditioning process of these fundamental fitness elements is the monitoring of exercise intensity in competition to objectively quantify the contemporary characteristics of performance and position-specific demands of the sport (Reilly, 2003b). Unfortunately, institutional rules and regulations currently forbid both the wearing of any electronic device to record movement and the sampling of physiological responses to exercise in official professional soccer competition. Monitoring physiological responses during exercise must always be socially acceptable, non-invasive and not interfere with performance (Drust, Atkinson, & Reilly, 2007); factors which are currently unfeasible with contemporary professional soccer rules. Consequently, information on exercise intensity via measures such as heart rate, lactate concentrations, oxygen uptake and body temperature are unavailable at the highest levels of play although recently, promising work has been conducted in an attempt to estimate the energy cost of physical activity using analysis of player movements on video recordings (Osgnach, Poser, Bernandini, Rinaldo, & di Prampero, 2010). Nevertheless, the permanent ban imposed by the game’s authorities partly contributed to the development of a process for indirectly determining physical exertion in professional soccer competition through the analysis of locomotor activities known as motion analysis (Bloomfield, Polman, & O’Donoghue, 2007).

The evaluation of physical performance in match-play via motion analyses within a professional football club setting and its applicability to fitness testing, training and preparation for elite competition are the raison d’être of the present doctoral thesis. This document presents, discusses and evaluates the content and contribution of a selection of published papers from a larger body of research produced over the course of my work in a professional soccer club. It outlines the journey and subsequent development of my work and several original research outputs that I feel collectively have shaped and made a novel and substantial individual contribution to the literature on motion analysis of professional soccer performance.

CHAPTER 2 THE CONTEXT, RATIONALE AND AIMS OF THIS PROGRAMME OF RESEARCH

2.1 Introduction

It is critical to employ sound scientific principles of physical conditioning and coaching in order to enhance sports performance. As part of the coaching process, empirical information from analyses of performance in competition is essential to provide a platform upon which objective decisions for training and preparation can be made. The role of the sports scientist in this process, within professional soccer, is to be the vehicle for interfacing novel technology and research with practice and play in the context of the sport (Reilly & Mujika, 2008). As a sports scientist working in a professional soccer team setting, many key issues and problems arose and were encountered in my day-to-day work over a period spanning four-seasons (2007-2011) providing opportunities for new lines of investigation. It was against this ‘pragmatic’ backdrop that the programme of work which comprises the bulk of the thesis was conducted. This applied research was conducted primarily with the main aim of providing practically relevant and usable match analysis data to support and drive training and preparation for competitive performance. The research model applied over the four-year study period and used within this thesis is therefore positioned mostly towards the applied end of the basic-applied research continuum presented by Atkinson & Nevill (2001) and expanded upon more recently by Drust et al. (2007).

At the beginning of the 2007/2008 competitive season, a need for information on competitive physical activity profiles was identified in collaboration with my club’s coaching, fitness and fellow sports science personnel to address specific questions on physical performance and aid in informing current training and match preparation strategies. In addition, inclusion of information on injury and skill-related performance (e.g., technical and tactical data) was deemed to be essential (albeit when pertinent and possible) by our coaching and research personnel to complement data on physical activity to increase our overall understanding of competitive performance. In 2007, I decided to draw up a critical review article (presented as paper 1 in Chaper 3) synthesising the scientific literature on methodological considerations and practical applications of motion analysis data regarding physical performance in professional soccer match-play. A critical review of the current state of knowledge corresponds to the starting point for conducting applied research outlined by Bishop (2008) in his applied research model for the sports sciences.

Paper 1 was written with the joint aim of increasing awareness in practitioners, sports science personnel, and researchers both in my club and in the industry internationally of the use of motion analysis both past and present to measure and better understand competitive physical performance. Indeed, despite the appearance of several comprehensive review articles on physiological performance and/or fitness testing in soccer (Drust et al., 2007; Hoff & Helgerud, 2004; Impellizzeri, Rampinini, & Marcora, 2005; Reilly, Drust, & Clarke, 2008; Stølen et al., 2005; Svensson & Drust, 2005), I considered the lack of a practice-informed review covering the recognised discipline of motion analyses prior to writing paper 1, to be surprising. This review paper was subsequently published in 2008 and a copy is provided in the appendices at the end of this thesis (paper 1: appendix 1a). In chapter 3 of this thesis, paper 1 simultaneously forms the basis for the introduction to the present study area and this doctoral thesis. The reference of paper 1 is:

Paper 1. Carling, C., Bloomfield, J., Nelsen, L., & Reilly, T. (2008). The role of motion analysis in elite soccer: Contemporary performance measurement techniques and work-rate data. *Sports Medicine, 38*, 839-862.

Following on from findings reported in paper 1 and a subsequent real-world needs-analysis ascertained between my club's coaching and fitness staff and myself, several novel research projects in this field were devised and eventually conducted. The conception of several of the other original papers presented in this thesis arose from a day to day needs-analysis by myself and fellow practitioners as well as from the constant call to shape policy and practice in order to aid my club in achieving its goals. In essence, the present set of works aimed to expand our knowledge and understanding of physical performance in contemporary official professional competition mainly in players in my club and more broadly for a wider audience in elite soccer. In each case, the instigated research projects investigated a theme regarding motion analysis that had either not been covered in the scientific literature or in which only limited information was available. Two main applied themes deemed worthy of further investigative research using motion analysis were thus identified:

1) analysis of general characteristics and position-specific demands of physical performance in official match-play,
2) factors potentially affecting physical performance in official match-play.

Respectively, this work has led to the publication in a number of international peer-reviewed journals of four papers investigating general characteristics of physical activity in my team and game demands in relation to playing position, and five papers that examined factors potentially affecting match-play performance. In Chapter 3, these published works are individually contextualised by a short rationale and the aims are described for each study. Following on from Chapter 3, a general overview of materials and methods and a description of the experimental approach used across the nine studies are provided in chapter 4. Chapters 5 and 6 provide an overview of each paper's findings and demonstrate the conceptual links between study themes and the set of works presented in each respective research theme. A critical commentary on respective study designs and their limitations and which identifies their contribution to the scientific literature is provided. While it is acknowledged that there may be some repetition of each study's findings on reading the original articles, this discussion also aims to provide a fresh look at the papers and their results and practical implications. Chapters 5 and 6 also include snippets of data not included in the final publications. Pertinent findings obtained from more recent research found in the literature that has been conducted after these articles were published are also presented. The papers are presented in a conceptual sequence within the two main themes of research, rather than a strictly chronological sequence. This was done in an attempt to demonstrate the coherence and synergy within the collection of works. Copies of the nine original research papers (and paper 1) are included as appendices at the end of the thesis. Finally, chapter 7 continues with a discussion of the global impact of these works, current work in progress and considers future directions for research.

CHAPTER 3 THE ROLE OF MOTION ANALYSIS IN ELITE SOCCER: TECHNIQUES, CONSIDERATIONS AND PRACTICAL APPLICATIONS

3.1 Introduction

Over the last four decades, academic and practitioner based interest in motion analysis as a sub discipline of match analysis has grown substantially (Carling & Williams, 2008). As a reflection of this interest, a large number of professional soccer teams across all continents are now using a range of motion analysis techniques to monitor physical performance during competition and impinge on daily practice and game preparation. As mentioned earlier, for the purposes of the present thesis, I felt it necessary to include a synthesis of my review article (paper 1). This was done not only to provide an introduction to issues and considerations within the present field of study but as a means for setting the scene for the remainder of the research presented in this thesis that I have conducted in my club over a four year period (2006-2010). In this review, I judged it necessary to collate and critically appraise data collection techniques, as well as findings from research presented in the established body of accumulated knowledge on the general characteristics of performance and the position-specific requirements of play. I also identified a need for discussion of the interpretation and reporting of data derived from motion analyses and their reliability, objectivity and accuracy. Finally, I presented practical implications for conditioning and preparation for contemporary professional soccer as well as a discussion of features potentially affecting the performance of players in competition. For the purposes of the present thesis and where appropriate, output from more recent published research not available at the time of paper 1 is highlighted. Discussion of research output is generally limited to analyses of elite male 11-aside soccer thereby reflecting the context of the work conducted in this thesis.

As mentioned earlier, over the course of writing paper 1 and the constant need to analyse and identify where improvements could be made in our day to day work, two main research themes linked to the analysis of team performance were identified by myself in collaboration with our coaching fitness and sports science staff. These two themes were considered worthy for investigation with the aim of informing and eventually shaping practice in my club and form the basis for the 9 original research papers presented in this thesis. An overview of the rationale and aims is provided for these original research projects each of which was conducted, written and published over the four-year study period. These papers covered: 1) general characteristics of physical performance in match-play in players my team and the individual demands relative to playing position, and; (2) factors potentially affecting physical performance in match-play.

3.2 An overview of motion analysis techniques

3.2.1 Manual techniques

Over the last four decades, numerous techniques have been used to elucidate the physical demands of soccer match-play, based upon measures of distance covered and fluctuations in running intensity throughout a game (Randers et al., 2010). For a detailed summary of progress over recent times in this field of study and additional information on methodologies, the reader is directed to two books I have co-authored (Carling et al., 2005; Carling, Reilly, & Williams, 2009) and two recent review papers (Barris & Button, 2008; Leser, Baca, & Ogris, 2011). Nevertheless, previous methods of monitoring movements of players during competition have included tape-recorded commentaries, video-recordings, film analysis, synchronized trigonometric techniques and more recently computer-aided video analysis. Up until the last two decades or so, manual coding systems were generally employed for collecting motion analysis data on athletic performance in soccer. Two definitive studies using manual techniques to analyse professional soccer play were respectively conducted by Reilly and Thomas (1976) and Bangsbo, Nørregaard and Thorsøe (1991). The former employed a subjective assessment of distances and exercise intensities recorded manually or onto an audiotape recorder. A learnt map of pitch markings was used in conjunction with visual cues around the pitch boundaries. The latter combined analysis of video recordings of player movement in match-play with individual locomotor characteristics pre-established according to runs performed at different exercise intensities. The time for the player to pass pre-markers and known distances was used to quantify the speed for each activity of locomotion.

While data collected using these methodologies were generally shown to be convenient, reliable and inexpensive, and their use in contemporary motion analysis research on elite soccer play is still frequent (see works by Andersson, Randers, Heiner-Møller, Krustrup, & Mohr, 2010; Gabbet & Mulvey, 2008; Mohr, Krustrup, Andersson, Kirkendal, & Bangsbo, 2008; Mohr, Krustrup, & Bangsbo, 2003), they are associated with several recognised limitations. In general, manual coding methods are highly dependent on observer experience and rely on subjective interpretations of distances covered and running speeds. They are also considerably labour-intensive, thus time-consuming, and generally limited to the analysis of a single player at a time. To a certain extent, the data collection process is recognized as being subject to inaccuracies, notably when recording positional information. Moreover, these techniques do not allow accurate quantification of transitional changes between running speeds (James, 2006) and notably the acceleration and deceleration phases inherent to sprint-type activities. These limitations combined with the natural progression in information and video technology eventually led to the development of computer hardware and software and electronic devices dedicated to the analysis of physical activity in match-play.

3.2.2 Computerised techniques

In the late 1990s, the development of commercial video-based semi-automatic player tracking systems (e.g., AMISCO Pro, Sport-Universal Process, Nice, France, and Prozone, Prozone Ltd, Leeds, UK) revolutionised motion analysis of competitive physical performance in professional soccer. These pioneer systems greatly streamlined and extended the frontiers for collection, analysis and presentation of athletic performance data. Using digital video footage of games obtained from a set of permanently fixed cameras positioned strategically to cover the entire playing surface, the movements of all 22 players (and referee) are tracked simultaneously using advanced image processing techniques. This form of analysis provides an unobtrusive means of collecting competition-specific information on technical, tactical and physical performance. These systems have been widely adopted across European professional soccer and are generally considered in the professional soccer community as setting the standard in motion analyses of soccer play (Carling & Williams, 2008). Analysis is completed post-match but requires manual operator intervention to correct errors, mainly when interruptions in player tracking occur due to occlusions from cluttering (Barris & Button, 2008; Barros et al., 2007). Players are occasionally lost on camera viewpoints and cannot be tracked by the software in situations where multiple players cluster in restricted playing areas (e.g., a crowd of players in the penalty area awaiting a corner kick). Results are generally available 12-24 hours post-competition as strict quality control checks of the raw data files are necessary. Independent testing of data on player movements generated by these systems has nevertheless shown sufficient levels of accuracy, reliability, and validity (Di Salvo, Gregson, Atkinson, Tordoff & Drust, 2009; Randers et al., 2010; Zubillaga, 2006) thereby reassuring applied practitioners and academics of their scientific legitimacy. As a further procedural constraint, these systems are generally restricted to usage in a team's home stadium. To counter this limitation, many teams have signed reciprocal agreements to share data when playing home and away against other clubs using the same system. Work is also underway to develop portable real time video analysis systems using advanced mathematical algorithms to allow live tracking of players during games (Redwood-Brown, Cranton, & Sunderland, in press).

Alternatively, tracking technologies including portable devices such as Global Positioning System (GPS) receivers and electronic transponders are being employed within the professional soccer club setting to localise players and track their movements. These systems permit the concomitant collection of motion analysis data and heart rate responses to exercise. Information on the frequency and intensity of accelerations and impacts such as tackles and collisions are also incorporated in the analysis to propose a physical load index that quantifies the stresses placed on the player. Additional information on workings, reliability and applications of GPS and electronic transponders in team sports can be obtained in a review written by Aughey (2011) and in an original research article by Frencken, Lemmink & Delleman (2010) both of which were published after paper 1. In general, the recording of any physiological data is limited by the rules and regulations of the competitions in which players are involved (Impellizzeri et al., 2005). Usage of these systems in professional soccer is therefore restricted to training sessions, pre-season friendly matches and youth competition as players are equipped with electronic material which is currently forbidden at professional and international senior level. As with the commercial video-based player tracking systems mentioned beforehand, these devices are also relatively costly thereby restricting usage to the upper echelons of the game. Furthermore, doubts still subsist as to the ability of GPS in reliably and accurately measuring activities performed at high-intensities due to low sampling rates (<5HZ) even though measurement rates have considerably increased (currently 15HZ) since the publication of paper 1 (Coutts & Duffield, 2010; Jennings, Cormack, Coutts, Boyd, & Aughey, 2010; Varley, Fairweather, & Aughey, 2012). In particular, care is needed when interpreting data collected on performance in single sprints and when rapid changes in direction and variations in running speed occur.

3.2.3 Additional technical considerations

In general, at the time of paper 1, none of the above mentioned computerised systems was yet considered the ‘‘gold standard’’ method for indirect quantification of workload in soccer. Two book chapters I have recently authored have re-reviewed the current literature (Carling, in press; Carling & Bloomfield, in press) and have shown this is still the case at the time of writing of this thesis. In addition, the development of a single validation test protocol for evaluating the validity, reliability and objectivity of data derived using any form of motion analysis is still lacking. Indeed, this might be one of the reasons why there is insufficient evidence in the literature, both past and present, demonstrating the scientific legitimacy of some systems used to analyse match performance. There are also issues regarding the interpretation of physical performance data notably the lack of agreement on definitions used to define and classify high-intensity and/or sprint-type running actions. For example, no consensus exists on the speed threshold that must be attained and the necessary time spent at this speed for discrete activities to be classed as a high-intensity effort. This lack makes objective comparisons of datasets across published studies, especially regarding the high-intensity components of running performance, difficult to achieve. Consensus between coaching and conditioning personnel, sports scientists and performance analysts on definitions is necessary.

3.3 Overview of motion analysis data regarding physical performance in match-play

3.3.1 Introduction

Motion analysis provides a means to quantify work activity profiles and physical requirements of contemporary professional soccer as well as the specific demands across individual playing positions. Irrespective of the collection methods employed, data obtained from motion analyses are translated into distances covered or the frequency of time spent in a variety of discrete locomotor activities to quantify and evaluate physical performance. These discrete activities are generally classed and coded according to pre-determined intensities based on the speed of running movements (Reilly, 1997). Activities are commonly defined as walking, low-, moderate-, and high-intensity (or cruising) and sprinting movements. Other game-related activities include backwards and sideways running, accelerations and decelerations, jumping, shuffling, swerving and turning movements (Bloomfield et al., 2007; Robinson, O'Donoghue, & Wooster, 2011). Finally, physical efforts when in individual possession of the ball (such as distance covered in dribbling) and actions involving challenges for the ball (e.g., number of headers and tackles) can also be incorporated in the overall analysis.

3.3.2 Physical activity profile of the elite player and positional demands

On average, consensus across data in the literature shows that contemporary male professional outfield soccer players cover distances ranging from 10-13km while goalkeepers run 4-6km per game. The overall distance covered provides a global representation of the intensity of exercise and the individual contribution to the total team effort (Reilly, 2003b). Data collected around the year 2000 on the total distance covered by top-flight English players (Strudwick & Reilly, 2001) showed a considerable increase in this measure over the two and a half decades separating results from findings using the same manual motion analysis techniques in a pioneer study published in 1976 (Reilly & Thomas, 1976). In general, activities at lower levels of intensity tend to dominate the overall performance profile, emphasising the predominantly aerobic nature of the game. The ratio of low- to high-intensity exercise in terms of distance covered is about 5:2 or about 7:1 when based on time (Reilly, 2007). Again, consensus across published studies shows that the majority of movement is spent in low to moderate intensities, with approximately 10% of the total distance covered by professional players over the course of matches spent in high-intensity type activities. In addition, the majority of high-intensity actions, irrespective of playing position, are short in both distance (<20m) and duration (<4 seconds) (Spencer, Bishop, Dawson & Goodman, 2005a). While high-intensity movement makes up only a small part of the total distance covered, elite soccer players nevertheless perform between 150 and 250 intense actions per game (Iaia, Rampinini, & Bangsbo, 2009). Research in the English Premier League has shown that players perform a run at high-intensities (>19.8 $km{\cdot}h^{-1}$) every 72-s (Bradley et al., 2009b) and Strudwick and Reilly (2001) observed a change in running activity every 3.5s, a high-intensity bout every 60s, and a maximal effort every 4 minutes. Another common feature of competitive play is that only a small percentage (~2%) of the total distance covered by players is achieved in individual possession of the ball including actions such as dribbling or running with the ball (Di Salvo et al., 2007).

In general, players have to perform many types of exercise over 90-minutes, ranging from walking to maximal running and the intensity of movement can vary at any time; therefore the activity profile is intermittent in nature (Bangsbo, Mohr, & Krustrup, 2006). High-intensity efforts are unpredictable and sometimes follow each other resulting in dense phases of work known as repeated high-intensity activity. Juxtaposed on the activity profile are different skill-related activities performed with or without the ball such as dribbling, passing and shooting or challenging for possession. Unorthodox modes of motion such as running backwards and sideways are also common and the additional energy cost associated with these movements should be taken into account in the overall analysis (Carling & Williams, 2008; Reilly, 2005).

In general, soccer play makes demands on the majority of the body's energy systems (Krustrup et al., 2006). Players must have sufficient aerobic and anaerobic capacities to perform prolonged intermittent-type exercise and to sustain performance in and recover quickly from repeated high-intensity bouts. An ability to develop high power output is also necessary for explosive actions such as jumping to head the ball or accelerating to close down an opponent. Finally, muscular strength is important in resisting opponents when challenging for possession. Further information on the physiological and metabolic responses to intermittent exercise can be obtained in several comprehensive reviews by Bangsbo et al. (2006), Bangsbo, Iaia and Krustrup (2007), Bangsbo and Krustrup (2009), Glaister (2005) and Spencer et al. (2005a).

Across playing positions there is significant variation in the general fitness components (Svensson & Drust, 2005) and competitive physical activity profiles (Bloomfield et al., 2007; Burgess, Naughton, & Norton, 2006) with these mainly linked to the tactical demands specific to each role. As such, match performance data should be analysed and interpreted according to individual playing position rather than for a positional group as a whole. For example, it is recognised since the earliest analyses that fullbacks run statistically significant greater total distances than central defenders (Bangsbo et al., 1991; Reilly & Thomas, 1976). In the contemporary game, fullbacks and wide midfield players generally report the largest distances covered in high-intensity running (Di Salvo et al., 2007). More recent work in professional soccer has shown that physical activity profiles even differ significantly among central midfield players according to individual tactical role (e.g., offensive versus 'holding' type central role; Dellal et al., 2011). Additional analyses available since the publication of paper 1 have notably extended the above body of research by demonstrating large differences in high-intensity characteristics across playing positions according to whether actions were 'explosive' (sprint characterized by a fast acceleration) or 'leading' (sprint characterized by a gradual acceleration) in nature (Di Salvo et al., 2010; Di Salvo, et al., 2009). Combined, this research suggests the need for a criterion model in order to tailor training programmes to suit the particular needs of each playing position and the situations individuals commonly experience during a game.

3.3.3 Fatigue and variations in match performance

Motion analyses of professional soccer play have frequently demonstrated intra-match declines (Iaia et al., 2009) and inter-match variations (Gregson, Drust, Atkinson, & Di Salvo,

2010) in physical performance. In effect, game profiling shows that players may experience impaired performance transiently after short-term periods of intense activity, at the beginning of the second-half, overall in the second- versus the first-half, in the final period towards the end of games, and during periods of fixture congestion. Collated information in paper 1 showed that on average, a 3.1% drop in the total distance run between halves (range: -9.4% to +0.8%) has been reported across studies on elite soccer. While Di Salvo et al. (2007) reported no statistical difference across halves in high-intensity running performance for players in professional Spanish football clubs and other top players participating in UEFA Champions League games, the inverse was more recently observed in English Premier League matches (Di Salvo et al., 2009) suggesting a need for additional research.

Analyses of play in the English Premier League (Bradley et al., 2009b) and other high-standard players (Mohr et al., 2003) have reported substantial declines in high-intensity running both during the last 15-minute interval of games (drops up to -45%) and in the 5-minute interval following the 5-minute period during which activity peaked (drops up to -47%). Research has also demonstrated a significant drop in sprint performance in sub-elite players during a test of repeated sprint ability performed immediately after an intense period of match-play (Krustrup et al., 2006) suggesting that soccer players transiently experience fatigue temporarily during the game. However, similar data are unavailable in professional soccer players. Research into the underlying physiological mechanisms suggests that accumulated fatigue setting in towards the end of a soccer game may be caused by reduced glycogen concentrations in individual muscle fibres (Mohr, Krustrup, & Bangsbo, 2005). The physiological mechanisms behind temporary fatigue observed after dense periods of intense exercise in soccer remain unclear although accumulation of potassium in muscle interstitium and a concomitant change in muscle-membrane potential has been suggested to be a contributing factor to fatigue (Bangsbo et al. 2007). A significant fall in physical activity at the beginning of the second-half notably in comparison to the opening period of the first-half has also been reported (Mohr, Krustrup, Nybo, Nielsen, & Bangsbo, 2004). Impaired performance was linked to players resting during the half-time break leading to a drop in muscle temperature and the lack of a warm-up routine as was systematically performed prior to the match kick-off.

It is acknowledged that ‘natural’ variations in physical activity profiles occur over consecutive games, at different stages of the season and across seasons (Gregson et al., 2010; Mohr et al., 2003). For example, the total distance covered and running at high-intensities in a professional Italian soccer team increased during the second-half of the season (Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007b). Across the season, changes in performance might be linked to alterations in the physical condition of the players as the activity profile in match-play can fluctuate in conjunction with the amount of fitness training that is completed by the team (Drust et al., 2007). Physical performance can also be affected during periods of fixture congestion in which matches are played successively over a short time frame (Dupont et al., 2010; Odetoyinbo, Wooster, & Lane, 2009; Rey, Lago-Penas, Lago-Ballesteros, & Dellal, 2010). This latter point is covered in more detail in section 3.7.3.

3.4 Implications of motion analysis data for fitness training & testing

From the point of view of training, general exercise-to-rest ratios or low- to high-intensity exercise ratios can be calculated using motion analysis data to accurately represent the demands of the sport and provide objective guidelines for optimising the conditioning elements of training programmes (Reilly, 2007). Information on the frequency of repeated high-intensity efforts and time spent in recovery between discrete intense bouts of exercise is also considered particularly pertinent in contemporary soccer for designing high-intensity conditioning programmes (Spencer et al., 2005a). The specific demands across playing positions identified earlier in this thesis have important implications for adopting a more individualised approach to physical conditioning.

Performance profiling can also be used to highlight individual deficiencies such as a susceptibility to fatigue, shown by an inability to repeat and maintain performance in high-intensity efforts over the course of games. The incapacity to recover quickly after an intense bout of exercise or a general drop-off in performance towards the end of play might suggest a need for supplementary and/or conditioning programmes tailored to individual playing positions. In similar fashion, during an intense period of competitive fixtures, profiling physical activity may give objective confirmation of the coach's subjective diagnosis that some players are coping well and others are failing to do so when actual performance is compared to benchmark data. Results from such investigations have implications for the recovery protocols (e.g., nutritional intakes, sleep, and spa and compression treatments) employed by fitness and medical staff between matches and fitness programmes which aim to enable players to maintain high levels of physical and technical performance throughout the duration of play and across the entire competitive season.

A strong relationship has been observed between player fitness determined in selected field tests and physical performance in competition obtained from motion analyses. For example, individual field test scores of repeated sprint ability (Rampinini et al., 2007a) and intermittent running performance (Bradley et al., 2011b; Krustrup et al., 2003; Randers, Jensen, Bangsbo, & Krustrup, 2009) are notably associated with the distance covered in high-intensity running by elite players in match-play. Unfortunately, no information is currently available on the relationship between performance in aerobic, intermittent and repeated sprint tests and repeated high-intensity activity in match-play (e.g., several successive high-intensity efforts performed over a short time interval) especially as the latter is considered to be a fundamental contributor to success in contemporary elite soccer (Gabbet & Mulvey, 2008).

Motion analysis data drawn from match-play have also been employed to aid in the design of laboratory- and field-based protocols to simulate soccer-specific intermittent exercise and the intensities associated with competitive play. These protocols have been used to measure the effects of fitness training interventions (Small, McNaughton, Greig, & Lovell., 2009b), warm-up programmes (Lovell, Midgley, Barrett, Carter, & Small, 2011), nutritional strategies (Clarke, Drust, Maclaren, & Reilly, 2008; Sari-Sarraf, Doran, Clarke, Atkinson, & Reilly, 2011), temperature (Clarke, Maclaren, Reilly, & Drust, 2011; Drust, Cable, & Reilly, 2000), interactions between mental work and physiological responses (Greig, Marchant, Lovell, Clough, & McNaughton, 2007), fatigue on soccer skill performance (Russell, Benton, & Kingsley, 2011a) and injury risk (Rahnama, Reilly, Lees, & Graham-Smith, 2003; Small, McNaughton, Geig, Lohkamp, & Lovell, 2009a, Small, McNaughton, Greig, & Lovell, 2010).

Despite the large number of protocol designs used to simulate match-play, Drust et al. (2007) suggested there is a need to increase ecological validity by enhancing their specificity to soccer via inclusion of more specific game activities and development of a more individualised basis for physical efforts. Their direct validity to match-play is limited by factors such as the absence of a ball and opposition, inclusion of straight-line running only, and minimal opportunities to self-regulate physical effort (Edwards & Noakes, 2009). However, since the publication of paper 1, new soccer-specific running performance tests have been developed and validated (albeit in amateur soccer players) in an attempt to counter the aforementioned limitations commonly demonstrated in previous protocols (see works by Russell, Rees, Benton, & Kingsley, 2011b; Williams, Abt, & Kilding, 2010).

Finally, information from motion analyses has been used in an attempt to determine the effects of fitness training and/or recovery interventions on subsequent physical performance in match-play. Up until now however, controlled intervention studies have only been performed in youth soccer players (Helgerud, Engen, Wisloff, & Hoff, 2001; Impellizzeri et al., 2006) mainly due to difficulties in conducting similar research in the professional soccer club setting. In addition, the transfer of quantifiable outcomes following any form of training intervention into meaningful changes in match performance remains a challenge in professional soccer due to the random and natural variations inherent to match-play.

3.5 The present body of work on general characteristics and position-specific demands of physical performance: rationale and aims

3.5.1 Introduction

The body of research using motion analysis described earlier has comprehensively identified the work activity profiles and physical requirements of contemporary professional soccer match-play as well as the specific demands across individual playing positions. It has also demonstrated the practical implications of this information for applied practitioners and researchers. In addition, investigations have enabled identification of substantial variations in physical performance across matches as well as indicators concerning the extent of fatigue experienced by players during competition. Yet, in motion analyses as with any area of research in the area of sports sciences, the challenge for future researchers is to overcome remaining research design hurdles and devise ways to more fully understand the complexities of invasive field games such as soccer (Drust et al., 2007). It is also important to continually build upon and add to existing findings in an attempt to reinforce knowledge and the scientific rationale for the design and application of future evidence-based interventions in practice and preparation for competition. This is particularly important in the ever-evolving environments within professional soccer club settings and in which practitioners are constantly searching for the best means to aid their team and players to progress. In the following section, gaps in the available literature on motion analysis that I felt merited attention are identified and an overview of the rational and aims is provided for four original research projects that I subsequently conducted and published over the four-year study period.

3.5.2 Paper 2 (Appendix 2a): Analysis of physical activity profiles when running with the ball in a professional soccer team

In professional soccer, research has shown that only a small amount of the total distance covered by players is in possession of the ball (Di Salvo et al., 2007; Rampinini et al., 2007b). In general, there is consensus across the motion analysis literature that players are only in possession for approximately 2-3% of the entire match duration. Yet the ability to run with the ball is considered by coaches to be a key component of match-play performance in professional soccer and activity is thought to be highly dependant on playing position. Highly ranked professional soccer teams are shown to run greater distances with the ball than counterparts from lower ranked teams (Rampinini, Impellizzeri, Castagna, Coutts & Wisløff, 2009). In addition, research has shown that physical efforts of professional players when in possession of the ball have increased in the contemporary game compared to in previous decades (Di Salvo et al., 2007; Williams, Lee, & Reilly, 1999). Running with the ball is also known to substantially increase physiological stress compared with normal locomotor activities (Hoff, Wisløff, Engen, Kemi, & Helgerud, 2002; Reilly & Ball, 1984; Rupf, Thomas & Wells, 2007). Thus physical conditioning drills incorporating running with the ball can be a useful basis for concomitantly developing fitness and technical skills.

Despite these findings, only limited research has been conducted to characterise this area of performance and identify position-specific demands. Detailed information is lacking on the range of speeds at which outfield players receive possession and subsequently run with the ball, including the length and duration of running actions and number of touches taken. Similarly, there is little evidence on whether in-game declines in this component of play occur, for example across match halves and towards the end of games. Four specific aims for paper 2 were thus formulated: 1) to determine physical activity profiles in the reference team when running with the ball, 2) to examine the potential occurrence of fatigue in this component over matches, 3) to investigate technical aspects of individual ball possession; and, 4) to identify whether or not differences in game demands exist across playing positions. It was hoped that the results derived from paper 2 would have implications for designing training drills to develop and optimise physical and technical skills with the ball as well as impacting on the design of protocols used for testing performance in this particular component of play. The reference for paper 2 (appendix 2a) is:

Paper 2: Carling, C. (2010). Analysis of physical activity profiles when running with the ball in a professional soccer team. *Journal of Sports Sciences, 28,* 319-328.

3.5.3 Paper 3: Analysis of repeated high-intensity running performance in professional soccer

The physical preparation of the elite player has become an indispensable part of contemporary professional soccer mainly due to the high fitness levels required to cope with the ever-increasing energy demands of the game reported in paper 1. Along with a player's capacity to run with the ball, sprint-type activities in particular are widely considered to be a crucial element of performance in professional soccer competition. As mentioned earlier in this thesis, per game, top-class soccer players perform 150 to 250 intense running actions (Mohr et al., 2003) and perform a run at high intensities (>19.8 $km{\cdot}h^{-1}$) every 72s (Bradley et al., 2009b). This intermittent exercise is characterised by short-duration sprints (<5s) separated by recovery periods that are sufficiently long (>60s) to allow near or full-recovery after an intense effort. In contrast, repeated-sprint type exercise in which similar sprints of short-duration are interspersed with shorter recovery intervals (<60s) can lead to marked decrements in subsequent running performance (Girard, Mendez-Villanueva, & Bishop 2011). In professional soccer, the ability to recover and subsequently reproduce intense efforts (termed repeated-sprint ability) is widely accepted among practitioners and sports science personnel to be a critical component of contemporary performance (Iaia et al., 2009). Yet, there is limited information on the ability of elite soccer players to perform specific bouts of exercise during which they repeat several successive intense running efforts of short duration over short time intervals (repeated-sprint bouts) and to my knowledge none in male players at professional standards.

Up to now, research in this area has been limited to amateur male (Orendurff et al., 2010), international youth male (Buchheit, Mendez-villanueva, Simpson, & Bourdon, 2010) and international female (Gabbett & Mulvey, 2008) participants. The quantity of information provided on the frequency and characteristics of repeated-sprint bouts is also relatively inconsistent. The frequency of bouts and the mean number of sprints per bout as well as the duration and nature of recovery periods between successive sprints within these bouts warrant investigation at professional standards especially in relation to individual playing position. Furthermore, no information is available on the capacity of players to maintain performance in consecutive sprints within these repeated-sprint bouts (e.g., is there a progressive decline in maximal and/or mean velocity across successive sprints?). Finally, while the strong relationship established between physical fitness in elite soccer players and work activity profiles in competition was presented in paper 1, data examining the relationship between the ability to repeatedly perform high-intensity running actions in actual competition and scores obtained from tests of repeated sprint ability are scarce (Rampinini et al., 2007a).

Consequently, paper 3 aimed to characterise repeated high-intensity movement activity profiles in my team in match-play and determine whether there are demands specific to each playing position. The construct validity of tests commonly used to analyse this component of performance was investigated by testing the relationship between results from a laboratory test of repeated sprint ability and actual running performance in match-play. It was hoped that findings would provide a detailed insight into repeated high-intensity activity profiles and the extreme demands of match-play in a top 5 ranked professional soccer team in French soccer and would complement information reported in paper 2. The results would also have consequences for the design of the conditioning elements of training programmes and for evaluating the logical validity of repeated sprint ability tests used to determine high-intensity running performance in professional soccer players. The reference for paper 8 (appendix 2b) is:

Paper 3: Carling, C., Le Gall, F., & Dupont, G. (2012). Analysis of repeated high-intensity running performance in professional soccer. *Journal of Sports Sciences, 30,* 325-336.

3.5.4 Paper 4: Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play?

Much research has been devoted to quantifying the occurrence of fatigue in professional soccer match-play using information derived from motion analyses (see reviews by Mohr et al., 2005; Reilly et al., 2008). Decrements in physical performance are widely recognised as occurring in the second half as a whole, towards the end of play, and transiently over the course of games and were discussed in paper 1. Yet no study has investigated in detail whether declines in physical performance are associated with changes in skill-related measures over the course of matches in professional soccer players. In the only related study conducted in real professional soccer match-play situations, a concomitant decline in measures of physical and skill-related performance was observed in the second-half of games in the Italian Serie A League (Rampinini et al., 2009). From their results, the authors suggested that the onset of physical fatigue observed over the course of games is accompanied by a drop in skill-related performance. Research conducted in non-competition environments has investigated the concomitant relationship in variations in physical and skill-related performance as theoretically many game skills in soccer match-play are performed in a fatigued state (Lyons, Al-Nakeeb, & Nevill, 2006). While the reported findings provided useful information on variations in skill-related performance after the exercise protocol was performed, investigations were frequently conducted in controlled laboratory or field environments using simulated soccer activity and study populations mainly included non-professional participants (Abt, Zhou, & Weatherby, 1998; Ali & Williams, 2009; Rampinini et al., 2008; Stone & Oliver, 2009).

A search of the literature showed that, up to now, no study had investigated whether the proficiency and frequency of soccer specific-skills in professional soccer match-play (e.g., passing completion rates, number of possessions) are affected in the same way as physical performance that is declines commonly observed towards the end of games and following short periods of intense physical activity. The disproportionate amount of goals observed in professional football in the latter stages of match-play relative to other periods indirectly suggests decay in elements of physical and skill-related performance (Carling et al., 2005). The residual fatigue potentially experienced by players shown as a drop in distances covered when participating in several matches during a tight time-frame and potential accompanying drops in skill-related performance had also received no attention. Therefore, paper 4 examined whether observed decrements in physical performance in professional soccer match-play are concomitantly associated with a reduction in scores in skill-related performance (proficiency of actions and number of involvements). Information from this study was deemed useful in determining if there is a future need for practicing soccer-specific skills in fatigued conditions and/or for additional conditioning interventions to aid players in my team in maintaining performance. Results also indirectly provided an opportunity to examine the ecological validity of laboratory and/or field tests commonly used to investigate the association between declines in physical and skill-related performance. The reference for paper 4 (appendix 2c) is:

Paper 4: Carling, C., & Dupont, G. (2011). Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? *Journal of Sports Sciences, 21,* 63-67.

3.5.5 Paper 5: Effects of physical efforts on injury in elite soccer

The physical demands of contemporary professional soccer match-play are high and players are frequently subjected to fatigue and a high risk of injury across the competitive season (Carling, Le Gall & Orhant, 2010). In order to suggest preventive strategies specific to soccer play, it is necessary to have detailed information on the mechanisms involved prior to sustaining injuries. Analyses of incidents, combining game-specific and medical information, are frequently employed to describe how injuries and high-risk situations of injury occur (Andersen, Larsen, Tenga, Engebretsen, & Bahr, 2003; Andersen, Tenga, Engebretsen, & Bahr, 2004; Hawkins & Fuller, 1996; Rahnama, Reilly, & Lees, 2002). At professional levels, a large proportion of injuries are incurred during running actions (Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001) but little is known about the specific characteristics of these movements (Woods et al., 2004). Up to now, only qualitative estimations of running speeds at the time of injury have been provided (Andersen et al., 2003, 2004; Arnason, Tenga, Engebretsen & Bahr, 2004). Furthermore, no quantitative information on a potential link with acceleration or deceleration phases or the duration of the final running action prior to injury is available. While professional soccer players commonly experience transient fatigue in match-play notably after periods of intense exercise (Bradley et al., 2009b; Mohr et al., 2003) subsequently manifested by a substantial drop in high-intensity work, no information exists on an eventual relationship between a drop in physical performance and injury risk in match-play.

In my earlier review paper (paper 1, appendix 1a), I suggested that there was potential for using motion analysis to determine whether dense periods of intense exercise and 'inadequate' recovery time between high-intensity efforts might predispose players to injury. The main purpose of paper 5 therefore was to investigate the association between physical efforts of players and occurrence of injury in match-play. In addition to complementing the results on physical and skill-related performance presented in paper 4, the information would inform the prescription of specific fitness training protocols to potentially aid players in my team to resist transient fatigue and possibly reduce the risk of injury. Findings would also inform the design of common experimental soccer-specific exercise simulations that use information derived from motion analyses to explore the link between game induced physical fatigue and injury risk. The reference for paper 5 (Appendix 2d) is:

Paper 5: Carling, C., Le Gall, F., & Reilly, T. (2010). Effects of physical efforts on injury in elite soccer. *International Journal of Sports Medicine, 31,* 181-185.

3.6 Factors affecting physical performance in match-play

The 'statistics' on distances covered and movement speeds observed in match-play and presented earlier may not always be a fair reflection of how a team and player performs since many factors, both extrinsic and intrinsic, can affect physical activity profiles in professional soccer. Motion analyses have been used over recent years to investigate a myriad of variables that potentially shape and affect the physical performance profile of players in competition. Indeed, while individual playing position is probably the most determining element in the end analysis, other important factors identified over the course of collating data in paper 1 and more recently in the literature, include the effect of:-

- geographical location of teams and playing style inherent to different leagues (Dellal et al., 2011; Rienzi, Drust, Reilly, Carter, & Martin, 2000),
- standard of play (Bradley, Di Mascio, Peart, Olsen, & Sheldon, 2010; Mohr et al., 2003),
- quality of teams (Di Salvo et al., 2009; Rampinini et al., 2007b; Rampinini, et al, 2009),
- playing formation (Bradley et al., 2009a, 2011a),
- the age of elite players (Harley et al., 2010; Pereira Da Silva., Kirkendall, & Leite De Barros Neto, 2007),

- the fitness of elite players (Bradley et al., 2011b; Krustrup et al., 2003; Rampinini et al., 2007a; Randers et al, 2009),
- score line status (Bloomfield, Polman, & O'Donoghue, 2004b; Lago, Casais, Dominguez, & Sampaio, 2010; O'Donoghue & Tenga, 2001),
- home/away games (Lago et al., 2010),
- short periods of fixture congestion (Odetoyinbo et al, 2007; Dupont et al., 2010; Rey et al, 2010),
- environmental conditions notably altitude (Nassis, in press) and heat and humidity (Ekblom, 1986; Mohr et al., 2010).

The identification of effects of the above factors on physical performance in competition is beneficial to applied coaching and fitness practitioners particularly for informing training and pre-match preparation strategies to aid the team and individuals to maintain and/or adapt performance whenever they encounter such situations.

3.7 The present body of research on factors affecting physical performance in match-play: rationale and aims

3.7.1 Introduction

Where possible, all the aforementioned factors listed in section 3.6 should be taken into consideration if the analysis and interpretation of data are to enable an accurate and pertinent reflection of actual match performance. However, following compilation of research findings presented in paper 1 and those available after its publication, I concluded that other commonly encountered but potentially crucial performance-environmental themes that might affect physical activity profiles in contemporary elite soccer competition had either received scant attention or had yet to be explored. These themes included player dismissals, substitutions, team formations (playing systems), prolonged periods of fixture congestion and environmental conditions such as cold weather. In my club, myself and coaching and fitness practitioners considered that coverage of these five research topics was necessary to increase our understanding of factors potentially affecting match-play performance and eventually devise strategies to cope with these issues. I subsequently conducted research on each of these individual themes leading to publication of five original research articles. A general introduction and synopsis of the rationale and aims for each respective study theme is provided in turn.

3.7.2 Paper 6: The effect of an early dismissal on player work-rate in a professional soccer match

In my review of motion analysis (see paper 1, appendix 1a), I presented indirect evidence on the potential adverse effect of a player dismissal on physical performance in a professional soccer match. While a drop was observed in the second-half distance covered in an

English Premier League team playing with nine outfield players after the first-half expulsion of the goalkeeper, it was not possible to ascertain whether this fall was directly related to the sending-off. Over the course of a season, professional soccer teams occasionally finish matches with nine outfield players after a player is dismissed and are subsequently deemed to be at a disadvantage both physically and tactically. Yet no quantitative evidence in the motion analysis literature is available on the impact, following the loss of an outfield player, on physical activity profiles in outfield players who remain on the pitch.

In 2008, my team played a total of 91 minutes following the loss of an outfield player after only 5-minutes of play during a French League 1 game. This match provided a unique opportunity to examine the effects of this early dismissal on ensuing work activity profiles in the remaining outfield players. Determining how outfield players in my team coped physically and whether a pacing strategy might have been adopted over the remainder of the game were research questions deemed worthy of investigation. According to Drust et al. (2007), the individual activity profiles of soccer players include elements of self-pacing, since decision making about opportunities to become engaged in play dictates individual activities. Indeed, there has been much recent speculation on whether soccer players adopt pacing strategies to regulate the expenditure of energy and delay fatigue (Drust et al., 2007; Edwards & Noakes, 2009; Reilly et al., 2008). Yet, up to now, no motion analyses studies of competition have attempted to verify this theory. Thus, these questions led to the development of paper 6 (Appendix 3a), the reference of which is:

Paper 6: Carling, C., & Bloomfield, J. (2010). The effect of an early dismissal on player work-rate in a professional soccer match. *Journal of Science & Medicine in Sport*, *13*, 126-128.

3.7.3 Paper 7: Work-rate of substitutes in elite soccer: A preliminary study

In motion-analyses of professional soccer play, there is consistent evidence that declines in physical performance occur across game halves (Barros et al., 2007; Rienzi et al., 2000) and towards the end of competition (Bradley et al., 2009b; Mohr et al., 2003). Therefore, there is a need for countermeasures to fatigue in order to maintain physical performance throughout match-play and especially towards the end of competition mainly due to the high frequency of scoring occasions and goals conceded in latter periods of play (Carling et al., 2005). While physical conditioning processes aim to provide players with maximal ability to resist fatigue, the introduction of substitutes before the onset of fatigue towards the end of games is seen by practitioners as a valuable means for restoring potential imbalances in physical performance (Drust et al., 2007; Reilly et al., 2008). Indeed, as part of an investigation determining activity profiles of elite soccer players, Mohr et al. (2003) reported that the amount of high-intensity running performed in the final 15-min interval of games was 25% higher in substitutes compared to that in players who had participated in the entire match. To my knowledge, this was the only paper to have investigated this particular issue in professional soccer.

The purposes of paper 7 were to further knowledge of physical activity profiles and contributions of substitutes in order to provide answers to questions on this topic asked by coaching staff in my club and extend the research in the study conducted by Mohr and co-workers. First, I wanted to verify speculation on whether players who were substituted actually demonstrate a reduction in physical performance or whether substitutions are made mainly for tactical reasons as suggested by Reilly et al. (2008). Second, I examined physical performance scores in substitutes in direct comparison to those reported in team mates in the same playing position who remained on the pitch and against those observed in players they directly replaced. Third, I conducted an analysis of physical efforts in substitutes in comparison to when the same players were chosen to start games. These latter two questions were used to ascertain whether substitute players in my club aided in maintaining and/or increasing the overall physical efforts of the team until the end of match-play and whether they performed physically at a similar level to when they started games. The reference for paper 7 (Appendix 3b) is:

Paper 7: Carling, C., Espié, V., Le Gall F., Bloomfield, J., & Jullien, H. (2010). Work-rate of substitutes in elite soccer: A preliminary study. *Journal of Science & Medicine in Sport, 13,* 253-255.

3.7.4 Paper 8: Influence of opposition team formation on physical and skill-related performance in a professional soccer team

The physical activity profiles of players can be influenced by the style of play in individual teams as well as cultural or geographical differences (Rienzi et al., 2000). However, there has also been speculation, but little scientific evidence from motion analyses of professional soccer match-play, surrounding the potential influence of team formations (playing systems) on physical activity profiles in competition (Bradley et al., 2009b; Drust et al., 2007). In my opinion, and that of the coaching practitioners in my club, it was necessary to examine physical activity patterns and skill-related performance across a variety of popular formations to attain an expression of contemporary soccer play. For example, a preliminary investigation showed that the individual playing formations employed by professional soccer teams in the English Premier League influenced high-intensity activity profiles and different technical elements of a team's and player's performance (Bradley et al., 2009a). While previous research has identified a strong relationship between competitive physical performance in a reference team compared to that reported in direct opposition (Rampinini et al., 2007b), no evidence existed on the potential influence of opposition playing formation on physical and skill-related performance in a reference team. Similarly, we collectively deemed that a potential link between match-related decrements in physical performance and opposition team formation was worthy of exploration. A pertinent line of analysis was to investigate whether playing against certain formations led to increased physical exertion thus a greater chance of accumulated fatigue in our players.

Therefore, Study 8 was conducted bearing these questions in order to inform our coaching and fitness personnel on whether fitness, technical and/or tactical demands in competition varied in my team according to the type of formation employed by opposition teams. The reference for paper 8 (Appendix 3c) is:

Paper 8: Carling, C. (2011). Influence of opposition team formation on physical and skill-related performance in a professional soccer team. *European Journal of Sport Science, 11*, 155-164.

3.7.5 Paper 9: Are physical performance and injury risk in a professional soccer team in match-play affected over a prolonged period of fixture congestion?

In contemporary European professional soccer, teams can participate in over 60 official matches per season. Hence, there is potential for professional soccer players to experience residual fatigue and eventually a high risk of injury over the playing season and particularly during dense competitive schedules (Ekstrand, Waldén, & Hägglund, 2004). Research has demonstrated accrued physiological stress and muscle trauma and a reduction in the anaerobic performance of players with perturbations persisting up to 72 hours after competition (Ascensão et al., 2008; Fatouros et al., 2010; Ispirlidis et al., 2008). Thus, when the time span between games is short, the physiological changes in players might still be present in the ensuing match. In addition, a 6-fold increase in match injury incidence was reported in a professional soccer club when two games were played in a week compared to a single match (Dupont et al., 2010). In contrast, a related paper I co-authored during the same period as the present program of work showed that a very short interval between three successive fixtures did not result in a higher incidence of match injury in players belonging to my club (Carling, Orhant, & Le Gall, 2009). Therefore, additional investigations in this recurring theme are warranted.

Several studies have used motion analyses to investigate changes in physical activity profiles in professional soccer players during dense periods of matches (Dupont et al., 2010; Odetoyinbo et al., 2007; Rey et al., 2010). Perhaps surprisingly, despite the recognised deleterious physiological changes mentioned earlier, no statistically significant differences in the physical activity profiles of players were reported across successive matches played in a short time. However, declines in the distances covered at high-intensity were generally observed suggesting the presence of residual fatigue in players. In these studies, physical activity profiles were examined across only two or three games played successively over a 3-7 day time-scale and no measures of between-match variability described as a % coefficient of variation (Gregson et al., 2010) were provided. Similarly, no corresponding data were reported on whether there was an increased risk of or severity of injury over congested fixture periods. In general, no information is available on physical performance and injury rates in teams who play a large number of successive games interspersed by short intervals between matches over a longer period.

In December 2009, my team participated in eight official matches (League and European competition) played consecutively over a 26-day period. Consequently, this dense competitive schedule provided a unique opportunity to analyse the effects of a prolonged period of fixture congestion on physical performance and injury rate and severity. The information gleaned from the analyses would also allow our club to conduct an indirect evaluation of squad rotation strategies, post-match recovery treatments and functional injury prevention protocols in place at the time of this study. The reference for paper 9 (Appendix 3d) is:

Paper 9: Carling, C., Le Gall, F., & Dupont, G. (2011). Are physical performance and injury risk in a professional soccer team in match-play affected over a prolonged period of fixture congestion? *International Journal of Sports Medicine, 32,* 1-7.

3.7.6 Paper 10: The effect of a cold environment on physical activity profiles in elite soccer match-play

Over the competitive soccer season, training and matches are frequently performed by players in unfavourable environments. Indeed, there are several climatic conditions that raise major concerns in relation to performance notably high altitude, heat and humidity, cold temperatures and pitch condition (Bangsbo, 1994; Dvorak & Racinais, 2010). Only three research studies have attempted to address the issue of ambient temperatures on physical activity profiles in the intermittent endurance type sport that is soccer (Ekblom, 1986; Mohr et al., 2010; Özgünen et al., 2010). While all three investigations reported substantial declines in second-half high-intensity running distance in hot and humid conditions, results were obtained from a small number of matches thereby limiting the statistical power of the findings.

There is also speculation about the negative effects on physical performance of playing in cold environments (Carling et al., 2005; Reilly, 2003a, 2007). It is recognised that exercise in cold air can lead to greater energy expenditure than exercise performed in a thermoneutral environment (Armstrong, 2000). In addition, physical performance characteristics related to soccer such as muscular strength and power output can be affected (Nimmo, 2004) and prolonged exercise in very cold conditions can predispose players to dehydration which in turn can lead to impaired high-intensity endurance performance (Armstrong, 2006; Edwards & Noakes, 2009). Yet, despite the mass of knowledge accumulated using motion analysis on various factors affecting physical efforts in professional soccer, no empirical evidence exists on the potential adverse effects of participating in cold weather conditions. Indeed, the issue of training and playing team sports, in particular football, in extremely cold conditions has not been studied in a satisfactory manner, and recommendations have not been issued by sport's governing bodies (Dvorak & Racinais, 2010). Since 2004 and especially over three recent consecutive seasons (2007/2008, 2008/2009, 2009/2010), professional soccer matches in France have been regularly played in exceptionally cold conditions (see http://www.lfp.fr/corporate/article/les-clubs-mettent-le-froid-ko.htm). Yet, it is unknown to what extent these cold temperatures commonly influence physical performance in professional soccer match-play.

The general aim of paper 10 thus was to investigate the effect of cold temperatures on physical activity profiles in players belonging to my team in official matches. It was hoped that findings would inform and subsequently aid current competition preparation strategies including pre-match warm-up routines and nutritional and cold-weather clothing interventions in my club whilst simultaneously adding to the current state of knowledge in this research field. The reference for paper 10 (Appendix 3e) is:

Paper 10: Carling, C., Dupont, G., & Le Gall, F. (2011). The effect of a cold environment on physical activity profiles in elite soccer match-play. *International Journal of Sports Medicine, 32*, 1-4.

3.8 Summary

Strength and conditioning personnel aim to equip soccer players with the optimal physical skills required for their sport. A primary step in this process is the monitoring of exercise intensity during competition to quantify the general characteristics and position-specific demands of play. Irrespective of the technique employed, motion analyses can be used to indirectly quantify the physical efforts of soccer players in competition, investigate factors affecting performance, and deliver information to be used for objective decision making in the structuring of conditioning elements for training and match preparation. This overview of motion analysis considerations and applications has set the scene for the present thesis and the nine original research investigations I conducted over a four-year period in a professional soccer club setting.

CHAPTER 4 OVERVIEW OF MATERIALS AND METHODS

4.1 Experimental approach to the research problem

As a sport scientist engaged in a professional soccer club, the intended outcome of this programme of work was to produce competitive performance-based research findings that were clearly usable and relevant with regards to elite training and match performance (Bishop, 2008). Research using computerised motion analysis in players in my club was based around investigation of general characteristics of their physical performance in match-play and the demands specific to individual playing position that had not been covered in the literature. Work was also conducted in an attempt to identify new factors that potentially affect the competitive physical activity profiles of our players.

Performance in official competition was analysed for players belonging to a single male professional soccer team playing in the highest standard of football in France (French League 1) and regularly participating in European competition. The combination of analyses of physical activity profiles in players from a high performance environment (professional standard) and in real situations (official match-play) aimed to enhance and ensure strong ecological validity across the set of research papers.

4.2 Participants and match sample

As mentioned earlier, performance in official competition was analysed for players belonging to a single male professional soccer team that competed in the French League 1 (highest standard in French soccer). Analyses were performed over four consecutive seasons (2007/08, 2008/09, 2009/10 and 2010/11). Over this period, the reference team recorded one Top 10 finish, two consecutive Top 5 finishes and jointly won its National Championship and National Cup Competition at the end of the final season (2010/11). Only player and team performance in official match-play was examined. Competitions included domestic League and Cup and European matches (participation in the UEFA Europa League in 2009/10 and 2010/11). Performance data were collected and analysed using samples sizes ranging from 15-80 games with the number of match observations ranging from 70-390. The population sample size employed across studies ranged from 7-28 players. Information on sample sizes used within each respective study is summarised in Table 1.

From the outset, I recognised the limitations of this experimental approach in terms of sample size and the datasets subsequently derived from using a restricted population. Thus the potential statistical power of the results and the extent to which findings are applicable to other elite soccer environments can be considered as limitations. Indeed, a sample size containing 80 players is suggested to provide sufficient statistical power to enable meaningful detection of real systematic differences in match-play physical performance and take into consideration the natural variability in physical activity across games (Gregson et al., 2010). However, recent work has shown that doubling the number of matches effectively halves the sample size required to achieve the desired power in such studies. For example, a sample size of 13 players requires analysis of 10 pre and 10 post matches (Gregson, 2012) which was achieved in several of the present studies. The patterns observed across these studies might also be a reflection of only my team (as players came from a single club) and/or of the League in which my club competes. The inclusion of additional clubs across several geographical locations and international standard teams would have provided a wider and perhaps more precise picture of the physical characteristics and demands of contemporary professional soccer and again increased the general applicability of findings.

Another recognised limitation in the current body of research was the occasional inability to analyse performance across all playing positions. This was mainly due to the choice of team formation restricting collection of full datasets mainly in centre-forwards. The 4-3-3 (and occasionally 4-5-1) playing formation generally employed in my club includes only one centre-forward and players in this role were frequently substituted over the course of games.

Table 1. Respective sample sizes for players, games and individual match observations across the nine original research papers.

Paper	Players	Games	Match Observations
2	7	15	105
3	8	25	144
4	21	45	297
5	18	30	390
6	9	80	339
7	28	30	228
8	20	80	105
9	11	37	60
10	7	35	245

Finally, all analyses were completed during actual match play and results in studies of this nature also reflect the interaction between all players involved in games and not just the players or teams in question (Carling et al., 2005; Rampinini et al., 2009). The extent to which opponent behaviour and other extrinsic factors such as the playing situation and game context impacted upon the present findings was generally not quantified. On several occasions notably at the beginning of this work, opposition physical performance data were unavailable due to refusal of clubs to share information. Only in paper 8 was opposition standard (dependent on League position) statistically verified to ensure that this did not confound the analyses comparing performance against three different playing formations. In hindsight, systematic inclusion of this analysis would have strengthened the impact of findings in other studies presented in this thesis but was not always possible notably due to the refusal of several opposition teams to share their data. Despite the pragmatics of these caveats, however, the aim as described earlier was to construct a clearer, more evidence-based framework for the application of high performance motion analysis data in training and match preparation of professional players belonging to my club.

Over the course of this work, player consent and approval by my club for all studies were obtained. However, these data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season (Winter & Maughan, 2009). Therefore, usual appropriate ethics committee clearance was generally not sought or required for the purposes of publication. To ensure team and player confidentiality, injury, fitness and match performance-related data in all studies were nevertheless anonymised before analysis.

4.3 Motion analysis data collection techniques

Competitive motion analysis data were gathered for the reference team over the four seasons by the same private match-analysis service provider (Sport-Universal Process, Nice, France). In October 2006, on demand of my club, a semi-automatic computerised player tracking system (AMISCO Pro®) was installed by the service provider in my club's home stadium. In my club, this system was mainly adopted to provide data on physical performance on a match to match basis but also to provide opportunities for applied research. This multiple camera system passively tracks the movements of every player using a sampling rate of 10.0 Hz over the entire course of matches. The system has been widely adopted across contemporary European professional soccer (Carling & Williams, 2008). Installation of the system involved the calibration and synchronisation of eight stable cameras positioned in the stadium gantry. Signals and angles obtained by the encoders were sequentially converted into digital data and recorded on six computers for post-game analysis. Additional information on workings and quality control (accuracy, reliability, validity) of match-related performance data derived from this system can be obtained elsewhere (Barris & Button, 2008; Carling et al., 2005, 2009; Di Salvo et al., 2007; Randers et al., 2010; Zubillaga, 2006).

For the present purpose, it should be noted that I previously contributed to the original system design (Brulé et al., 1998) and aided in match-day data collection processes and quality control. As such, the process is akin to the employment of match analysis data obtained from other testing sources but by methods that were designed, overseen and quality assured by myself. All motion analyses data reported in the following 9 original research studies were collected using this computerised match analysis system. Raw data from all game analyses were extracted by myself from the information supplied by the service provider and collated using Microsoft Excel.

4.4 Match performance measures

Over the course of this work, information on physical and skill-related performance (tactical and technical) and injury in match-play was collected. In general, measures of physical performance included analysis of the total distances run and distances covered at a range of running speeds and in individual possession of the ball. The frequency of and recovery time between high-intensity actions were also calculated. Decrements in physical performance scores across halves, towards the end of games, after intense periods of exercise, and during periods of match congestion were investigated. Measures of skill-related performance included the time spent in ball possession, frequency of and number of possessions gained or lost, number of duels and percentage of duels won or lost, and frequency and percentage success rates in passing and shooting. Finally, information was collected on injuries sustained in competition (e.g., incidence, severity, type, location, contact/non contact).

It is important to mention that I made efforts to use the same speed thresholds for determining the distances run in different movement categories across all nine papers although ultimately this was not possible. For example, high-intensity running was defined as movement performed at speeds above or equal to 14.4km·h^{-1} in paper 4, 19.1km·h^{-1} in papers 2,5,6,and 7, and 19.8km·h^{-1} in papers 3,8,9 and 10. A lack of standardisation in speed thresholds reported in the scientific literature, arbitrary choices made by fitness conditioning staff in my club, individual requests of reviewers during the review process coupled with the desire to compare results reported in related investigations unfortunately led to inconsistency across the current set of studies.

4.5 Statistical procedures

4.5.1 Introduction

In investigative research using match analysis there are no standardised experimental or observational study designs and, as such, some investigations may be the first to use a particular design (O'Donoghue, 2010). Therefore, statistical analysis of the datasets derived in the present body of work was dependent upon individual research design and dictated by the purpose of the studies. In this thesis for example, both hypothesis and non-hypothesis driven investigations are presented depending on the specific nature and aims of, and questions asked in individual studies (e.g., descriptive, comparative, associations).

In the large mass of studies that have used motion analysis to evaluate physical performance, simple inferential statistical testing is the method most commonly encountered to explore datasets derived from game analyses (see Abt & Lovell, 2009; Barros et al., 2007; Bloomfield et al., 2007; Bradley et al., 2009b, 2010; Castagna, Impellizzeri, Cecchini, Rampinini, & Alvarez, 2009; Dellal et al., 2011; Dupont et al., 2010; Mohr et al., 2003, 2010; Orendurff et al., 2010; Rampinini et al., 2007b; Rampinini et al., 2009; Rey et al., 2010). In the present set of papers, all data were firstly described using simple descriptive statistics. Inferential statistical analyses were subsequently employed to determine whether differences in scores (means, medians) across samples were significant. These analyses included both comparison of data obtained in independent (e.g., measures across different playing positions e.g., papers 2, 3, 8) and related samples (repeated measures from the same player, e.g., papers 4, 5, 6, 7). Analyses also included tests of relationships between fitness and match data (e.g., paper 3) and inter-match variability in performance (e.g., paper 9). Ultimately, statistical procedures evolved over the peer review process and final selection of comparative tests was often dependent upon the individual requests of reviewers.

4.5.2 Statistical tests

In all studies, descriptive statistics for all raw and relative variables were calculated and are reported as means and standard deviations (mean±SD). This was done in part to enable comparison with datasets previously reported in other investigations of motion analysis. Prior to inferential statistical testing, the normality of distribution of each dataset was evaluated using the Kolmogorov-Smirnov test completed by Lillifors' correction. In all investigations, except paper 4, parametric statistical analyses were used. T-tests and analysis of variance (ANOVA) were frequently employed to investigate for differences in mean scores across the different measures of physical performance. Two or three-way ANOVAs were applied where appropriate and notably when interactive comparisons of the effect of factors such as time intervals and playing position on physical performance were necessary. When continuous measures were available across the same players, a paired t-test or repeated measures ANOVA was used. In paper 4, non-parametric tests (Wilcoxon's signed rank test and Friedman's repeated-measures analysis of variance on ranks) were employed due to the failure of the dataset distribution to satisfy the assumption of normality. It is worth mentioning that an error was not picked up in the description of statistics in paper 4 and was only noticed during the writing of this thesis. The non-parametric tests explored statistical differences in median values across datasets and not mean values as indicated in the published text. In all studies, follow-up univariate analyses were performed where appropriate. These generally included Bonferroni-corrected pair wise comparisons or Tukey's Honestly Significant Difference tests.

Additional statistics used in this body of work include coefficients of variation (CV) and their 95% confidence intervals, as presented in paper 9. This statistic is used to examine match-to-match variability (as % change) in physical performance data (Dupont et al., 2010; Gregson et al., 2010; Mohr et al., 2003; Rampinini et al., 2007b). CV values are used in paper 9 to compare variability in measures across eight consecutive matches played over a 26-day period. In paper 4, when a statistical difference was obtained between datasets, the differences in raw mean values and their confidence intervals are reported to highlight inter- and intra-match declines in performance scores (Hopkins, 2000). In paper 3 the known-group effect difference statistic using the median split technique (Rampinini et al., 2007a) is used to assign players into two groups for comparison of physical performance in match-play according to highest or lowest ranked performance observed in a laboratory test of repeated sprint ability (RSA). Finally, Pearson's product-moment correlations are also employed in the same study to examine relationships between scores obtained in the RSA test and measures of competitive performance (Rampinini et al., 2007a). Additionally, a scale was provided as a means to qualitatively interpret the magnitude of these associations. The correlation coefficients (r) were interpreted in accordance with the following scale (Hopkins, Marshall, Batterham, & Hanin, 2009): ≤ 0.1, trivial; >0.1-0.3, small; >0.3-0.5, moderate; >0.5-0.7, large; >0.7-0.9, very large; and >0.9-1.0, almost perfect.

An alpha level of $p<0.05$ was generally selected as the criterion for significance for all statistical procedures. However, in response to reviewers' requests, and to guard against the risk of a false positive finding due to the occasional use of multiple t-tests on a large number of performance variables, a pseudo-Bonferroni adjustment was used in four of the studies (papers 2,5,6,7) to control for any potential inflation of Type-I error rates (Castagna et al., 2009; Di Salvo et al., 2010; Rampinini et al., 2007b, 2009; Randers et al., 2010). A stricter operational alpha level of $p<0.017$ was used in papers 2 and 5 and $p<0.025$ in papers 6 and 7. These alpha levels were obtained by dividing $p<0.05$ by the number of categories of performance variables respective to each study.

Later on over the course of the work, reviewers of my papers also proposed the inclusion of Cohen's *d* effect sizes (see papers 2, 3, 4, 5, 8, 9) (Cohen, 1988). This statistic has been included in recent motion analysis studies of physical activity in professional soccer (Abt & Lovell, 2009; Dellal et al., 2011; Di Salvo et al., 2009, 2010) as a means to reinforce the interpretation of findings by investigating the practical significance of identified statistical differences between scores. A scale of magnitude was also provided to aid qualitative interpretation of each respective effect size statistic. The scales used again varied according to individual reviewer demands but values of 0.2, 0.5, and 0.8 were generally considered to represent small, medium, and large differences respectively (Cohen, 1988).

CHAPTER 5 DISCUSSION AND CRITICAL EVALUATION OF THE FINDINGS REGARDING THEME 1: GENERAL CHARACTERISTICS AND POSITION-SPECIFIC DEMANDS OF PHYSICAL PERFORMANCE

5.1 Paper 2 (Appendix 2a): Analysis of physical activity profiles when running with the ball in a professional soccer team.

5.1.1 Introduction

As part of the multifactorial demands of soccer play, the ability to run with the ball is considered essential at all levels of the game, from youth categories up to professional playing standards (Huigjen, Elferink-Gemser, Post, & Visscher, 2009, 2010; Reilly, Williams, Nevill & Franks, 2000). Yet in-depth empirical analyses regarding this aspect of play at professional levels are scarce. The aim of this paper thus was to broaden understanding and knowledge of the physical characteristics of running performance with the ball during professional match-play. It also examined the demands relative to playing position.

5.1.2 Results and discussion

In paper 2, analyses showed that, on average, players covered 1.7% of their total distance run in individual possession of the ball. Across playing positions, values varied significantly ranging from 1.5% of the total distance in fullbacks, central defenders and centre-forwards jointly to 2.2% in wide-midfielders. These results corroborate available data showing that only 1.2-2.4% of the total distance covered by professional soccer players is in possession of the ball (Di Salvo et al., 2007) and confirming that efforts in this component of play are strongly dependent on playing position (Bloomfield et al., 2007).

Unlike previous research designs, the total distance covered with the ball was broken down to isolate the speeds at which players ran with the ball. While mean speed in possession in all players was approximately $13 km \cdot h^{-1}$, the proportion of the total distance covered with the ball varied statistically across four categories of movement speed. Indeed, the majority (34%) of the total distance in possession was covered at speeds $>19.1 km \cdot h^{-1}$. Thus, despite the small percentage covered with the ball in relation to the overall efforts of players, these results suggest that running with the ball at high speeds is a fundamental component of physical performance in match-play. In order to develop this component of play in accordance with the patterns identified above, it seems that players, irrespective of their positional role, should be performing training drills during which they run with the ball at high speeds. Studies have shown that energy expenditure, hence the training stimulus, is generally higher when running with the ball compared to normal running (Reilly & Ball, 1994; Rupf et al., 2007). Thus, running drills performed at high-intensities would provide a useful means to develop fitness whilst simultaneously aiding technical development. In addition, player motivation during physical conditioning drills is suggested to be higher when the ball is used (Helgerud et al., 2001) and may encourage adherence to physically intense training programmes.

In professional soccer, analyses of physical activity profiles generally indicate a decline in second-half and end-match running performance (Iaia et al., 2009; Reilly et al., 2008). In this study, no drop in the physical efforts in ball possession was observed across match halves. The same result was observed in the final third of games with results also unaffected by playing position. This positive finding suggests that players' efforts in ball possession were unaffected by game-related accumulated fatigue and they were able to maintain performance over the course of games. Perhaps surprisingly a slight rise in the overall distance covered in ball possession was observed in the second-half (+1.5%) despite a significant decrease (-30%) in the final 15-minute period before the half-time interval. Di Salvo et al. (2007) also reported an increase in distance run with the ball in the second half (~5%) in a larger cohort of European professional soccer players. A reasonable suggestion could be that players consider individual movement with the ball to involve a degree of risk and might be less willing to attempt such actions over the course of the first half, especially as the match result is unlikely to be decided during early stages of play. A study associating changes in score-line with physical performance in possession of the ball is definitely warranted to test this theory. A related study published after paper 2 has shown that professional players perform less high-intensity activity when winning than when losing but no information on individual movement with the ball was provided (Lago et al., 2010).

In paper 2 combined physical and technical analyses showed that when players received the ball, they were generally moving and not stationary as mean speed at ball reception was observed to be ~10km·h^{-1} while opponents were within a distance of approximately 4m from the player. This result suggests that to be realistic, passing drills designed to train a player's first touch should be carried out while he or she is moving and not in a static position and also performed in 'pressure' situations. Further scrutiny of the dataset showed that 47 individual possessions were performed per player per match and on average players only spent a total of 53 seconds in possession. Again, it seems that strong levels of technique are necessary in order to make the most of the limited time each player is in possession of the ball. Indeed, the mean duration and number of touches of the ball per individual possession were considered to be low: 1.1s and 2.0 respectively.

The distances covered according to movement speed were highly dependent on playing position. In comparison to the other positions, wide-midfielders ran significantly more distance with the ball at higher running speeds (14.1-19.0km·h^{-1} and >19.1km·h^{-1}). Performance in all technical variables also varied significantly according to playing position. Noteworthy results included the substantially larger time spent in individual possession and number of touches per possession in wide-midfielders and the lower distance between the player and nearest opponent on ball reception in the fullback positions. These findings again demonstrate a need for practitioners to design and apply realistic position-tailored physical conditioning and technical training drills to adequately respond to the specific demands of competition. Notably, players in wide positions would probably benefit from individualised training interventions.

The above observations on skill-related variables are also clearly applicable to the design of technical training drills for youth soccer players. Inferences from the limited frequencies of possessions, touches per possession and time spent in individual ball possession generally, suggest that participation in large-sided games might not provide adequate competitive conditions for development of these skills in younger players. Practitioners could consider small-sided games as an alternative to 11-aside games for simulating match-related conditions to respond to the general and position-specific technical patterns of play identified above. For example, work by Owen, Wong, McKenna and Dellal (2011) has reported significantly more dribbles and ball contacts per player in 3 vs. 3 compared to 9 vs. 9 games.

The results from this study also have direct implications for the design of endurance fitness testing and training protocols involving the ball (Chamari et al., 2005; Hoff et al., 2002), soccer-specific skill tests for evaluating running performance with the ball (Reilly et al., 2000; Russell, Benton & Kingsley, 2010; Taskin, 2008) and simulations of match-play incorporating ball actions (Russell et al., 2011a,b). To ensure ecologically-sound test conditions, protocols should adequately replicate specific physical and technical characteristics identified in competition and this study is a first step in providing this information. For example, tests used for evaluating dribbling capacity in young high-level Dutch players (Huigjen et al., 2010) and professional Turkish players (Taskin, 2008) involved measures of the time taken to cover distances of 20-30m respectively with the ball. In comparison, the mean distance covered with the ball by professional players in this study was approximately 4m although this figure did vary significantly across playing positions. It seems in general that there may be large disparities between actual running characteristics in match-play and experimental tests designs used to measure soccer specific-skills. Further considerations on this debate can be found in two recent reviews published after paper 2 (Ali, 2011; Russell & Kingsley, 2011). This discussion on discrepancies between experimental test protocols simulating play and actual match-demands also fits in nicely with the results presented in papers 4 and 5.

In paper 2, I made no attempt to differentiate between actions in which dribbling and running with the ball were performed. This was done to avoid any potential subjectivity issues due to arbitrarily defined match events as used in previous studies (e.g., Bloomfield, Polman, & O'Donoghue, 2004a; Rowlinson & O'Donoghue, 2009). Nevertheless, a future study using validated and reliable definitions would be pertinent to code and subsequently characterise the physical and technical patterns that might be specific to dribbling or running actions with the ball. Consensus between coaching practitioners and researchers is required to achieve recognised definitions. I also suggest that additional work is merited to address whether or not the quality of opposition influences the physical and technical characteristics of running with the ball in teams and across individual playing positions. Related work in professional Italian soccer has shown that distance covered in high-intensity running with the ball was highest in top-5 ranked compared to bottom-5 ranked teams (Rampinini et al., 2009).

Finally, research tying in the contributions of substitutions in this particular component of play would again have complemented findings presented in paper 7. Thus additional analyses performed on the dataset for the purposes of this thesis showed that substitutes covered a greater distance per minute (23.3 ± 46.70m·min^{-1} vs. 46.7 ± 35.40m·min^{-1}, p=0.039, Cohen's *d* = 0.43) and more distance in walking/jogging (5.7 ± 4.80m·min^{-1} vs. 12.3 ± 11.00m·min^{-1}, Cohen's *d* = 0.75) and low-intensity activities (2.8 ± 3.80m·min^{-1} vs. 5.9 ± 5.20m·min^{-1}, Cohen's *d* = 0.61) with the ball than the player they directly replaced. This result would indicate the value of replacing players when an increase in the ability of the team to carry the ball and maintain possession especially towards the end of games is required.

5.2 Paper 3 (Appendix 2b): Analysis of repeated high-intensity running performance in professional soccer.

5.2.1 Introduction

In paper 3, I attempted to provide a detailed insight into repeated high-intensity activity profiles and the extreme demands of match-play in players in my club. Repeated high-intensity movement in competition was also analysed in relation to performance scores observed in a repeated sprint ability test (RSA) performed on a non-motorised treadmill. Thus the main aim of the study was to investigate in detail a component of physical performance commonly considered in professional soccer circles as paramount to contemporary match-play (Osgnach et al., 2010). I felt that study 3 would be a clear and logical extension of the work conducted in paper 2 which investigated another key element of play; the physical efforts of players in possession of the ball. It was also the first to purposely investigate repeated high-intensity activity in male soccer competition at professional playing standards.

5.2.2 Results and discussion

In general, the majority of successive high-intensity efforts (67%) were performed in match-play following recovery periods lasting over one minute in duration. Thus it would seem that players generally had adequate time to recover 'physiologically' following a high-intensity effort (Girard et al., 2011). In hindsight, and after reviewing paper 3, I feel that an analysis of mean recovery times over periods when the ball was in play might have provided a more accurate picture of the recovery intervals separating intense efforts. A previous study has reported that only 55% of the match duration involves the ball being in play and soccer players are generally not required to perform high-intensity efforts during stoppage time (O'Donoghue et al., 2005). Further analyses performed showed that players only performed on average approximately one repeated high-intensity bout per match (defined as a minimum of three consecutive high-intensity actions with a mean recovery time ≤20s separating efforts) and these bouts generally comprised only three consecutive high-intensity efforts.

Although these data were collected in a single reference team, the results suggest that the repeated high-intensity component of physical performance in my team, and perhaps in professional soccer match-play generally, might not play as crucial a role as perhaps believed. To support this theory, over the four season study period, my team achieved one top-10 and 2 top-five finishes, was combined National Champion and Cup winners in the 2010/2011 season, and twice participated in European Competition (UEFA Europa League) qualifying on both occasions for the knockout phases. A low occurrence of repeated high-intensity running sequences (albeit using a different definition) has also been reported in international youth soccer competition with up to 30% of players not registering a single bout (Buchheit et al., 2010). While the distances covered in high-intensity running differentiate between playing standards (Mohr et al., 2003), findings elsewhere also support the present theory although none specifically analysed repeated high-intensity movement as done here. For example, players in high-ranked teams in the English Premier League (Top 10) covered less distance at high-intensities than lower-ranked peers (Di Salvo et al., 2009). Research by Rampinini et al (2009) in the Italian Serie A League also reported greater distances covered in high-intensity running in bottom-5 versus top-5 teams. Similarly, the distance covered in high-intensity running in a reference team playing in the Italian Serie A was shown to be statistically higher against teams finishing in the first eight places in the League (Rampinini et al., 2007b). Combined, these results suggest that high-intensity running activity might be of greater importance in lower standard professional soccer teams. Further work is nevertheless necessary to compare repeated high-intensity activity according to team ranking.

Alternatively, these results could be interpreted as implying a need for my team to improve its performance in this particular element of play. Using a similar definition of a repeated sprint bout, substantially more of these intense sequences (4.8 vs. 1.1 per player per match observed in paper 3) were observed in international female soccer players (Gabbet & Mulvey, 2008). A reasonable explanation I can provide for this discrepancy may be the respective methods employed to collect data and particularly the use of manual versus coding techniques. O'Donoghue (2004) for example showed that motion analysis techniques significantly overestimated time spent in high-intensity activity. More recently, a 39% difference has been reported between the distance covered at high-intensities calculated using a computerised tracking system and manual coding techniques (Randers et al., 2010). The strict inclusion criteria employed here to define high-intensity movements (runs performed at velocities >19.8 km·h^{-1} and minimum 1-s duration) might also explain the low frequency of repeated sprint bouts in our players. In a study conducted in English Premier League players, Bradley et al. (2009b) defined high-intensity work as any movement performed at velocities >19.8 km·h^{-1} but for a minimum duration of 0.5s compared to 1s used here. These discrepancies in definitions across studies confirm the viewpoint expressed in my earlier review article (paper 1) that there is an urgent need for consensus among practitioners and researchers to ensure standardisation in the classification of movement thresholds (according to speed and duration) used in motion analysis investigations. An alternative method to using set speed thresholds could be the representation of movement speed as a series of instantaneous points along a continuum allowing a more comprehensive assessment and quantification of running activities at any instant (Osgnach et al. 2010).

Despite the questionable overall importance of repeated high-intensity activity, these intense sequences of running differed significantly across playing positions. Fullbacks performed the most repeated high-intensity bouts while the frequency of consecutive high-intensity actions with short recovery durations between efforts was more common in central midfielders. On average, fullbacks performed approximately four times as many repeated high-intensity bouts per match compared to central-defenders. While the recovery activity separating consecutive high-intensity efforts was generally active in nature in all players with the major part of this spent walking, central midfielders spent a larger part of their recovery periods recovering at higher intensities. Overall, these findings have consequences for the design of the conditioning elements of training programmes for players in these particular positions. For example, practitioners might want to specifically develop the ability of central-midfielders to recover actively at higher levels of intensity. Practitioners will also reflect on the inclusion of additional repeated sprint training interventions to enable fullbacks to repeatedly perform and reproduce high levels of performance in sporadic but extreme sequences of high-intensity running. Detailed information on training methods to improve this component of fitness can now be obtained in a recent review paper by Bishop, Girard, and Mendez-Villanueva (2011).

A noteworthy result not discussed in paper 3 was the shorter recovery time interspersing individual high-intensity actions within repeated high-intensity bouts observed in central-defenders in comparison to the other playing positions (11.4s versus a mean of 13.9s). While players in this position globally performed the least amount of high-intensity work, it seems that when they were called on to perform several intense actions successively, recovery time between efforts was considerably shorter. Thus the importance of repeated high-intensity activity should not be underestimated in this particular playing position.

While position-specific data could not be satisfactorily analysed due to the small sample size, a closer analysis in all players of results on mean and maximum velocity of consecutive high-intensity actions making up repeated high-intensity bouts demonstrated no significant changes between the first and final effort, irrespective of the number of consecutive high-intensity efforts (3, 4, 5, or 6). This result suggests that our players were able to maintain performance across several consecutive intense efforts again casting doubt on the necessity for additional or individualised fitness training mentioned above. A reasonable ‘physiological’ explanation for this lack of a decline in velocity across multiple successive high-intensity efforts may be due to the relatively short length of the runs (~16m). In field sports such as soccer, the short sprint distances allow adequate replenishing of the phosphocreatine system between consecutive efforts (Abt, Siegler, Akubat, & Castagna, 2011; Balsom, Seger, Sjodin, & Ekblom, 1992; Bishop, Spencer, Duffield, & Lawrence, 2001). One omission from paper 3 was the potential inclusion of analyses of the high-intensity efforts making up repeated sprint bouts in terms of the length and/or acceleration patterns of these actions. In professional soccer, sprints longer than 30m demanded a markedly longer recovery time than the average sprint (10-15m) during the game (Bangsbo & Mohr, 2005). Also, the potential effects of acceleration type (leading versus explosive as defined by Di Salvo et al., 2009) merit investigation. If and how these factors affect a player's ability to repeatedly reproduce high-intensity performance remain to be elucidated.

In this study, I also examined the relationship between the scores from a repeated-sprint ability test (RSA) performed on a non-motorised treadmill and match-related repeated high-intensity running performance. Players reporting the lowest performance decrements in the RSA test performed statistically more consecutive high-intensity efforts separated by short recovery times (≤20s) compared to those with higher decrements. It seems from this result that players with a greater resistance to fatigue in the treadmill test were able to perform a greater frequency of high-intensity actions with short rest intervals over the course of games. However, no statistical associations between the RSA scores and other match-related measures and particularly performance in repeated high-intensity bouts were reported. This finding is partly backed up by the results from a related study in a professional soccer team in which no relationship was observed between the fatigue decrement observed in a field test of repeated-sprint ability and distances covered at high-intensities in match-play (Rampinini et al., 2007a). These results thereby suggest a lack of empirical support for the construct validity of this and similar RSA test protocols as predictors of high-intensity match performance in professional soccer although the present study design might well have been statistically underpowered due to the low number of participants and match observations analysed.

A future potentially worthwhile research theme not mentioned in paper 3 would be to investigate the link between performance in similar tests and transient and end-game fatigue patterns in repeated high-intensity running bouts. For example, are declines across high-intensity efforts within repeated high-intensity running bouts more prominent when these intense sequences are performed at the end of games and are declines greater in players reporting lower performance in RSA tests? Related research in sub-elite players has shown that performance in repeated sprints is reduced immediately after compared with before a game and after an intense period of activity during match-play (Mohr et al., 2005).

The results also have implications for the design hence logical validity of tests of repeated-sprint ability in terms of the frequency, distance and duration of repeated high-intensity actions and the nature of recovery between efforts. The majority of field and laboratory tests generally involve repetition of ~6 sprints over a distance of 30m with an active recovery period between efforts of 25s (Carling et al., 2009; Reilly, 2007; Svensson & Drust, 2005). Here, motion analyses of match-play demonstrated a mean recovery time of approximately 14s between consecutive high-intensity efforts within repeated high-intensity bouts. Further analysis of the most extreme demands of match-play showed that players performed up to five consecutive high-intensity actions (HIA) within a 1-min period (one bout every 12s) and 7 HIA within a period of 111s (one bout every 16s approximately). The duration of these recovery intervals are substantially lower than those frequently employed in test protocols. To ensure the design of more ecologically valid assessment protocols of a player's capacity to respond to the most extreme demands based on these observations, these findings tend to suggest that fitness personnel use RSA tests containing 6-7 successive high-intensity actions (running speed >19.8km·h^{-1} sustained over a length of ~20m) with 15s active recovery intervals between efforts. During these recovery intervals, both low- and moderate-intensity exercise could be performed as analyses showed that our players spent 61% of their recovery time between high-intensity efforts moving at running speeds ranging from 0.7 to 7.1km·h^{-1} and 30% at speeds from 7.2 to 14.3km·h^{-1}.

Another potential application of these findings not covered in paper 3 is the integration of the present repeated sprint data in exercise protocols to simulate the intermittent nature of soccer match-play. While current protocols provide a valid and reliable replication of the physical activity profiles inherent to the game (Nicholas, Nuttall, & Williams, 2000; Russell et al., 2011b; Thatcher & Batterham, 2004; Williams et al., 2010), none to my knowledge have included random periods of repeated sprint-type activity or take into account the differences in intense movement patterns across playing positions identified here and in other studies. Inclusion of such information could potentially enhance the validity and sensitivity of these exercise protocols for measuring the effects of fitness training interventions or for identifying differences in performance across various standards of play and/or playing positions.

Several criticisms can be levelled at the study design and specifically at the treadmill protocol. Firstly, the reliability of the present test has been only determined in amateur soccer players (Nédélec, Berthoin, & Dupont, 2011). Thus additional research is required to determine the reliability of the present test and its applicability for use at professional standards of play. Secondly, a passive recovery interval between efforts was used which on reading the above findings does not accurately depict the actual patterns seen in competition. Although I did not mention this in paper 3, this rest protocol was chosen as previous experiences during familiarisation testing showed that players frequently stopped their movement after each individual effort despite encouragement to remain on the treadmill and recover actively. Although players were familiar with exercising on the non-motorised treadmill, running conditions (biomechanical, physiological) are not identical to those experienced in field tests. However, our club uses this particular protocol and equipment on several grounds. These included logistical reasons, the complementary physiological data derived from testing (e.g., power indices), instantaneous data on accelerations and decelerations, and benefits in injury rehabilitation interventions such as the monitoring of imbalances in lower member forces during running.

On the basis of these results, I feel that there is still a need for additional research combining larger population sizes and inclusion of teams from a range of geographical locations. This would reduce the potential risk of statistically underpowered studies and enable a wider and potentially more accurate picture of repeated high-intensity movement patterns and position-specific demands in professional soccer competition. For example, a large scale study I recently participated in has identified substantial disparities in high-intensity activity between players belonging to teams in the English Premier League compared to peers in the Spanish Liga (Dellal et al., 2010). Larger-scale research would also allow analysis of performance in relation to opposition quality which was not done here. Unfortunately, specific information on whether repeated high-intensity performance is opposition dependent is currently unavailable in the literature. Similarly, the repeated high-intensity demands imposed by different opposition team formations would complement findings in paper 8. Finally, while this type of intense movement pattern only contributes a small proportion to the overall motion activity during competition, it may be critical to the result of games (Spencer et al., 2005). Yet the relative importance of repeated high-intensity efforts to team performance and notably to the overall outcome of matches remains unexplored and definitely merits investigation.

5.3 Paper 4 (Appendix 2c): Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play?

5.3.1 Introduction

In paper 4, changes relative to physical and skill-related performance over the course of match-play were examined in midfield players belonging to my soccer club. This work was conducted in an attempt to determine whether the onset of physical fatigue observed over the course of games was accompanied by a drop in skill-related performance.

5.3.2 Results and discussion

In this study, measures of physical performance manifested by the total distance run and that covered in high-speed running showed a statistically significant decline between halves and during the final 15-minute interval of normal time. This change was not accompanied by a drop in any of the skill-related game scores (frequency and proficiency of actions). Concomitant analyses of skill-related and physical performance showed that the former was also unaffected in the 5-minute period following the most intense 5-minute period of exercise whereas a statistically significant drop in the distance subsequently covered in high-speed running (movement >14.4$km \cdot h^{-1}$) was observed.

These results suggest that the players were generally capable of maintaining performance in soccer-specific skills (technical proficiency and number of ball involvements) throughout an ever changing competitive environment and this was the case even when a drop in physical efforts occurred. The results are at odds with observations obtained from controlled simulations of game-play or using set amounts of exercise which generally demonstrate that when soccer players experience fatigue, their technical ability in shooting or passing at a target declines substantially (Ali & Williams, 2009; Impellizzeri et al., 2008; Lyons et al., 2006; McMorris & Rayment, 2007; Rampinini et al., 2008; Stone & Oliver, 2009). On the other hand, studies by Abt et al. (1998) and Williams et al. (2011) showed that intermittent exercise simulations performed on a treadmill and in field conditions respectively did not affect the ability of the players to execute some technical skills. Importantly, the present observations also concur with the lack of a drop across halves in proficiency in passing and shooting skills reported in professional Italian soccer match-play (Rampinini et al., 2009). In contrast, the number of skill involvements dropped in the second-half in the Italian players whereas this was not the case in players in my team.

A reduction in the distance covered in high-intensity exercise was accompanied by a drop in the frequency of several skill-related variables performed during the final 5-minutes of competition in our players. This result might suggest that accumulated fatigue towards the end of competition affected the player's involvement in game actions. However, it is in my opinion that these drops were more likely to be a reflection of the significant reduction observed in the time the ball was in play during this end period (compared to the first five minutes of play for example) rather than being fatigue-induced as skill proficiency in passing did not change significantly. The lower amount of playing time might have led players to not only work less physically but also provided them with fewer opportunities to play the ball. Thus, I suggest that analysis of declines in match-related performance should always take into account the possible confounding effect of the time the ball is in play. Interestingly, following publication of paper 4, a study conducted in Italian professional soccer players has provided new evidence partly confirming the above findings on end-game performance (Rampinini et al., 2011). Immediately after completing a match, a field test showed that while the players' repeated sprinting ability declined, proficiency in short passing remained stable.

Several reasonable explanations may be forwarded to explain the discrepancies between findings from controlled experimental investigations and those reported in this study. Firstly, there may have been a lack of sensitivity due to the gross nature of the present skill-related measures in detecting changes in skill proficiency compared to those investigated in controlled experimental field and/or laboratory conditions. However, in a recent review of the matter published after paper 9, Russell and Kingsley (2011) suggest that match-specific cognitive processes such as game intelligence, decision-making and visual search strategies are not realistically accounted for in many skill-tests and the experimental conditions used generally lack ecological validity in comparison to competitive conditions. Most tests involve assessments where only ‘pure’ technique is measured such as the ball being aimed (e.g., shot or pass) at a static target. The development of more ecologically sound experimental protocols is necessary to examine the relationship between measures of fatigue and skill-related scores in order to make more reliable, accurate and realistic assumptions for real match-play environments. A test simulating soccer-specific exercise recently designed by Russell et al. (2011a) is one step in this direction. The authors incorporated a randomized lighting system used for target identification during passing and shooting which incorporated perceptual abilities, such as decision making and visual searching. The discrepancies between the present and other study findings may also be simply due to the ability of players in the professional game to achieve higher standards in soccer skills than peers at lower levels of play (Russell et al., 2010).

An alternative explanation for these findings might be that the players adopted a pacing strategy (Edwards & Noakes, 2010) to control physical exertion in an attempt to reduce energy expenditure and maintain skill-related performance in the second-half and especially towards the end of games. Nutritional strategies in an attempt to reduce dehydration and preserve muscle glycogen levels could also have played a part in offsetting fatigue and maintaining performance (Ali & Williams, 2009) although information on dietary strategies was not recorded in this study. In addition, the fatigue experienced transiently or towards the end of games in my team will probably have occurred in opponents too although opposition performance was not measured here. Such a reduction would probably be reflected by lower levels of exertion when adversaries are attempting to win back possession and disrupt technical actions. In future studies, concomitant analyses of opposition play definitely warrant inclusion. The high levels of aerobic and anaerobic fitness deemed necessary for professional soccer might have provided our players with greater ‘protection’ against potential diminutions in skill performance and/or involvements over the course of games compared to a likely inferior physical ability in lower standard or younger populations frequently used in controlled experiments. Indeed, a strong association between aerobic fitness and declines in skill proficiency during match-play and/or after simulations of high-intensity match-play exercise has been reported although work was conducted in young amateur soccer players (Impellizzeri et al., 2008; Rampinini et al., 2008). Moreover, the observed lack of a drop post-match in passing proficiency in professional players mentioned earlier lends further weight to this theory (Rampinini et al., 2011).

In motion analyses of professional soccer, physical performance has been shown to decline albeit non-significantly during short periods of fixture congestion (Odetoyinbo et al., 2007; Dupont et al., 2010; Rey et al., 2010). However, none of these studies investigated whether impairments in skill-related measures occurred across successive games. Thus, the result showing that none of the physical or skill-related measures of performance were impaired during short periods of fixture congestion (three successive matches in ≤7 days) is noteworthy. The use of evidence-based post-match recovery treatments in place at my club (described in more detail in paper 9) might partly explain this ability to maintain all aspects of match performance over short but dense periods of competition. It may also be that the time interval between successive matches was sufficient to allow full recovery as players had a minimum of 48h and a maximum of 72h rest between games. In the recent study mentioned earlier in this discussion, neuromuscular and sprinting performance, muscle soreness and passing proficiency in professional soccer players recovered to baselines levels 48h post-match (Rampinini et al., 2011). Further research is nevertheless necessary to confirm whether similar results might occur in our players during even tighter congestion periods (e.g., three games in ≤5 days) or during a prolonged period of fixture congestion (as in paper 9) encountered over the season.

The present study was not without limitations. Firstly, a deliberate choice was made to include only midfield players for analysis as physical and skill-related performance across playing positions are greatly dependent on ball possession. In forwards for example, a drop in physical performance and ball involvements may simply be due to the opposition dominating possession in the defensive zones of the forward's team. In contrast, midfield players are expected to respond continually to attacking and defensive demands thus their efforts are less likely to be affected by ball possession. Secondly, in-game variations in performance may have been under-estimated as pre-defined 5-minute periods (e.g. 0-5 minutes, 5-10 minutes) were used in this study. A recent report has shown that 'rolling' as opposed to pre-defined game intervals provide a more accurate representation of decrements in match performance after intense periods of play (Varley, Elias, & Aughey, 2012). Finally, these results raise the question of the definition and analysis of what is 'skill' and the measures used in this study to determine it. Is this simply the pure technical ability to make a pass or is it a context-specific match quality that encompasses both technical ability and the capacity to use that technique within ever-evolving game and pressure situations thanks to efficient anticipation and decision-making abilities?

From a practical point of view, the findings from this study will generally reassure coaching staff in my club as to the ability of our players to maintain skill-related performance throughout games even when they experience accumulated or transient physical fatigue. Indeed, over the three seasons of data used in the analysis, it is worth mentioning for the purposes of this thesis that my team scored a large proportion of its total number of goals from 75-minutes onwards (~19% vs. 12% of goals during the first 15-minutes of play). The results also suggest that there is no need for our players to deliberately execute technical skills in match like situations of physical fatigue that is either accumulated or transient, in an attempt to accustom them to performing under such conditions. They also imply that physical conditioning interventions in an attempt to resist fatigue and aid skilled performance especially during the latter moments of match-play are unwarranted. However, larger sample sizes including a wider range of clubs are probably necessary to verify the present findings and increase their applicability to other professional soccer environments.

While this study has presented novel information on the association between physical and skill-related performance in professional soccer match-play, I feel that it has also created further opportunities for research. A study reconciling measures in controlled laboratory/field conditions and match-play environments is warranted to compare relative changes in performance in the same population and preferably in players at professional standard. Similarly, information on the frequency and/or outcome of other important technical actions such as dribbles, longer passes and set-plays related to physical performance might be pertinent. In addition, the effects of transient fatigue on soccer skills following high-intensity exercise are immediate but these effects dissipate very quickly (within 2-minutes) following cessation of exercise (Lyons et al., 2006). Therefore, in a future study, it would be worthwhile examining proficiency in skill-related actions that fall within the first 2-minute following the most intense 5-minute period of high-speed activity. An investigation to determine the effect of repeated sequences of high-intensity running (as presented in paper 3) on skill proficiency and involvements is also merited.

One suggestion for additional research omitted mention in paper 4 is an investigation of the speed accuracy trade-off theory (Stone & Oliver, 2009) but using data from actual match environments. For example, it would be worthwhile determining via analyses of technical actions performed in a fatigued state (e.g., passes performed after an intense period of activity or towards the end of play) whether professional soccer players sacrifice speed of execution to maintain accuracy or if impairments simply do not occur in either of these components. Recent work by Russell et al. (2011a) has shown that academy players' passing accuracy was maintained across halves in a game simulation whereas the speed of actions was slower during the second-half compared with the first-half. Finally, in future studies of this nature, the potential effects of score line, opponent quality and standard of play on the association between physical and skill-related match performance should be accounted for and comparative longitudinal analyses of performance across age groups and genders would be welcome.

5.4 Paper 5 (Appendix 2d): Effects of physical efforts on injury in elite soccer.

5.4.1 Introduction

In paper 5, the characteristics and potential influence of physical efforts on occurrences of injury during match-play were investigated in my soccer club. Analysis of movement activity prior to and at the time of 10 injury cases was examined. Thus, the main aim here was to determine whether intense periods of exercise or inadequate recovery time after sprint-type activities predisposed our players to injury.

5.4.2 Results and discussion

In professional soccer competition,, a large proportion of injuries are sustained during running actions (Hawkins et al., 2001) yet little is known about the characteristics of these movements. In the few reports that have attempted to characterise movements at the time of injury (Andersen et al., 2003, 2004; Arnason et al., 2004), running speed was determined subjectively and no data were provided on starting, average or maximal running speed or on the length or duration of actions. The present study used a novel approach as it was the first to associate injury data with measures of physical performance derived from computerised motion analysis of play to provide quantitative information describing events involved in the occurrence of match injuries.

Results showed that the final run over the course of which the injury occurred was performed at an average speed of ~17km·h^{-1}. Prior to injury, players had frequently started their final effort at low speeds before accelerating to attain the high-intensity speed threshold (>19.1km·h^{-1}) and then decelerating to lower speeds when the injuries were generally sustained. Further analysis of high-intensity efforts over the course of which injuries occurred showed that the characteristics of these actions were substantially different (albeit non-significantly) compared to a normative profile of the player's 'habitual' efforts. The mean length and duration of these high-intensity actions was nearly double the length and duration of the player's usual efforts. In addition, games skills and physical contact with opposition players were frequently superimposed on the locomotor activities prior to injury. Finally, a significantly lower than usual recovery time between the penultimate and final high-intensity action prior to injury occurrence was observed and players had covered 35% more distance at high-intensities than they habitually performed in the 5-minute period before the injury was sustained. These findings suggest that when there is 'inadequate' time for recovery during intense sequences of high-intensity exercise and the distance and duration of individual high-intensity actions are greater than usual, players may be at increased risk of sustaining injury in competition.

Interestingly, the majority of the injury cases occurred during deceleration phases following high-intensity running actions. Research in the English Premier League showed that players performed an average of 54 'brutal' decelerations per game (Bloomfield, Polman, & O'Donoghue, 2009). These actions lead to high levels of eccentric stress notably in the hamstring muscle regions and an increased risk of muscle strain (Woods et al., 2004). There may also be a link between the physiological strain associated with the acceleration and deceleration actions that frequently occurred prior to injury situations. The recognised increased energy cost of these locomotor actions (Osgnach et al., 2010) combined with the lower recovery time between high-intensity efforts preceding the present injury situations could have led to greater levels of transient fatigue potentially increasing the risk of injury.

In light of these findings, the injuries sustained could be linked to game-induced transient fatigue potentially coinciding with reduced functional ability in areas such as proprioceptive performance (Rozzi, Lephart, & Fu, 1999), dynamic joint stability (Jackson, Gutierrez, & Kaminski, 2009), force production (Apriantono, Hiroyuki, Yasuo, & Shinya, 2006), neuromuscular responses (Gleeson, Reilly, Mercer, Rakowski, & Rees, 1998; Minshull, Gleeson, Walters-Edwards, Eston, & Rees, 2007), and running mechanics (Kellis & Liassou, 2009; Sanna & O'Connor, 2008; Small et al., 2009a, 2009b). In theory, these results suggest that players with a higher capacity to resist fatigue and who are able to recover quickly during intense periods of exercise might have a lesser chance of sustaining injuries during such phases of play. To my knowledge however, no study has investigated the link between measures of physical fitness such as repeated sprint ability or intermittent endurance performance and the risk of injury in professional soccer.

These findings have implications for the prescription of injury prevention protocols and particularly physical conditioning interventions to enhance players' ability to decelerate safely following high-speed running actions. They also have pertinence for the design of exercise protocols that are used to simulate competitive physical activity profiles and explore the link between game induced fatigue and injury risk in muscle and joints. Previous experiments have used soccer-specific exercise simulations within the laboratory (Greig, 2008; Greig & Siegler, 2010; Oliver, Armstrong, & Williams, 2007; Rahnama et al., 2003, Rahnama, Reilly, & Lees, 2006) and the field setting (Delextrat, Gregory, & Cohen, 2010; Small, et al., 2009a,b, 2010) to monitor changes in physical measures. However, these protocols tend to measure the occurrence of fatigue in muscles after fixed durations (e.g., start, middle and end of exercise) to deduce whether there is an increased risk of injury. Moreover, simulations use a 45- or 90-minute exercise period divided into 15-minute work intervals that are often identical in terms of the order, number and type of locomotor actions performed and thus the overall intensity of exercise. Generally the design of such simulations does not accurately represent the 'random' nature of physical activity over the course of soccer match-play. Thus, given the present findings, I suggest that future research should employ protocols that investigate 'impairments' in performance in muscles and joints following dense periods of intense exercise randomly performed over the exercise period. Once again, this discussion fits well with the considerations on the design of soccer-specific exercise simulations previously discussed in papers 3 and 4.

In this study design, there were several limitations requiring discussion. Firstly, only a small number of injury cases were available and all were from a single club. The total of 10 injuries is lower than the a minimum of 20-50 cases recommended for studies of risk factors in sports injuries (Bahr & Holme, 2003). The sample size also limited the types of injury investigated and the patterns were not fully representative of those commonly observed in elite soccer. For example, the major part of the injuries here was sprains (60%) compared to a total of 18% of all injuries recently observed in a study in 23 European professional soccer clubs (Ekstrand, Hägglund, & Waldén, 2011). One reason for the present low sample size was the strict inclusion criteria employed. Only injuries that forced the player to immediately leave and not return to the field of play and which were clinically confirmed to be an injury by the club physician (thus avoiding fake injury incidents) were included for investigation. To reduce the effects of opposition behaviour, only injury incidents where no foul-play was observed (i.e., decision by referee to award a free-kick) were considered. Each injury incident was also cross-referenced to determine whether the same match had been analysed by the computerised motion analysis system further reducing the total number of injury cases. A strength of the present study however was that the methodologies and definitions of injury used closely follow those recommended by International Soccer Injury Consensus Groups (Fuller et al., 2006; Hägglund, Walden, Bahr, & Ekstrand, 2005) and will aid in providing consistent thus comparable results with those reported in similar future studies.

The validity of the method employed for determining a 'normative' physical activity profile for players can be also questioned as mentioned in the discussion on paper 6. The movement patterns in soccer are random, vary greatly over different match periods, between games and at various stages of the season and, as emphasised throughout this thesis, are dependent upon many factors such as score line or opposition standard. Here, a normative profile was calculated using data from only five games which in hindsight may not be sufficiently large to provide a stable enough indicator of physical performance (Gregson et al., 2010; Hughes, Evans, & Wells, 2004). This was due to a limited number of complete match performance datasets for several of the players in whom injuries were sustained.

Despite these limitations, I feel that this preliminary investigation has provided important practical insights into the characteristics of movements preceding injury in a professional soccer team. Again, within the limitations of the sample size, it has also provided answers to some of the points raised regarding physical activity profiles and injury in my initial review article (paper 1). The findings have implications for injury prevention interventions and the design of exercise protocols to simulate soccer match-play. Work is nevertheless needed to strengthen the study design. Additional research using larger cohorts and more injury cases is required to build upon and confirm these findings. Future directions for research into the effects of physical efforts leading to injury could combine motion analysis data with more detailed analyses of end events preceding injury. These include common game-related manoeuvres such as turns, swerves and cutting actions. Preliminary work in English Premier League soccer players by Robinson, O'Donoghue, & Nielson (2011) for example has investigated the link between sharp changes in running paths quantified using a complex path change identification algorithm (built into a computerised motion analysis tracking system) and the risk of sustaining injury. Finally, changing between playing surfaces may be a precursor for injury in soccer (Williams, Hume, & Kara, 2011). The present study design has implications for comparing the characteristics of physical efforts prior to injury on natural versus synthetic pitches.

CHAPTER 6 DISCUSSION AND CRITICAL EVALUATION OF THE FINDINGS REGARDING THEME 2: FACTORS POTENTIALLY AFFECTING PHYSICAL PERFORMANCE IN MATCH-PLAY

6.1 Paper 6 (Appendix 3a): The effect of an early dismissal on player work-rate in a professional soccer match.

6.1.1 Introduction

In paper 6, the effect on physical activity profiles of an early dismissal of a midfield player (after 5-minutes play) was analysed in remaining outfield players (midfield and defenders) in my team who completed the match. This study was conducted to provide information on how the players coped from a physical point of view over the remainder of the match (91-minutes of play).

6.1.2 Results and discussion

Overall, a greater level of physical exertion, determined via measures of total distance run and lower recovery times between high-intensity efforts, was observed in players compared to their habitual performances in match-play in which no dismissal occurred. In this particular game, our players may not have had the same opportunities to determine their efforts both collectively and/or individually mainly due to the tactical implications of the dismissal. They were probably forced to work harder than usual, resulting in a significant increase in physical activity compared to their habitual game performance. This result also suggests that in other games in which no dismissal occurs, the players might not always utilise their full athletic potential partly confirming speculation that the physical efforts of professional soccer players are to a certain extent self-chosen (Edwards & Noakes, 2010; Reilly et al., 2008). Confirmation that the players were forced to work harder than usual might also be reflected by the substantial decline in the distance covered in sprinting during the second-half; a result that did not habitually occur in other matches (calculated using a ‘normative’ match profile for each player). Thus it would seem to a certain extent that players accumulated fatigue after the early dismissal. Unfortunately, in this game, information on any concomitant changes in the opposition’s physical efforts and how this potentially affected my team’s activity was unavailable.

Despite the observed drop across halves, sprint performance was consistent across second-half 15-minute intervals. This result implies the use of a pacing strategy by the players to ensure that they could endure the entire game. Players might have consciously applied appropriate pacing strategies to potentially ‘spare’ intense physical efforts for the crucial game actions late on. Detailed information regarding the physiological background to self-regulation of physical exertion in soccer match-play can be obtained in a review by Edwards & Noakes (2010) published following paper 6. Nevertheless, as suggested by Edwards & Noakes, dynamic considerations during the game (skin temperature, thirst, accumulation of metabolites in the muscles, plasma osmolality, and substrate availability) generally enable soccer players to avoid total failure of any single peripheral physiological system either prematurely or at the conclusion of a match.

The present findings, albeit from a single match, have several practical implications. First, they aid in understanding how a professional soccer team coped 'physically' with an early dismissal. Notably, analysis of running patterns showed how the players probably tried to remain 'operational' until the end of the game perhaps through the use of a pacing plan. Ideally though, I would have liked to conduct post-match interviews with the players concerning their approach to the game following the dismissal but this was not possible. This information would have enabled me to determine whether the players made a conscious decision about their physical activity, or whether they made tactical decisions first which subsequently affected their activity profiles as the game progressed. Second, in this particular game, my team in which the dismissal occurred obtained a draw away from home (result: 1-1) despite playing over 90-minutes with only nine outfield players. This positive result has implications for our coaching staff and could lead to the adoption of similar tactical strategies (e.g., playing formation, defensive organisation) to aid players in enduring the remainder of future matches played under similar constraints. Indeed, data not included in paper 6 show that despite being dominated in terms of the proportion of match time spent in possession (60% vs. 40%) my team won a larger amount of challenges for ball possession (43% vs. 57%) and managed to create 10 scoring opportunities in comparison to 13 for the opponents. Finally, these findings might also have important implications for the implementation of post-match recovery interventions and can be related to observations in papers 4 and 9. Practitioners will recognise that in similar situations, outfield players will probably endure greater than usual levels of physical strain although overall exertion levels will no doubt vary across different teams due to the individual tactics they employ to cope with the dismissal (e.g., defensive stance using a deep lying compact team shape to reduce the necessity to run large distances). Nevertheless, any greater than usual level of exertion might impact on a player's capacity to recover from competition and thus affect future athletic performance especially if the time span between successive games is short (Odetoyinbo et al., 2007).

A limitation that would have merited mention in the present study was the comparison of performance of each player in a single match against a normative profile obtained from analysing 15 matches. Research has shown that high-intensity activity within one game does not provide an accurate indication of an individual's capacity to perform intense work if it is based on a single observation (Gregson et al., 2010). The high-intensity activity completed by professional soccer players during match-play is highly variable as studies have regularly shown coefficient of variation values above 20% across games (Gregson et al., 2010; Mohr et al., 2003; Rampinini 2007b). Further research using a larger sample of games and player dismissals is thus required to complement these findings and allow more extensive investigations of the impact of sending offs on physical activity profiles. It would also provide an opportunity to examine concomitant changes in team and player tactics and technical performance (e.g., playing system, ball possession, zone coverage, completion rates in passing). Additional research could also consider how players respond physically to a teammate's dismissal at different moments across games and the effects of match location (home and away) and score status (Lago et al., 2010).

Finally, there is potential for a study to evaluate the contributions of substitutions in attenuating declines in physical performance endured across teams after the loss of an outfield player. In hindsight, inclusion in the paper of data on the physical activity profiles of substitutes would have been pertinent but was not possible due to the Journal's word count limitations. Interestingly, additional analyses conducted on this game showed that high-intensity running performance (sprint and high-intensity activity combined) per minute in two second-half 'post for post' replacements (midfielder and forward) was substantially higher in the substitutes compared to the players they replaced (11.7 ± 1.0m·min^{-1} versus 19.8 ± 10.2m·min^{-1}, ES for the difference = 1.1). This contribution to the physical efforts of the team as a whole would have helped attenuate any declines observed in players who played the full game. This later point on the efforts of substitutes is examined in greater detail in paper 7.

6.2 Paper 7 (Appendix 3b): Work-rate of substitutes in elite soccer: A preliminary study.

6.2.1 Introduction

In paper 7, I conducted an analysis of the effects on physical performance of making substitutions during match-play. Physical activity profiles were analysed in midfield and forward players. This project stemmed from a need identified in my club and with regards to the scientific literature for elite players to maintain optimal physical performance throughout play and especially towards the end of competition (Reilly, 2007). This paper, therefore, demonstrates a continued interest in the need for identifying countermeasures to fatigue during competition and can clearly be linked back to the work conducted in paper 6.

6.2.2 Results and discussion

Results showed that midfield substitutes in my team ran substantially greater, albeit non-significant overall distances and distances at high-intensities than the midfield player they replaced. Analyses also showed that physical activity profiles were globally similar to those observed when starting matches. In addition, the overall distance covered and that run at high-intensity in midfield replacements were superior to values observed in remaining midfield players who had started the game. This finding partly supports work previously conducted in other top-class players showing that substitutes ran significantly more distance (+25%) during the final 15-minutes of play compared to players who had started the games (Mohr et al., 2003) although individual playing position was not accounted for as done in the current study. As there is a tendency for professional soccer players to experience fatigue reflected by a drop in physical activity towards the end of games (Bradley et al., 2009b; Mohr et al., 2003), these results suggest that midfield player substitutions provide a valuable means of maintaining and potentially increasing team efforts until the end of match-play.

In contrast, workload was lower in replacement forward players compared to the forwards they replaced and less than that observed when the same players started matches. Reasonable practical explanations for this finding might include decreased motivation in these players due to non-selection in the initial starting line-up, an inability to 'get into' the game due to the tactical requirements of this position, and/or an insufficient warm-up programme performed prior to entering the field of play. Interestingly, additional analyses I have performed (not included in paper 7) might support the latter theory as the total distance run per minute by forward substitute players was greater (albeit non significantly) over the entire time they played compared to the opening 10-minutes play as a substitute ($121.1 \pm 9.9 m \cdot min^{-1}$ versus $119.8 \pm 9.0 m \cdot min^{-1}$, effect size for the difference = 0.14). This result also suggests that making earlier substitutions might be more beneficial in allowing forward players to efficiently utilise their physical potential and be more involved in play.

In summary, these findings were a first step in identifying the physical contributions of substitutes in soccer and complement data reported in paper 6. Further research is needed to identify the reasons for the lower physical exertion observed in forward replacements and eventually to inform interventions to improve preparation and thus the physical contributions in these players. These potentially include increasing player motivation, improved warm-up strategies (changes in duration/intensity of routines whilst preserving energy stores), and tactical adjustments, for example, to team shape and/or formation. Work is also needed to investigate whether the physical contributions of substitutes vary in relation to score status. For example, a pertinent question might be to ask whether substitutes work harder when their team is chasing the game. A related study conducted after publication of the present work has shown a 50% drop in high-intensity efforts performed by professional soccer players when winning compared to losing (Lago et al., 2010). Finally, the present results support previous speculation (Reilly et al., 2008) that substituted players were probably replaced for tactical reasons as there was no evidence of a drop in second-half physical activity prior to leaving the pitch. However, empirical evidence of changes in technical or tactical scores was not provided in paper 7 or by Reilly and co-workers. Therefore, future work should aim to compare the tactical and/or technical contributions of substitutes compared to both the players they replace and to team mates remaining on the pitch. Indeed, while the present forward players apparently did not perform 'physically' at their optimum levels, it would be worth examining whether they were 'effective' notably in terms of goals scored or creating scoring opportunities.

6.3 Paper 8 (Appendix 3c): Influence of opposition team formation on physical and skill-related performance in a professional soccer team.

6.3.1 Introduction

In paper 8, athletic and skill-related performance was compared in the reference team in games against three opposition team formations commonly employed in French professional soccer. The main aim of this novel project was to identify whether physical, tactical and technical characteristics of team-play and the demands across playing positions vary according to the formations used by opposition teams and thus broaden knowledge in one among a multitude of key features that can affect performance across individual playing positions and for the team as a whole.

6.3.2 Results and discussion

The results showed that to a certain extent opposition team formation governed the overall physical demands (represented by differences in the total distance run and efforts at lower intensities) for my team as a whole but not its efforts performed at high-intensities. In contrast, none of the measures of physical performance across the individual playing positions were affected by opposition team formation. For the team as a whole the distances covered in high-intensity activity in relation to ball possession varied significantly according to opposition team formation, notably against a 4-2-3-1 system although effect sizes for these differences were low (range for Cohen's d = 0.3-0.4). Thus the statistical differences observed might have low practical significance. Nevertheless, workload at high-intensities was greater for my team as a whole when opposition teams operating a 4-2-3-1 formation were in possession of the ball. This difference might be linked to the defensive and offensive tactical demands imposed by this particular system (Bangsbo & Peitersen, 2000). Indeed, my team had substantially less possession (-4.7%) in games against this particular formation and players probably had to work harder defensively to regain possession and prevent scoring chances. This is partly confirmed by the greater number of aerial and ground duels observed when competing against teams operating a 4-2-3-1 formation.

From a practical point of view, the present results do not lend support to the implementation of specific physical conditioning regimes to prepare for matches against a certain type of formation employed by opposition teams. While the team as a whole may have needed to adjust its overall efforts against different team formations, physical activity across individual playing positions was not governed by opposition playing system. Moreover, while game-related decrements (across halves and in the final 15-minute interval) in physical efforts were present in the reference team, these were not influenced by the formations operated by opposition teams. Thus it seems the ability of my team to respond physically up until the end of games was unaffected by the demands imposed by all three opposition formations. However, in this study, the link between opposition playing system and the extent to which transient fatigue occurs (e.g., declines in running performance immediately after dense periods of intense high-intensity activity as done in paper 4) was not explored and warrants investigation.

While generally not the case for individual playing positions, the tactical and technical demands for the team as a whole varied substantially according to opposition team formation. The frequency of certain technical actions (e.g., passes, percentage of 1-touch passes, number of ball touches per possession, and frequency of duels) was heavily influenced by the opposing formation. As mentioned earlier, my team also had significantly less ball possession in games against a 4-2-3-1 system compared to the other two formations. These results have consequences for implementing specific training drills to aid my team’s tactical and technical preparation against this particular playing system and/or for perhaps altering our playing formation. Indeed, the higher frequency of one-touch passes against a 4-2-3-1 system suggests a need for drills to practice this aspect of play to prepare optimally for matches against this formation. Similarly, the low amount of time spent in ball possession observed in games against this same formation requires players to make the most of limited time spent with the ball. In turn, there are implications for pre-match opposition analysis briefings and team selection policies as the starting line-up chosen by coaching personnel might in part be determined by the opponent’s formation. Further work is nevertheless required to compare variations in physical and skill-related scores against other team formations (e.g., 3-5-2, 4-3-2-1, 4-4-1-1) employed across professional European soccer.

In this study, the standard of opposition (determined by League position) was verified to ensure that this factor did not confound the results and to hopefully strengthen their pertinence and applicability. Two weaknesses acknowledged in this study were the relatively low numbers of players analysed in each playing position and the lack of information on centre-forwards. Indeed, findings published in a related study that I have recently co-authored have demonstrated a substantial decline in high-intensity running activity across game halves in centre-forwards playing in a 4-5-1 formation whereas this was not observed for centre-forwards in 4-4-2 and 4-3-3 systems (Bradley et al., 2011a). In addition, data reported in opposition teams that played a 4-3-3 formation were combined here with those using a 4-5-1 system. Both myself and two match observers found it difficult to distinguish between these two systems as several teams frequently played a 4-3-3 formation when in possession but intermittently reverted to a 4-5-1 when no longer in possession. Thus interpretation of the present findings may to a certain extent be confounded especially as substantial differences in activity profiles were shown to exist between 4-3-3 and 4-5-1 formations employed by teams in the English Premier League (Bradley et al., 2009a). I feel that further collaborative work is necessary between match analysts and coaching practitioners to establish more objective and reliable means for determining common team formations.

Finally, the present findings can be linked back to other studies presented in this programme of work. Their influence might increase when there is occurrence of any one or a combination of other factors affecting physical and/or skill-related performance that I have presented in this thesis. For example, the impact of a dismissal or of substitutions, and potential drops in performance during periods of fixture congestion might be further accentuated in matches against opponents using a certain playing formation (e.g., 4-2-3-1 as seen here). These factors certainly merit further investigation but necessitate a larger scale approach including more teams and games.

6.4 Paper 9 (Appendix 3d): Are physical performance and injury risk in a professional soccer team in match-play affected over a prolonged period of fixture congestion?

6.4.1 Introduction

In paper 9 the potential effects of a prolonged period of fixture congestion on physical performance and injury rate and severity in a reference team were explored for the first time. Match data were collected and compared across eight games played consecutively by my team over a 26-day period.

6.4.2 Results & discussion

Major findings from paper 9 were that the overall distance run per minute and that covered in low-intensity running varied significantly across the eight successive games. This result could imply that the team as a whole might at times have experienced residual fatigue over the dense sequence of matches. However, analysis of fluctuations in physical performance over the series of games showed that the total distance run only declined significantly in the second and third games suggesting that the drops were more likely due to random variation in performance. There were no differences in high-intensity running across games although a high coefficient of variation (~34%) in this measure was observed suggesting that players did not reproduce consistent high-speed activity profiles across the games (Gregson et al., 2010). Further analyses showed that the total distance covered and that run in high-intensity efforts was unaffected across match halves over the period of fixture congestion. Finally, measures of physical activity over this dense period of fixtures were globally comparable to that in matches played outside this period and to the work activity profiles reported for the eight different opponent teams combined.

In light of these findings, it seems therefore that despite the significant variation in running activity observed across games, my team as a whole was generally able to maintain physical performance over an extended period of fixture congestion. This finding may be partly reflected by the results obtained as a total of seven victories and one defeat were recorded over the eight successive games (27 goals scored vs. 7 conceded). Thus, the team generally coped well and was able to respond ‘physically’ to the demands of a prolonged period of match congestion. In general, these promising results are in agreement with the observations presented later on in paper 4 and elsewhere (Dupont et al., 2010; Odetoyinbo et al., 2007; Rey et al., 2010) that demonstrated no significant changes in physical performance over two or three games played consecutively within a tight time-frame. I can forward several reasonable explanations for the positive nature of these findings. These include squad rotation strategies, post-match recovery techniques and self-regulation of efforts. These points will be discussed in turn.

Over the series of matches, 19 players were used in total, six players participated in every game as a starter or substitute, and a single outfield player (a central-defender) completed every game. These rotation policies, although occasionally forced on the team due to injury or suspension, no doubt contributed to keeping players ‘fresh’ and helped maintain the physical performance of the team as a whole across the eight games. While the results also highlight the importance of ‘squad strength’ and the individual contributions of its members, longitudinal variations in performance across individual players or team units could not be statistically analysed due to the frequent changes in team selection. Nevertheless data not presented in paper 9 on a central-defender who completed all eight games are shown in Figure 1. It can be seen that performance achieved in high-intensity running (distance covered per minute) was similar in the final versus the first game in the series of matches. Potentially, the physical efforts of substitutes could have played a part in preventing declines in running activity relating back to observations made in paper 7. Here, analyses showed that the distances the substitutes covered at high-intensities were substantially greater in comparison to those run by the players they directly replaced. This result again demonstrates the value of replacing players to aid a team in maintaining physical performance especially during periods of fixture congestion.

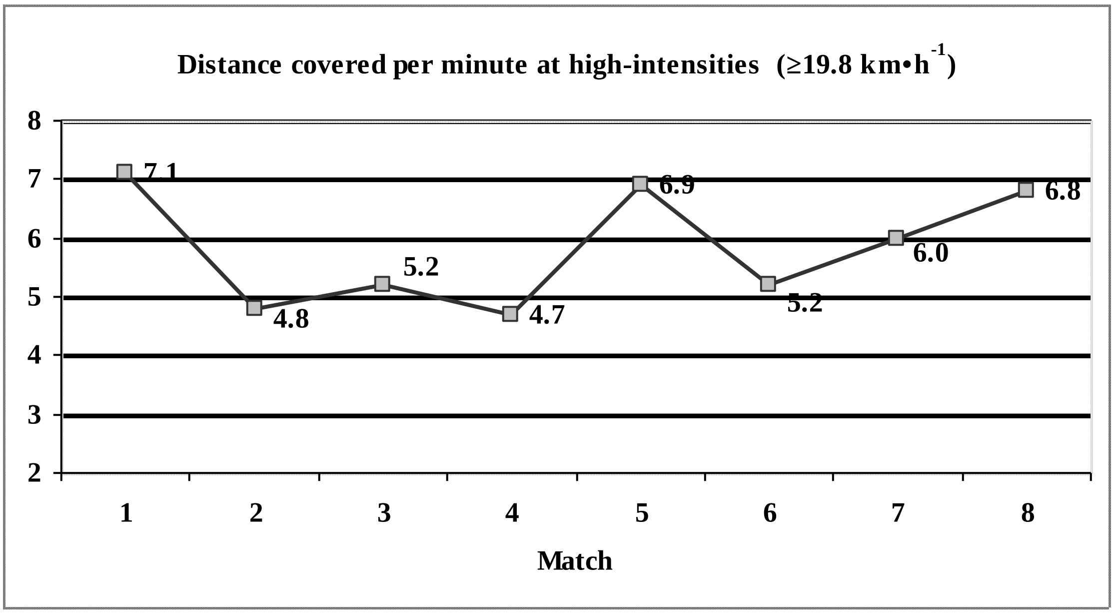

Figure 1 Distance covered per minute at high-intensities in a central-defender in eight successive games played over a 26-day period.

Players who participated in this congested fixture period systematically benefited from interventions including contrast therapy (hot and cold water immersion), lower-limb compression garments and sports massage treatment. Similarly, nutritional advice was provided in an attempt to ensure that players had adequate nutrient and fluid intake throughout the series of games but individual dietary intake could not be adequately controlled. Interestingly, related research conducted in elite youth players has shown that similar post-match recovery strategies using hydrotherapy and/or cryotherapy techniques (e.g., sauna, cold water immersion, jacuzzi) were effective in maintaining running performance in consecutive games played within a short time delay (Buchheit, Horobeanu, Mendez-Villanueva, Simpson, & Bourdon, 2011; Rowsell, Coutts, Reaburn, & Hill-Haas, 2011). While the present evidence indirectly suggests support for the use of post-match recovery techniques to help maintain performance over prolonged periods of fixture congestion, further experimental research, ideally using a treatment versus control group in whom no recovery interventions are performed, is necessary. This would provide an opportunity to directly quantify the effectiveness of post-match recovery strategies on competitive physical activity profiles in soccer players which up to now has not been achieved at professional standards. One reason for this is the understandable reluctance of coaching practitioners to allow controlled research experiments in the professional club setting with some players receiving treatments and some not.

Interestingly, related research I have recently conducted has examined the effects of adherence to post-match recovery treatment on physical activity profiles during periods of match congestion in players in my club. This work was presented at the Third World Congress on Science and Soccer held in Ghent, Belgium (14-16th May, 2012) (Carling et al., 2012). Our research group investigated the effects of adherence to post-match recovery modalities (cold water immersion, lower-limb compression garments and sports massage) during short periods of match congestion (three consecutive games played 48-72 hours apart). This was done by correlating the total number of recovery treatments received per participant during the 3-game period and the % change in distances covered observed between the 1st and 3rd game. No significant associations were reported and players generally maintained physical performance across the short period of fixture congestion. These preliminary findings suggest that while not compromising performance, adherence to post-match recovery treatments did not necessarily aid players in sustaining physical activity levels during short periods of match congestion. Again, additional research (treatment versus control group) and analysis of performance over longer periods of match congestion are definitely warranted. However, as shown in the motion analysis literature generally, the workload imposed on individual players and the team as a whole differs greatly across games and will have a direct effect on the efficacy of any post-match recovery intervention. Game simulations could therefore be more valid and sensitive alternatives to test the efficacy of control and recovery conditions.

The self-regulation of physical efforts has also been suggested as a means used by players to maintain performance when participating in congested fixture periods (Odetoyinbo et al., 2007; Rey et al., 2010). Such ‘pacing’ strategies could explain the present findings and aforementioned lack of a decline in physical performance during successive games with a short recovery period observed in previous studies. Yet in paper 9, team activity profiles did not statistically differ to those observed in games played outside this period suggesting habitual performance was maintained despite fixture congestion. Another viable suggestion not originally mentioned in paper 9 was that immediately after completing the 8-game sequence, the players had their two-week mid-season break from competition (imposed by the French Professional Football League). Thus players were perhaps able to perform maximally over the congested fixture period knowing that they had ample time for recovery later. It would have been interesting to compare the same data if no break was forthcoming after the 8-game period. Indeed, related work by Ekstrand and colleagues (2004) showed that professional European players who ‘underperformed’ in the 2002 World Cup had played 25% more matches during the last 10 weeks of the season compared to players who performed better than expected.

In contemporary professional soccer, there is concern over the competitive demands being placed on players and the translation of these physical and mental demands into injury syndromes and underperformance (Ekstrand et al., 2004). Here, injury rates and severity did not increase over the prolonged period of fixture congestion compared to data from games played outside this period. This result complements previous research I have conducted in my club showing that shorter periods of fixture congestion did not affect injury risk (Carling et al., 2010) and again, probably strengthens the case for squad rotation policies and post-match recovery strategies. In addition, adherence by players to functional injury prevention and rehabilitation protocols currently in place at my club no doubt contributed to these positive results (Carling, Le Gall, & Orhant, 2011).

Overall, I feel that these results have extended the growing body of literature covering the effects of fixture congestion on physical performance in professional soccer match-play and clearly complement information presented in paper 4 in which variations in performance in my team were analysed over shorter periods of fixture congestion. Further research is nevertheless necessary using a larger sample of teams to enable investigation of inter-individual variations in physical performance over a prolonged period of fixture congestion as well as examining changes relative to individual playing positions. Gregson et al. (2010) for example observed substantial differences in between-match variations (expressed as a coefficient of variation) in high-intensity distance run across playing positions with highest values reported in players in central positions. An analysis of the frequency of repeated high-intensity running bouts (several consecutive intense efforts performed over a short time interval) would also complement the work conducted in papers 3 and 4. Indeed, short periods of match congestion were shown to affect the rate of recurrence of such actions in international field hockey players notably in the latter game of the series (Spencer et al., 2005b). In future studies, there is also room for analysis of physiological markers of fatigue such as creatine kinase (Lazarim et al., 2009) combined with subjective markers (e.g., ratings of perceived exertion, delayed onset of muscle soreness). Information collected via questionnaires on the occurrence of psychological ‘staleness’ in players during periods of fixture congestion would also be pertinent. While studies in amateur players have shown that physiological perturbations and declines in fitness scores occur up to 72-hours post-match (Ascensão et al., 2008; Fatouros et al., 2010; Ispirlidis et al., 2008), a report published after completion of the present study has shown that neuromuscular fatigue, muscle soreness and sprint performance in professional players returned to baseline levels within 48-hours after a match (Rampinini et al., 2011). Thus players at professional levels are seemingly able to recover quicker than peers at lower standards, possibly explaining the lack of decline in physical performance during short congested fixture periods reported here and elsewhere (Dupont et al., 2010; Odetoyinbo et al., 2007; Rey et al., 2010). Unfortunately, all these studies have only tracked post-match changes after a single game. Similar research addressing the cumulative physiological and physical effects of playing a greater number of matches over a short time frame is definitely warranted.

Finally, in hindsight, inclusion in paper 9 of data analysing changes in technical and tactical performance across the eight games would have been pertinent. Interestingly, additional analyses performed on my team’s attacking play for the purposes of this thesis showed that a greater number of shots (15 vs. 18), shots on target (33% vs. 39%), crosses (26 vs. 29), successful crosses (23% vs. 24%), duels won (52% vs. 57%), and more time in possession (51% vs. 63%) were achieved in the final versus the first game in the sequence. Thus these results tend to suggest that as with physical performance these elements of match-play were unaffected even after playing many games over a short time period.

6.5 Paper 10 (Appendix 3e): The effect of a cold environment on physical activity profiles in elite soccer match-play.

6.5.1 Introduction

Since 2004, the French Football Professional League has implemented various obligations and countermeasures to ensure that despite the extremely cold climatic conditions encountered during winter months over recent seasons, the health, safety and performances of players are not compromised. However, no information exists on the impact of cold temperatures on physical activity profiles in official competition. In paper 10, I aimed to present new information on this recurring issue and provide some responses to previous speculation on the matter (Carling et al., 2005; Reilly, 2003a, 2007).

6.5.2 Results and discussion

Physical performance in competition in defending and midfield players belonging to my team was compared across four temperature ranges. Endurance performance characterised by the total distance run was significantly related to ambient temperature but unaffected in cold temperatures. Reilly (2007) speculated that the intensity of exercise during match-play is sufficient to offset the potential deleterious effects of a cold environment on body temperature and ensure running activity is maintained over the course of games. The present results would thus seem to be in accord with this theory. Similarly, cold temperatures were not detrimental to distance covered in high-intensity activity across halves, in the final versus first 5-minute periods in each half of normal time, or for the entire match. Related work by Mohr et al. (2004) in sub-elite soccer players has shown that the distances covered in high-intensity running dropped substantially at the beginning of the second-half of games. This reduction in physical activity was associated with a drop in muscle temperature but no information was provided on the ambient conditions. Interestingly, the distances covered in high-intensity running by our players also dropped albeit non-significantly at the beginning of the second-half of games in all temperatures compared to the equivalent period at the beginning of the first-half. This result supports Mohr and co-workers (2004) recommendation that a re-warm-up should be conducted during the half-time pause. However, this decline was not more pronounced in colder temperatures. In addition, while prolonged exercise in very cold conditions (<5°C) can be associated with diuresis eventually leading to dehydration and potentially reduced high-intensity endurance performance (Armstrong, 2006), the lack of a decline in high-intensity activity towards the end of games suggests that in the present players, cold temperatures were not associated with a greater levels of accumulated fatigue. A possible reason for this finding might be that fluid ingestion by players over the course of games was sufficient to offset dehydration although drink intakes were not measured here.

Of interest, results showed that midfield players covered a significantly greater distance in the 30-45 minute period in the first-half of matches played at ≤5°C compared to the corresponding period in those played at ≥21°C. The distance covered in high-intensity running by these players progressively increased for each 15-minute period reaching its maximum just before half-time whereas the opposite was observed in warmer temperatures. Thus, high-intensity running performance in midfielders was seemingly affected at the beginning of games played in cold temperatures and only reached its highest level towards the end of the first-half. An investigation into the effectiveness of current pre-match warm-up regimens used in my club on performance at the start of games played in cold weather is definitely warranted. Similarly, experimental research to quantify the value of wearing protective cold weather garments is necessary especially as any potential confounding effect of clothing worn by players could not be adequately controlled in this study.

The research presented in paper 10 was mainly conducted to examine the impact of cold temperatures on physical activity profiles in competition. However, as an indirect consequence of the study design, practical information was also obtained on the deleterious effects of match-play participation in warmer temperatures. Previous work has shown that physical activity in soccer match-play is greatly affected in hot and humid temperatures (≥30°; Mohr et al., 2010; Özgünen et al., 2010). Here, the players also ran significantly shorter total distances in games played in warmer temperatures (ranging from 22-27°C). This result is noteworthy as it suggests that coaching and fitness personnel should also account for the adverse effect of warm conditions even in competition played at temperatures lower than 30°C.

On initial reading, the perceived inter-relationship between this and the four other factors investigated in studies in this area might not be obvious. Yet match analysts and coaching staff should always be aware of the role motion analysis data can play in monitoring possible impairments in performance as well as aiding players in maintaining health and safety (Carling et al., 2005). Thus, this report mainly complements paper 9 in providing pertinent information on conditions potentially unfavourable to professional match-play performance. It will also aid in planning contingency strategies to counter the liability of cold and warm conditions to player health and performance. These strategies to aid players in coping with the different forms of thermal strain encountered during competition include reflection on nutritional interventions (Armstrong, 2006; Pitsiladis & Maughan, 1999), warm-up routines (Mohr et al., 2004), and protective garments (Nimmo, 2004). Paper 10 has also added to the limited body of research in this area as well as the results recently presented in a series of research papers belonging to a special issue on playing soccer in extreme environments (Scandinavian Journal of Medicine & Science in Sports, Special Issue: Exercise in Hot Environments: From Basic Concepts to Field Applications, 2010, 20, Suppl s3, iv–v, 1-167).

A limitation of this study was the lack of control over the protocol used for temperature readings provided by the French Professional Football League (LFP). Due to constraints of my work, I could not be present at all games to record climatic conditions. Thus I had to rely on measures provided by the LFP. The protocol also failed to take into account additional environmental factors including relative humidity and wind-chill and changes in climatic conditions over the course of games as only one measure was taken 1 hour prior to kick-off.

I also feel that inclusion of injury-related data could have been pertinent to verify whether the changes in physical activity in cold conditions were accompanied by a greater risk of injury. Here, high-intensity running activity was notably affected at the beginning of games and complementary data on the risk of injury over the same time period might be pertinent although a substantially larger sample size would probably be necessary to ensure adequate statistical power. In future studies, a combination of data from motion analysis and physiological measures including dehydration, heart rate and thermal responses would also provide a more comprehensive analysis of the strain specific to matches played in cold environments. For example, two novel studies have recently investigated fatigue development in elite soccer in a hot environment by associating changes in heart rate, blood lactate, muscle temperature and body mass with variations in the physical activity pattern over the course of games (Mohr et al., 2010; Özgünen et al., 2010).

In paper 10, it would have been worth mentioning that the general lack of reports that include the ambient conditions under which games are played (Drust et al., 2007) combined with the difficulties encountered in leading the present study suggest that soccer-specific exercise simulations could be a useful alternative means for investigating the impact of cold temperatures on game activity patterns and physiological responses to exercise. For example, a recent paper has examined the effects of different half-time warm-up strategies on second-half soccer-specific speed, power and dynamic strength using a 90-minute soccer simulation (Lovell et al., 2011). However, up to now, research using game simulations in soccer players to investigate the link between exercise and temperature has been limited to studying the effects of heat on running performance (Clarke et al., 2011). In addition, it is well established that a decrease in muscle temperature in a cold environment induces profound impairments in neuromuscular function (Racinais & Oksa, 2010). The potential effects of cold temperatures on skill-related performance (e.g., technical proficiency and ball involvements) in professional soccer competition have not received any attention and therefore warrant coverage in a future investigation.

CHAPTER 7 IMPACT OF THIS RESEARCH AND FUTURE PERSPECTIVES

7.1 Introduction

This section discusses and critically reflects on the general impact of this programme of research on policy and practice in my club. Ongoing research and eventual directions for future investigations within the context of the present programme of research are presented.

7.2 Impact of this work on policy and practice in my club

This empirical programme of work has examined contemporary issues and considerations regarding competitive physical performance in a professional soccer club over a four-season period. It also aimed to inform both the methodology and direction of future studies to ensure that the knowledge base created leads to conclusions and recommendations that are of importance to both the scientific and applied community (Drust et al., 2007). In each study, I attempted to use an appropriate methodological design to match the identified problem whilst constantly adapting my research to fit in with the real-world context and demands of a high-performance sports environment. Ultimately it was hoped that the present research would be a vehicle to direct a more evidence-based framework for the application of motion analysis; making training and preparation more theory-based and generally impacting on policy and professional practice in my club. As a whole, these findings have allowed greater insight and appraisal of current practices. Given that real-life natural competitive situations were under investigation in a high sports performance, I can suggest that the outcomes of the studies possess high levels of ecological validity. Positively, several of the current findings have been validated and adopted by my club’s fitness and medical practitioners and coaching staff and used in structuring frameworks for physical conditioning programmes, technical training and preparation for competition. These will be addressed later.

One criticism that could be immediately directed at the present set of publications is the lack of a published controlled intervention study to provide objective evidence as to the subsequent impact and effectiveness of this work on fitness training regimens and ultimately, physical performance in competition. Ideally, some experimental evidence of a controlled intervention and its effect on actual performance in match-play would have been pertinent. However, the difficulties commonly encountered in incorporating official scientific research programmes into the daily practices in a professional soccer club environment are well-recognised by those working in the field. Moreover, transferring quantifiable training outcomes into identifiable changes in match performance remains a challenge in team sports such as soccer (Bishop, 2009). In relation to the present work and the scientific literature, these problems are reflected by a lack of investigations in professional soccer in which the effects of controlled physical conditioning interventions are evaluated on actual competitive physical performance and in relation to changes in fitness scores observed from physical tests. To my knowledge, only studies conducted in junior soccer players (Helgerud et al., 2001; Impellizzeri et al., 2006) have attempted to quantify concomitant changes in fitness and actual match performance after controlled physical conditioning interventions. Related issues hindering such interventions also encountered over the course of this work and observed in professional soccer environments generally include gaining regular access to first-team players and the reluctance of these to volunteer for intervention-based research is common. The refusal of coaching and conditioning staff to allow interventions in some and not all players in a squad is also comprehensible. Obtaining sufficiently large sample sizes of elite players is thus difficult. The eventual non selection of players following intervention programmes due to current form or injury also leads to problems obtaining continuous longitudinal datasets on game performance. Furthermore, the confounding effect of eventual changes in playing personnel and staff and training practices over the course of the season must somehow be accounted for. Finally, the inherent variability observed across matches in indicators of physical performance derived from motion analysis (notably high-intensity movement activity) casts doubt on their appropriateness as a stable enough indicator, pre- and post-intervention, for objectively determining the effects of a training intervention (Gregson et al., 2010).

Nevertheless, these results have had an impact in my club at different operational levels both in training and match preparation. Indeed, many of the findings have been accepted, adopted and complied with by the coaching, conditioning and playing staff at whom they were aimed at; factors outlined by Bishop (2008) as paramount if sports science based research is to realistically contribute to improvements in competitive performance. Examples include: the provision of feedback on pre-match opposition analysis, changes in warm-up strategies prior to match-play, evaluation of the utility of post-match recovery and injury prevention interventions, a critical needs-analysis of elements used in physical conditioning programmes and fitness testing, and implementation of training drills for skill-related development in players at academy level.

Examples of areas in which the present results have clearly had a quantifiable impact include improvements in the physical contributions of substitutes and changes in the pre-match warm-up regimen prior to matches played in cold conditions and in the development of strategies to reduce the risk of muscle strain and ankle sprain injuries in match-play. Changes in both the warm-up strategy of forward substitutes and the tactical and motivational instructions of coaching staff can be linked to a respective 7% and 23% increase in the total distance covered and that run at high-intensities in forward substitutes over 20 games analysed during the 2009/10 season compared to results reported in paper 7. It is also worth mentioning that during the course of our 2010/11 Championship winning season, five League games were directly won following goals scored late on by forward substitutes. Regarding the point on match injury, in the two seasons following publication of paper 5, drops of 40% and 55% were observed in the number of muscle strains and ankle sprains incurred in match-play and training following a systematic pre-season screening and injury prevention programme. The former for example included the implementation of Nordic hamstring strengthening exercises to aid in improving eccentric hamstring strength (Mjølsnes, Arnason, Østhagen, Raastad, & Bahr, 2004; Small et al., 2009a) and the latter employed proprioceptive training to aid prevention notably against ankle sprains (Ergen & Ulkar, 2008).

Areas in which this programme can be considered to have had a positive ‘qualitative’ impact include the content of pre-match opposition analysis presentations. These now formally take into account the impact of team formations employed by future opponents on physical and skill-related performance. Drills used by coaching personnel for developing fitness and ball control and running skills with the ball in our elite Academy players have also evolved and now incorporate several of the physical (e.g., speed of movement) and technical (e.g., pressure during ball control drills) elements of game performance identified in paper 2. The positive results reported over the prolonged period of fixture congestion in paper 9 have helped justify adherence to post-match recovery programmes and the advice provided by sports science and conditioning practitioners on lifestyle issues (e.g., diet, sleep) especially when the time interval between several successive matches is short.

Several of the present findings have the merit to question present practice and policy as well as querying current opinions, observations and techniques presented in the scientific literature. For instance, in light of findings reported in paper 3 and my club’s high ranking over recent years, doubts can be raised on the true importance of general and position-specific repeated high-intensity exercise and necessity to train this component notably in relation to physical performance in elite match-play and more importantly to the results of my club. Hence, critical reflection regarding the relevance of current fitness testing procedures and a needs-analysis to determine the real utility of high-intensity conditioning interventions is ongoing. Fitness testing in my club will be discussed in more detail later in this discussion.

Finally, on the basis of evidence reported in paper 4, the ecological validity of experimental test protocols previously used in the literature to examine the relationship between fatigue and skill-related performance in soccer is questionable in regard to the actual demands of competition. Similarly, recommendations are notably provided in papers 3, 4 and 5 in an attempt to refine the design and thus improve the validity of exercise protocols commonly used to simulate soccer specific physical activity profiles and explore links between factors such as fatigue, technical skills and injury risk.

7.3 Directions for future research

Since the publication of Paper 1, the body of research using motion analyses of contemporary professional soccer competition has continually developed and in turn broadened our understanding of the physical component of match-play. As in the present thesis, the majority of recent publications have also provided in-depth descriptive analyses of the physical characteristics of play and position-specific demands (Abt & Lovell, 2009; Di Salvo et al., 2009, 2010; Gregson et al., 2010; Osgnach et al., 2010) or have investigated other game-related factors potentially affecting performance (Bradley et al., 2010, 2011a, Dellal et al., 2011, Dupont et al., 2010; Lago et al., 2010; Mohr et al., 2010; Rey et al., 2010). Work presented in all these recent papers has been discussed throughout this thesis. Nevertheless, on the basis of the present research and findings reported elsewhere, I feel it is important to discuss and define future lines of research to address areas that have received insufficient or no coverage.

One such area I outlined in paper 1 is the lack of a single work load index to combine and quantify macroscopic motion analysis data (e.g., distance covered in and/or time spent in different movement intensities) with microscopic information containing discrete but physically taxing game actions. These activities include the numerous accelerations, decelerations, changes in direction, contacts, collisions, tackles and jumping and landing actions regularly performed in match-play. A recent preliminary investigation has notably demonstrated high metabolic loads imposed on professional soccer players during acceleration phases in competition (Osgnach et al., 2010). Related work I have recently co-authored presented data showing increased physiological strain (greater heart rate values and blood lactate concentrations) in elite soccer players during running bouts including directional changes and acceleration and decelerations phases compared to straight-line running (Dellal et al., 2010). Similarly, more detailed analyses of the specific characteristics of acceleration and sprinting phases and the speed at which players commence these intense activities would also be useful to determine specific demands in relation to playing position and eventually inform physical conditioning regimens to develop individual agility, strength and power. Preliminary unpublished data I have collected in my club have identified substantial variations in acceleration patterns (notably starting speed of actions) across playing positions. Similar research conducted in elite rugby union players (Duthie, Pyne, Marsh, & Hooper, 2006) has shown that sprinting efforts should be performed from a variety of starting speeds to mimic the movement patterns of actual competition and has had important implications for enabling position-specific fitness training in the sport.

In contrast, there are problems related to any holistic approach of reporting motion analysis data as this generally ignores the interaction between and within movements and playing activities. An alternative means for detailing physical activity and eventually identifying complex movement patterns that are hard to identify or even hidden from observation within player movements is the use of temporal pattern (t-pattern) detection. I briefly discussed this technique in paper 1. In theory, specific movement patterns such as frequent and rapid changes in pace and direction both on and off the ball could be reproduced to enhance physical conditioning practices. Up to now, this form of analysis has mainly been used for tactical analyses (Borrie, Jonsson, & Magnusson, 2002; Camerino, Chaverri, Teresa Anguera, & Jonsson, 2011) and physical activity has received limited attention (Bloomfield, Jonsson, Polman, Houlahan, & O'Donoghue, 2005). This is mainly due to the amount of work required to analyse and detail complex running patterns for every player over the entire course of games. One solution to this problem could be the use of artificial neural networks that can learn to recognise, classify and transform t-pattern movement data automatically into informative patterns to aid in understanding complex behavioural phenomena observed in soccer competition (Perl, 2004). To date, however, applied practitioners find it difficult to appreciate the value mainly in terms of the practicality and application of these and related methods for utilisation in their daily work (Carling et al., 2009).

Earlier on in this discussion, I identified the lack of controlled intervention studies evaluating the effects of physical conditioning programmes on actual performance in match-play. Yet before such a study can be undertaken, it is important to mention that no research in professional soccer has investigated the degree to which competitive physical demands are adequately replicated in training. Interestingly, related research in elite female soccer (Gabbet & Mulvey, 2008) and male field-hockey (Gabbet, 2010) players has shown this not to be the case. Hence I am commencing a project to compare data obtained in match-play and training in our players using computerised video tracking and global positioning technology.

The potential implementation of individualised speed thresholds tailored according to individual scores of fitness is also currently under scrutiny in my club in an attempt to enable a more precise interpretation of the physical efforts of individual players in training and match-play. Indeed, recent research by Abt and Lovell (2009) using running performance at the second ventilatory threshold has demonstrated that the speed at which professional soccer players run at high-intensity can greatly vary. Thus the distances covered at high-intensities calculated using a non-personalised default speed threshold can be substantially underestimated. Similarly, previous researchers (Mohr et al., 2003; Rampinini et al., 2007b) have reported the between-match variability for ‘high-speed’ activity as a composite value of different types of running activity (e.g. sprinting and high-intensity running combined) rather than a discrete coefficient of variation for each specific type of activity. Throughout this programme of research both categories of movement was generally combined (except in papers 6 and 7 on reviewer demand). Identifying the variability associated with discrete components of high-speed activity is nevertheless important as this information might not only provide a clearer indication of the specific fitness requirements of player’s within games but also enable researchers to identify which variables may most consistently reflect the intense efforts that are made within a game (Gregson et al., 2010). However, the sprinting distances in many team sports are often too short to allow for maximum speeds to be reached (Doğramac, Watsford, & Murphy, 2011) and while some players may be performing at maximal exertion (e.g., maximal but very short effort), the running speeds attained may not be sufficient for actions to be classified in the more intense categories of movement leading to the omission of some ‘high-intensity’ data. Using a percentage of each individual player’s maximal sprint performance obtained over a 40m dash (e.g., running speed at 10m, 20m and 40m) might be an alternative means for determining in match-play whether the player has attained the high-speed categories of movement.

As mentioned above, interpretation of motion analysis data from analyses of match-play in my club is now attempting to take into account individual scores from maximal (VO_{2max}) and submaximal (lactate threshold) treadmill testing of aerobic capacity as well as information from the treadmill test of repeated sprint ability presented in paper 3. However, translating laboratory determined physiological thresholds from continuous incremental running tests into a match scenario might not always be feasible due to the random, non-linear nature of soccer play. The major concern is the degree to which principles of steady-state are applicable to dynamically changing exercise intensities (Drust et al., 2007) thus reflection is ongoing. In addition, the results presented in Paper 3 show that repeated sprint ability is not related to the ability of our players to repeatedly perform high-intensity movement in competition. Interestingly, I recently presented new data on the association between both aerobic fitness and repeated sprint ability and match fatigue in players in my club at the Third World Congress on Science and Soccer held in Ghent, Belgium (14-16th May, 2012; Carling, Le Gall & Dupont, 2012). Results showed that measures of aerobic fitness and repeated sprint ability were either unrelated or inversely associated to measures of accumulated (drop in distance covered between halves and towards the end of games) and transient (drop in distance run after most intense period of exercise) match fatigue. Thus, these results cast doubt on the utility of repeated sprint tests in predicting players' capacity to repeatedly perform high-intensity exercise as well as resisting fatigue during match-play. On the basis of this research, physical conditioning and sports science staff in my club are currently reflecting on the inclusion of intermittent-type running performance protocols thus breaking with our traditional fitness testing practices.

Finally, there is speculation on the impact of high-intensity activities in relation to their contribution in deciding the outcome of games (Di Salvo et al., 2009). A recent descriptive study has shown that out of 360 goals scored in the German Bundesliga, the majority was preceded by a sprint action performed by the player who either scored the goal or provided the assist (Faude, Koch & Meyer, 2012). Yet, no study has attempted to quantify the real significance of repeated high-intensity movements and their meaningful role in preventing in scoring or preventing goals and goal scoring occasions. Findings reported in paper 3 tend to argue against the importance of their contribution to overall success in a high-ranked professional soccer team.

After completion of the present set of research papers, I feel that additional work is required using a large-scale multi-centre approach in an attempt to determine the real significance of physical performance in contemporary professional soccer especially in relation to tactical, technical and socio-psychological aspects of play as well as player health and injury. A valid question might concern whether there is a real necessity for additional and position-specific fitness conditioning programmes to attain standards beyond the physical requirements identified in both the present body of research and in the scientific literature generally. Indeed, should coaches and fitness personnel aim to achieve an ‘adequate’ level of fitness in their players and place more emphasis on perfecting tactical and technical skills and implementing systematic evidence-based post-match recovery and injury prevention routines?

To sum up, I hope that this work will encourage similar applied motion analyses research programmes in other professional soccer club and/or elite institutional settings. The aim would be for other researchers to collaborate in order to build on the present study designs or develop and validate their own to counter some of the limitations and their potential influence recognised over the course of the present research. There is still much potential for researchers and coaching practitioners to extend the body of knowledge presented in this thesis by exploring some of the remaining gaps I have identified above and apply their findings to optimise practice and preparation and ultimately, improve elite match-play performance and results.

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Appendix 1: The role of motion analysis in elite soccer: techniques, considerations and practical applications

Appendix 1a: Copy of Paper 1, Carling, C., Bloomfield, J., Nelsen, L., & Reilly, T. (2008). The role of motion analysis in elite soccer: Contemporary performance measurement techniques and work-rate data. *Sports Medicine, 38,* 839-862.

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The Role of Motion Analysis in Elite Soccer

Contemporary Performance Measurement Techniques and Work Rate Data

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Contents

Abstract

The optimal physical preparation of elite soccer (association football) players has become an indispensable part of the professional game, especially due to the increased physical demands of match-play. The monitoring of players' work rate profiles during competition is now feasible through computer-aided motion analysis. Traditional methods of motion analysis were extremely labour intensive and were largely restricted to university-based research projects. Recent technological developments have meant that sophisticated systems, capable of quickly recording and processing the data of all players' physical contributions throughout an entire match, are now being used in elite club environments. In recognition of the important role that motion analysis now plays as a tool for measuring the physical performance of soccer players, this review critically appraises various motion analysis methods currently employed in elite soccer and explores research conducted using these methods. This review therefore aims to increase the awareness of both practitioners and researchers of the various motion analysis systems available, and identify practical implications of the established body of knowledge, while highlighting areas that require further exploration.

A significant body of research into the host of factors contributing to optimal performance in sport has emerged over the past two decades.[1] This increased research activity has been particularly evident in soccer (association football), where the importance of scientific research and applied work has become increasingly accepted in the professional game.[2] Over this period, comprehensive reviews have been published on the physiology,[3,4] psychology,[1,5] biomechanics[6] and interdisciplinary[7] aspects of soccer. This growing acceptance of sports science is unsurprising considering the performance-enhancing role that it can offer elite soccer coaches continually searching for a competitive edge against rival teams.[8]

Among the traditional sport science disciplines, exercise physiology has arguably had the greatest impact upon practices within professional soccer. The optimization of physical fitness is now an integral facet of player and team preparation. The physiological demands of contemporary professional soccer implicate an increased work rate, a higher frequency of competition, and as a consequence, players are obliged to work harder than in previous decades.[9,10] The monitoring of players' work rate profiles during competition was originally achieved using manual video-based motion analysis techniques such as that developed by Reilly and Thomas.[11] The employment of such methods elicited essential scientific observations, but the perceived complexity and consumption of time required for coding, analysing and interpreting the output formed barriers to their adoption by performance analysts.[12] The original techniques were also restricted to the analysis of a single player, so therefore limited to university-based research projects.

Over the past decade, technological advances have included the introduction of increasingly sophisticated motion analysis systems that are now being used in elite soccer. These systems enable the simultaneous analysis of all players to be completed in a relatively short period, and provide a valuable pool of data that can inform and influence the daily practices of coaches. The use of these advanced approaches furthers our understanding of position-specific work rate profiles of soccer players and their fitness requirements, the intensities of discrete activities during match-play and the occurrence of a reduced work rate among players.[13,14] Moreover, these contemporary methods employed by elite clubs can be used to make objective decisions for structuring the conditioning elements of training and subsequent match preparation.

In recognition of the important role that motion analysis now plays as a tool for measuring the physical performance of soccer players, we begin by critically appraising the various methods of motion analysis available to researchers and practitioners in soccer. Throughout, we highlight that many of the latest computerized systems are not only logistically practical, but also offer a greater breadth of analysis compared with the more traditional labour-intensive methods. However, many of these systems still require scientific validation to ensure that data derived from these methods are both accurate and reliable. A presentation and critical appraisal of various validation protocols used for assessing contemporary motion analysis technologies is provided in an attempt to prompt further research into this area of investigation. Also considered are various issues concerning the interpretation of the data obtained through techniques of motion analysis. In the remainder of this review, motion analysis research into work rate profiles within competitive games, exercise patterns, positional demands, fatigue and other uses, is considered. Collectively, this review should serve to increase awareness of practitioners and researchers concerning the various motion analysis systems and the body of accumulated knowledge acquired using these approaches, whilst identifying areas that require further exploration.

1. Contemporary Techniques for Work Rate Analysis

1.1 Individual Player Analysis

Motion analysis has been applied for over 30 years to the study of work rates in professional soccer, since the classical study of Reilly and Thomas.[11] Research studies undertaken in the last 5 years by Scandinavian and Italian researchers[15-19] on top-level soccer have incorporated similar approaches to that employed over a decade earlier by Bangsbo and co-workers.[20] This original method involved the positioning of video cameras near the side of the pitch, at the level of the midfield line, at a height of approximately 15 m and at a distance of 30–40 m from the touchline. Each camera was used to film a separate player. After the game, the subjects were videotaped for reference purposes whilst performing specific activities (from walking to sprinting) in order to provide calibration values. The video tapes were played back on a television monitor and coded for various match activities. The duration of each activity was recorded, total time summed and frequency of activity calculated according to separate time blocks. The distance covered at each activity within each time block was the product of mean velocity and total time spent in the activity. The total distance covered during a match was calculated as the sum of the distances covered during each individual type of locomotor activity.

The main technological advancement evident in subsequent studies has been the employment of better quality cameras and more advanced input coding methods as a result of contemporary computer software. To this end, Bloomfield et al.[21] used the 'PlayerCam' facility (Sky Sports Interactive Service, British Sky Broadcasting Group, UK) to provide high-quality close-up video footage focusing on a single player's movements and actions. The footage was digitized and synchronized for manual coding using the Noldus Observer 5.0 Video-Pro behavioural analysis system,[22] which in turn automatically calculated the time spent in the defined movement activities.

These particular video-based methods used for manually measuring work rates have generally demonstrated, in the studies that have been reported to use them, high levels of reliability, objectivity and validity.[8] For example, a previous report that employed these methods stated that no systematic differences were reported in a test-retest analysis of a match, and the mean intraindividual difference in total distance covered was less than 0.2 km (coefficient of variation [CV] = 1%).[15] Nevertheless, human error through inaccurate data entry is possible due to the subjective nature of human movement recognition, variable observer reaction to events being performed by the player under scrutiny, and different interpretations of performance indicators relating to work rate and movement by different observers.[23] In addition, the methods previously described are restricted to the filming and analysis of a single player per camera. Video-based motion analysis may also be subject to errors due to changes in gait during game movements,[24] and provides only low spatial and temporal resolutions.[25] Furthermore, these techniques do not allow real-time analysis and are extremely labour-intensive in terms of the capture and analysis of data. In this respect, the detailed manual methodology used by Bloomfield et al.[26] to code manually and determine the physical demands of English Premier League football was described by the authors as extremely time-consuming and laborious. This criticism applied even for the collection of data from only 5 minutes of match footage because of the frequent changes of movement type, direction and/or intensity. A total of 1563 'purposeful movement' passages were observed for 55 players during 15-minute periods of Premier League soccer, which involved 23 487 changes in movement, direction, perceived intensity or individual soccer-specific events (e.g. pass, dribble, shoot). Players performed a mean of 28.4 ± 4.3 passages of purposeful movement for each 15-minute period of the match at a mean duration of 13.1 ± 3.2 seconds. These figures equate to a mean of 15.03 changes in activity for each passage at a rate of 0.87 per second. No significant differences were found between the amount of purposeful movement passages by match period or playing position, although strikers had a significantly shorter mean duration and frequency of passages lasting >15 seconds. Because of the level of detail in this manual-based time-motion analysis, the application and use of such methods of motion analysis are generally restricted to academic research projects because the intense competitive schedules of elite soccer clubs require data to be available usually within 24–36 hours post-match. The difficulties encountered in manually coding movements may lead some researchers to analyse a single selected period of action per player per game. Attempts can then be made to extrapolate the data from these periods to a projection for the entire match. However, incomplete recordings are limited in their ability to provide detailed individual work rates, as the work rate pattern is highly variable throughout a game and is therefore not so easily predictable.[27]

As technology has advanced, time-motion analysis has begun to incorporate electronic devices, mathematical modelling procedures for automatic tracking, sophisticated computer processes and satellite tracking. An overview of contemporary systems used to analyse workload in soccer is given in table I.

Many contemporary approaches are based essentially on an original method designed by Ohashi et al.,[40] which employed the calculation of players' position and speed through trigonometric techniques. For example, the motion characteristics of elite Japanese soccer players have been recently measured throughout a game's entirety using a triangular surveying method.[33] This method entailed recording the player's movement as angular changes, which were measured by two potentiometers linked to cameras mounted outside and overlooking the field of play. Coordinates for the player were calculated using the angular data from the cameras and were monitored every 0.5 seconds. The distance between two consecutive coordinates was calculated continuously to obtain the total distance covered. The major limitation of this particular methodology was that it did not allow simultaneous analyses of more than one player.[8] Limiting the analysis of the activity profile to one player per game does not allow comparisons to be drawn between the concomitant work rate profiles of team mates or those of opposing players, and can limit full understanding of the tactical importance of work rate.[27]

A further technological advancement in this field has been the development of the system 'Trakperformance' (Sportstec, Warriewood, NSW, Australia), which provides a means of mechanically following a single player using a conventional computer pen and commercially available drawing tablet on a scaled version of the specific playing field.[24,38] This method is an improvement from the classical cartographic approach previously used by Japanese researchers where movements of soccer players were traced onto a scaled map of the pitch presented on paper sheets.[41] The Trakperformance system functions by using ground markings around the pitch, which are employed as reference points for tracking the players. The

Table I. Contemporary systems and studies of their workings used to analyse work rate in contemporary elite soccer

Company/institution (country)	System	System type	Website	References
Citech Holdings Pty Ltd (Australia)	Biotrainer®	Electronic transmitter	http://www.citechholdings.com	28
Chukyo University (Japan)	Direct Linear Transformation	Automatic video tracking		29
INMOTIO Object Tracking BV (Netherlands)	LPM Soccer 3D®	Electronic transmitter	http://www.abatec-ag.com	30
Feedback Sport (New Zealand)	Feedback Football®	Automatic video tracking	http://www.feedbacksport.com	31
GPSports (Australia)	SPI Elite®	GPS tracking	http://www.gpsports.com	24
Hiroshima College of Sciences (Japan)	Direct Linear Transformation	Automatic video tracking		32
National Defense Academy (Japan)	Triangular surveying	Triangular surveying		33
Noldus (Netherlands)	Observer Pro®	Manual video coding	http://www.noldus.com	21,23,26
Performance Group International (UK)	DatatraX®	Automatic video tracking	http://www.datatrax.tv	34
ProZone Holdings Ltd (UK)	ProZone®	Automatic video tracking	http://www.pzfootball.co.uk	35
RealTrackFootball (Spain)	Real Track Football®	GPS tracking	http://www.realtrackfutbol.com	36
Sport-Universal Process SA (France)	AMISCO Pro®	Automatic video tracking	http://www.sport-universal.com	37
Sportstec (Australia)	TrakPerformance®	Computer pen and tablet	http://www.sportstecinternational.com	24,38
TRACAB (Sweden)	Tracab®	Automatic video tracking	http://www.tracab.com	39
University of Campinus (Brazil)	Dvideo	Automatic video tracking		25

miniaturized playing field is calibrated so that a given movement of the mouse or mouse-pen corresponds to the linear distance travelled by the player. This computerized system has demonstrated acceptable levels of accuracy and intra- and inter-observer reliability. For example, an error measurement level of 5% for player distances has been presented and a test of inter-observer reliability between three separate observers reported a Pearson's correlation of r = 0.98 for total distance travelled.[38] A further advantage is that movements can also be tracked in real-time (although operator skill does need to be very high and a sustained training period is needed for familiarization with the technique) and cost is significantly reduced compared with other commercially available tracking systems. Finally, the portability of this system means it can be readily employed to analyse work rates of players within training contexts.

1.2 Multiple Player Analysis

Few systems have the ability to analyse all the players in a team throughout a whole match, tracking each player both on and off the ball.[42] The AMISCO Pro® system developed in the late 1990s by Sport-Universal Process in collaboration with the French Football Federation was the first system to achieve the simultaneous analysis of the work rate of every player in a team throughout the entirety of a match.[37] This system measures on video the movements of every player, the referee and the ball by sampling activity up to 25 times per second during the whole game.[8,43] This process leads to the collection of around 4.5 million datapoints for position on the pitch as well as over 2000 ball touches per match. Along with the ProZone® system,[35,44] its chief commercial European competitor, these pioneer multi-player video tracking systems based on state-of-the-art computer and video technology are currently the most comprehensive and widely used commercial tracking systems in professional European soccer. These systems provide a detailed analysis of each player's work rates over the entire match, and create a 2-dimensional animated reconstruction of player movements together with an interactive graphical representation of all playing actions such as passes and duels.[45]

Video-based multi-player tracking systems such as AMISCO Pro® and ProZone® generally require the permanent installation of several cameras fixed in optimally calculated positions to cover the entire surface of play. This layout ensures that every player is captured on video, whatever the position and the moment in time. The number, position, orientation, zoom and field of vision of the cameras depend on factors such as the dimensions of the pitch and the structure of the stadium. The stadium and pitch are calibrated in terms of height, length and width and transformed into a 2-dimensional model to allow player positions (x, y coordinates) to be calculated from the camera sources. Complex trigonometry, propriety mathematical algorithms, image-object transformation methods for obtaining 2- or 3-dimensional space coordinates such as Direct Linear Transformation (DLT)[32] from video footage of soccer play, as well as various image processing and filtering techniques, can be used to identify each player's location on the pitch. The individual's movements can then be tracked on the video by computer software through either manual operation or automatic tracking processes, at every single moment of the game. The technology is facilitated by supportive information such as shirt colour, optical character recognition of shirt numbers and prediction of running patterns to help maintain accurate player identification and tracking. During set-play actions such as corners or free kicks, play can become compressed, so such supportive information may be required to help maintain accuracy in tracking individual players. For a further description of the workings of video-based player tracking, see Di Salvo et al.[35] and Barros et al.[25]

Despite being largely computer automated, these pioneer tracking systems still require some manual input as well as continual verification by an operator to make sure that players are correctly tracked by the computer program. Automatic tracking may not always be possible because of changes in light quality as well as occlusions due to a crowd of players gathering in a small zone at one time. In this case, it becomes necessary for an operator to correct these mistakes manually. Nevertheless, the Dvideo® system designed at the University of Campinus, Brazil, is reported to have a 95% automatic tracking rate.[25] However, this system uses a lower number of digital film images per second (7.5 Hz) than other video tracking systems such as AMISCO Pro® in order to reduce the amount of data to be processed. This footage would lower its capacity to measure in detail changes in running speed and direction. Work by Fernandes and Caixinha[46] has also shown when determining the positions of soccer player from digital video footage that a low frequency of images per second (2 Hz, for example) may lead to a higher rate of error when calculating distances covered.[46] A recent DLT-based video-tracking system used to analyse the work rates of professional Japanese players reportedly requires the use of a single digital camcorder, making it more cost effective compared with multi-camera systems.[29] However, it also employs a limited number of image frames per second (2 Hz) and requires manual frame-by-frame analysis of play. Furthermore, no information is available on the time required to analyse physical performance using this system and its reliability has not been investigated. Most of these video tracking systems used to date in elite soccer do not provide real-time analysis, the results generally being available within 24–36 hours of the final whistle. This time lag, however, seems acceptable for the many top-level clubs who have adopted these systems over the last decade.

The most recent commercial video-based automatic tracking systems such as DatatraX®[34] and the TRACAB® image tracking system[39] now provide real-time analysis, albeit using similar tracking methodologies based on multi-camera and image processing techniques. According to commercial information available from the supplier,[39] the TRACAB® system exploits enhanced techniques for video image processing and by using mathematical algorithms originally designed for object tracking and guiding missiles in the military industry. Similarly, DatatraX® uses pixel recognition to track the players automatically and voice recognition to code the match-specific events. Three manual operators are required to manage the process, two people to correct tracking mistakes in real-time for each team and one to perform the voice recognition coding procedure. The main benefit of both systems is that they provide coaches with a high level of instantly available detail concerning match performance, allowing informed decisions to be made during the match that may influence the eventual outcome. Although both companies claim to have high levels of accuracy for their systems, the validity and reliability have again yet to be scientifically established.

A major advantage of both the manual and automatic video-based tracking systems is that they do not require players to carry any electronic transmitting device. Carrying such material is strictly forbidden by various governing bodies of soccer. Their major disadvantage, however, resides in the high costs and the necessity of installing multiple cameras and a computerized network with at least one dedicated operator to organize the data collection and further operators to perform the analysis.[35] This apparent lack of portability means that teams can only employ these systems for matches in their home stadium. However, the DatatraX® and Feedbacksport®[31] systems can apparently still be operated at away venues using two portable cameras from the stadium gantry and some mathematical corrections for errors created when players are further away from the camera lens. In addition, the introduction of reciprocal contractual agreements has led to clubs being able to access work rate data when playing in opposition stadiums that are equipped with the same service provider's system.

Electronic transmitting devices have previously been described as the future of the computerized analysis of sport and are taking match analysis one step further in terms of data processing speed and accuracy.[8] These wireless and telemetric communication systems allow remote real-time data acquisition, and record movements and positions of every player and the ball up to several hundreds times per second. A small lightweight microchip transmitter is worn in clothing or in a strap around the chest of each player. The identification signal of the transmitter is registered in a fraction of a second by several antennae positioned around and outside the playing field. The reception time of the signal source to the recipient is synchronized and as a result the position is determined. These data are relayed to a central computer and immediately processed for immediate analysis. The LPM Soccer 3D® system developed by INMOTIO in collaboration with PSV Eindhoven Football Club provides positional measurements at over a 100 times per second, leading to the production of highly detailed and previously unavailable information on player accelerations, decelerations and changes in direction.[30] This system also combines physical data with physiological measurements through heart rate monitoring (built into the transmitter) as well as synchronized video footage to provide a comprehensive picture of the daily, weekly and monthly workloads experienced in training. Constraints of such systems include potential electronic interference, strength of the electronic signals from players due to the size of playing surfaces and the energy source required to accomplish this signal transfer.[24] Furthermore, no investigation has yet attempted to determine scientifically the reliability of these electronic measuring systems.

Global positioning system (GPS) technology has also begun to impact on the analysis of performance in elite soccer. As with electronic transmitting devices, its use is restricted to measuring player efforts during training sessions or friendly matches, although it is now permitted in competition for other codes of professional football such as Australian Rules Football. The GPS technology requires a receiver to be worn by each athlete, which draws on signals sent from at least four Earth-orbiting satellites to determine positional information and calculate movement speeds, distances and pathways as well as altitude.[47] The latest SPI Elite® GPS receiver designed by GPSports has been adopted by several teams competing in the English Premier Football League and comes with propriety software for simultaneous analysis of data from all players.[48] Similarly, a company in Spain known as RealTrack Football has also made commercial GPS specifically available for soccer teams.[36] It is possible to purchase kits with over 11 trackers in a set, with potential applications to training contexts and to the other football codes.

Although automatic tracking devices have established methods of providing data on work rate characteristics such as total distance run and time spent in various categories of movement, the latest systems are advancing the analysis of sports performance through a superior level of coordinated biofeedback to accompany the traditional physical feedback. In this respect, the SPI Elite® GPS is capable of monitoring heart rate and recording information on the frequency and intensity of impacts such as tackles and collisions by means of a built-in tri-axis accelerometer which also depicts three direction types (forwards, sideways and backwards). The accuracy and reliability of GPS receivers is relatively high: results of a test of accuracy showed a 4.8% error rate in measuring total distance covered and a test of intra-tester reliability reported a technical error of measurement (TEM) of 5.5%.[24] These TEM values can therefore be taken into consideration when interpreting the raw data. Recent technological developments have also led to increased miniaturization and portability.[49] An alternative device known as the Biotrainer® is also being produced by Citech Holdings Pty Ltd.[28] This system is described as a disposable patch, similar to a band-aid, worn by the athlete, which provides GPS tracking data both indoors and outdoors, as well as reportedly supplying real-time biofeedback on nine physiological outputs such as heart rate, body temperature and hydration level. Nevertheless, GPS receivers are still subject to problems of accuracy; the magnitude of error depends on land configuration and the number of available satellite connections. Furthermore, data in previous systems were usually collected at one measurement per second, which was insufficient in frequency for measuring detailed variations in speed and direction. However, the latest GPS receivers[48] are now reportedly capable of logging data at frequencies of 50 measurements per second. Although this development has potential to provide much more precise data and could be very useful in speed and agility assessments, the volume is therefore 50 times larger and creates potential problems in unit size, storage capacity and battery life. This new facility may also require extra manual work in data interpretation, which could ultimately delay any feedback. It therefore becomes the challenge for developers and researchers to investigate the optimal measurement frequency to provide appropriate data. Although the price of individual GPS units means they are now more within the reach of the non-elite player, purchasing enough receivers to cover the needs of every member of a squad of players may still be beyond all but the wealthiest of clubs.

2. Main Issues in Contemporary Motion Analysis Technologies

2.1 Validity, Objectivity and Reliability

The methodologies employed to collect motion analysis data must meet the requirements for scientific criteria for quality control.[8] These specifications include reliability, objectivity and validity. There is a need for a detailed analysis of the errors associated with the analytical procedures used by the systems.[27] To date, many of the contemporary commercial motion analysis systems discussed in section 1 have not undergone satisfactory quality control checks. Other than manufacturers' statements, very little scientific evidence exists to verify validity claims.[24] The lack of a single validation test protocol considered the 'gold standard' for testing the validity, reliability and objectivity of motion analysis data collection methodologies may be one reason for this low number of validation studies. Any validation protocol itself must also have undergone quality control testing and be easily transferable across the range of systems currently used in elite soccer. However, there are various issues that can play a part in preventing researchers from designing and undertaking validation projects. For example, researchers may face logistical problems such as gaining access to test systems using the playing facilities within soccer stadiums. The current laws of the game also prohibit players from wearing electronic equipment for testing the reliability of movement measurements within competition conditions.

If human input for data collection is still required when using a contemporary system, inter- and intra-observer reliability testing of the same competitive match(es) must be undertaken to assess measurement error. When automatic data collection processes such as tracking movement on video or via a GPS are employed, it is important to test the intra-reliability of the system itself by analysing the same match several times. It is also necessary to check the reliability of data by examining within-subject (player) error across a number of games, which has rarely been achieved in the literature.[27] Similarly, to ensure full validation of a system, comparison of the measurements obtained using contemporary analysis software and equipment should be made with those obtained from already established methods. There are also statistical considerations to be taken into account when examining the reliability of a system. The statistical procedures used to compare reliability measurements and the amount of disagreement between measurements deemed to be acceptable must be suitably defined at the outset of the study. In addition, the statistical test selected should aim to show agreement between observer measurements rather than differences. For more detailed information on reliability checks in match analysis, see the review by Drust et al.[27]

A validation procedure of a commercial match analysis system was designed by Di Salvo et al.[35] to compare data on running speeds of soccer players obtained via video-based tracking against those obtained from timing gate measurements. The subjects were asked to perform a series of short runs at different determined speeds over several marked courses. Correlation coefficients and absolute reliability coefficients between velocity measurements over runs of 50 and 60 m obtained from both systems were high ($r = 0.999$; total error 0.05, limits of agreement 0.12), indicating that the system can be confidently used to provide an accurate recording of running speed during soccer play. However, as this type of semi-automatic tracking system requires manual input, it would have been beneficial to have compared the reliability of data obtained from the runs by distinguishing between human and automatic tracking of the subjects' movement. Similarly, an intra- and inter-observer reliability study comparing the data from the whole duration of several matches played under real competitive conditions is necessary to gain an idea of the overall reliability of the system output. Validation protocols of video-based tracking systems that use marked courses or zones to evaluate running speed and distance should ensure the inclusion of all the different types of running actions previously identified by means of motion analyses. For example, as well as running in a straight line, moving in backwards and sideways directions, turning, shuffling and jumping actions, and dribbling should be carried out by test subjects. Similarly, adding and removing players to the area analysed is advisable to ensure analysis conditions are close to those observed in real competition. Validation procedures should also be carried out under different climatic conditions (such as variations in light), since environmental variables can affect the quality of the video recordings used for computer tracking.[8]

It is important to assess the reliability of data for each individual class of movement intensity. In a previous study, data obtained from manual coding using a computer interface of the time spent in high-intensity running by English Premier League players (during the same match) were compared between two different observers.[50] There was a relatively low level of inter-observer reliability between measurements and a significant systematic bias between observers for the percentage of time spent performing high-intensity activity ($p < 0.01$), with one observer recording much higher values than the other. The validation of a motion analysis system employing photogrammetric techniques to obtain the x and y positional coordinates from digital video images of soccer games has recently been achieved.[51] The test subjects were instructed to run at paced speeds following pre-established trajectories over predefined distances, and the measurements were subsequently compared with the distances obtained by means of the photogrammetric method. Results showed an error in distance measurement of <1.5% for each of the movement categories. In the same study, the accuracy of the system to determine general position and distance of targets was also determined. For this process, 40 markers were randomly distributed over a football pitch and the pitch was filmed from the main stand. The position of these markers was determined using a pre-calibrated 50 m measuring tape and later obtained through digitization of the frames. A low root mean square error for reconstruction of the coordinates in the x- and y-axis was obtained (0.23 and 0.17 m, respectively). Similarly, the authors reported an error of <2% for reconstructing the distance between two individual coordinates. Whilst the accuracy of this system in determining distances covered by players over set running courses seems sufficient, it would also have been pertinent to compare results from whole competitive games against hand-based motion analysis methods,[11,20] which have previously demonstrated high levels of reliability and validity (coefficients >0.9). This validation requirement should apply even if the measurement error in novel experimental technology may be less than that for a reference method such as that used by Reilly and Thomas.[11]

In a recent comparison of GPS and manual computer-based tracking systems for measuring player movement distance during Australian Rules Football games,[24] a number of ways were used to determine the validity and reliability of these methods for measuring distance covered. Validity checks for both systems were undertaken by comparing the data obtained by each system for distance covered by players running over a predetermined marked circuit against the distance calculated by a calibrated trundle-wheel pedometer. Intra-tester reliability of the distance calculated by both systems was also assessed over a range of running courses. Inter-tester reliability of distance covered from the tracking system was assessed by comparing data obtained both in competition and over a marked course. A comparison of the two tracking technologies for measuring movement distances was performed when data were collected simultaneously. Players wearing a GPS receiver ran around circuits of different lengths and geographic layout whilst two observers simultaneously tracked their movements. A calibrated trundle-wheel pedometer was then used to verify the actual track distance following the completion of the circuit. Both the GPS and the tracking system were found to overestimate the true distances (on average by <7%) travelled by players. The authors considered that these relatively small overestimations combined with an acceptable level of relative technical error of measurement both within and between trackers should not prevent the use of either of these technologies to monitor player movements. However, this particular manual tracking system relies on the subjective skills of observation and visual judgement on the part of the tracker. An omission was therefore the lack of testing of the reliability of data for the individual classes of movement and notably for movements at high intensities, which tend to be overestimated.[50]

2.2 Interpretation of Results

Ultimately, contemporary measurement systems are based on gathering data concerning the events in a match and the physical efforts of the players. In terms of the latter, the workload of the players is derived from data collected on speed, distance and time and compiled to form an assessment of physical exertion. However, the distance covered by players has been an area that has been adversely affected by methodological differences. This includes a lack of standardized approaches and a need for a more rigorous analysis of data. Furthermore, it is important to recognize that physiological evaluation is limited because the method makes the general assumption that energy is expended only when the player travels to a new location on the pitch, with sprinting usually classified as the most exertive motion. This is an important issue, which causes underestimation of the total energy expenditure of the players because several high-intensity movements are performed in soccer match-play without obvious changes of location on the pitch, for example a vertical jump, competing for possession or a high-speed shuffle. Furthermore, many contemporary systems assume players only travel in a forward direction and therefore do not provide detailed information on backward, sideways or other unorthodox movements that have been reported as more physiologically demanding than movements performed forwards at the same velocity.[8,9] To this end, other parameters such as agility (acceleration, deceleration, changing direction), physical contact, 'on-the-ball' activity and, critically, the sequence in which these activities happen, also contribute to physiological energy expenditure. Considering the dynamic nature of movements in soccer, this lack of information restricts a truly valid and thorough assessment of a player's expenditure in match-play. However, if the file containing the raw positional data can be accessed, as in the case of contemporary GPS receivers for team sports,[48] then algorithmic filtering may be employed to obtain these missing data.

Some major limitations exist with systems that centre on measuring distance covered through measurement of time spent in motion at different speeds. To this end, there is no agreement on what speed thresholds should be used in soccer; for example, thresholds for sprints have been reported set at speeds of >30 km/h,[15] >23 km/h[35] and >24 km/h.[52] These discrepancies in the definition of speed thresholds make it difficult to compare work rate data between different studies. However, the latest software used to analyse work rate data allows end-users to define their own speed thresholds, permitting a more objective means of analysing and comparing the physical efforts of players according to different intensities of movement.[43]

One of the main concerns with motion analysis data is the stringency of the speed thresholds used to categorize the motion types. Essentially, results are created by objective measurement systems by acknowledging the frequency of the occasions that a player enters a certain threshold and then the time that player spends within that threshold, and subsequently calculating distance covered. However, if a player were to perform a single effort at speeds on the boundary of a particular threshold, it is quite possible that the data would reveal that multiple efforts have been performed if the boundaries have been crossed. For example, if a threshold for 'sprinting speed' was set at efforts >24 km/h and a 1 Hz (second-by-second) raw output over 7 seconds reads 22-23-24-26-23-25-23, it is interpreted that this player sprinted on two occasions when realistically (subjectively), it could and perhaps should be only interpreted as once. Furthermore, it should also be noted that the interpretation here is that the player 'sprinted' for a certain duration, although this only accounts for the time spent at a speed >24 km/h. This result is easily misinterpreted, as it fails to account for the speeds ≤24 km/h that account for the acceleration phase of this 'sprint'. Instead, the interpretation should be that the player achieved speeds >24 km/h for a certain duration. This fact therefore applies to all motion category thresholds used to evaluate performance because it will also affect total frequencies and mean durations of each motion type. One way of combating this error is to filter or smooth the data using mathematical algorithms to make inferences on the data. For example, this may also be used to illustrate differences between rapid or gradual accelerations or decelerations by determining how quickly a player has moved through different threshold zones. However, this use of multiple equations within a data set requires further validation of the system.

Similarly, although differences have been identified in total distance covered in various levels of performance, with higher levels of performance corresponding with longer distances,[15] caution must also be taken when assessing a player's match performance based on the total distance covered. In this respect, players may be inefficient with their movement and in essence 'waste energy' by performing unnecessary movements, which may actually be detrimental to the team tactic, but result in a large distance covered, and may therefore be open to misinterpretation. Alternatively, a player may remain in low-intensity motion for a significant percentage of a match through being highly efficient in movement selection. This would produce a below-average total distance covered, number of sprints, workload and work rate, yet this player may have had the highest impact on the team's performance. In turn, an opposing player who is responsible for marking this type of player may also appear to have produced a lower workload than normal.

Finally, the overall reporting of results is usually provided macroscopically and in isolation. Traditionally, values for total overall distance, as well as total frequency and mean distance, time and/or percentage time spent in each motion type are reported.[9] This huge amount of data for each match can be a challenge in itself for professional soccer staff to make true assessments of match performance, monitor workloads and plan appropriate physical fitness regimes. In this respect, a recent programmed exercise protocol for netball based on mean 'bursts' of high-intensity activity and 'recoveries' of low to moderate intensity derived from time-motion analysis proved to be ineffective in enhancing match-play specific physical fitness.[53] To this end, a full range of 'bursts' and 'recoveries' are sought to design physical conditioning programmes that are specific to soccer match-play. Consequently, ratio scales should be used to present data based on levels of intensity.[54]

The holistic approach of reporting work rate data ignores the interaction between and within motions, movements and playing activities. Therefore, it is also important to perform temporal pattern (T-pattern) detection to identify patterns within the data. In this respect, the detection of patterns that are not identifiable through simple observation has great benefit not only in soccer match-play variables, but also in establishing the specific physical performance demands.[55] A T-pattern is essentially a combination of events where the events occur in the same order, with the consecutive time distances between consecutive pattern components remaining relatively invariant with respect to an expectation assuming, as a null hypothesis, that each component is independently and randomly distributed over time. The method of T-patterning has already been employed to establish playing patterns in soccer by identifying complex intra- and interindividual patterns for both individuals and teams using the detected behavioural patterns in combination with elementary statistics.[56] Figure 1 displays a player's movement pattern which identifies a varied range of motion. In this particular pattern, the player starts by shuffling backwards and then sprints forward. After this, he decelerates and finishes with a high-intensity shuffle, indicating that he slows down very rapidly. From this point, he skips sideways left at low intensity, turns left and jogs forward at low intensity, gradually increasing pace into a run and changing direction by moving diagonally left to complete the complex pattern. Preliminary investigation of pattern complexity between player positions suggests that a higher number of different patterns and pattern occurrences are detected for defenders than for forwards or midfielders.[55] The same also seems to apply for length of patterns. These findings, and their significance, need further examination, although they could be very useful for creating specific training programmes according to individual positional requirements.

3. Contemporary Motion Analysis Research

3.1 Analysis of Data on Overall Work Rate

There is a growing interest amongst practitioners within elite soccer in the work rate characteristics of soccer players using the data obtained from the various techniques and technologies described in the previous sections. Generally, the overall work rate in field sports can be expressed as distance covered in a game, given that this measure determines the energy expenditure irrespective of the speed of movement and the individual contribution towards the total team effort.[9] This activity can then be broken down into discrete actions for each player across the whole game for classification according to intensity, duration and frequency. Although caution should be taken when comparing the results of various studies because of the differing methodologies employed to obtain data, contemporary outfield male elite soccer players cover on average 9–12 km per match,[15,25,57,58] whilst some players may attain distances of around 14 km (see table II).[59] Observers of elite female soccer players have generally reported lower results than elite male players in terms of overall distance covered (8.7–12 km) but a similar level of physiological strain.[16,19,60-62]

From a coaching perspective, it may be of value to compare the overall distance run by individual

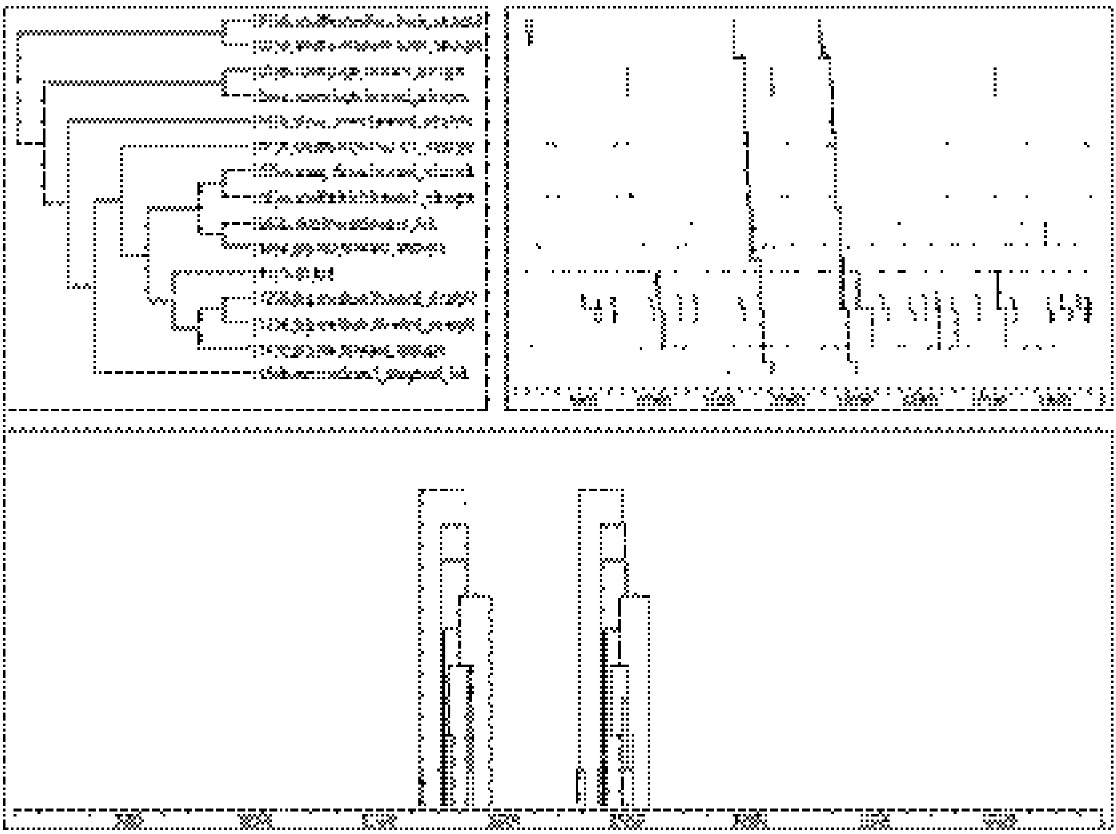

Fig. 1. An example of a temporal pattern (T-pattern) incorporating regularity of movements by a centre forward in a Premier League match (reproduced from Bloomfield et al.,[55] with permission from IOS Press).

players with that of team mates or opposition players to ascertain relative exertion rates. However, this distance may not be a fair reflection of a player's performance, as playing style, team formation, technical actions and tactical role also influence overall work rate. For example, Rienzi et al.[65] presented evidence that the distance covered by South American players was about 1 km less than the output of professionals in the English Premier League. The authors suggested that the higher sustained pace by players in the English game could explain this disparity. However, no motion analysis study has yet been conducted to compare the distances run by elite soccer players belonging to teams across a larger range of national championships.

Measuring the total distance run may also help in examining the evolution of work rates over several seasons to determine if the physical requirements of the game are the same and whether current training programmes and fitness tests are still optimal. Professionals in the English Premiership tend to cover greater distances during matches than those in the former First Division (pre-1992), which has had obvious consequences on contemporary fitness training programmes.[13] Data presenting the total distance run by 300 professional European midfield players have recently confirmed this upward trend.[43] Although contemporary elite players are running further than in previous years, the effects of playing position on distance run is consistent across the last three decades.[9]

A pertinent coaching issue may be to look at a division of the total distance run into data for defending (opposition in possession) and

Table II. Summary of motion analysis data from different systems of the total distances run and according to playing position by contemporary soccer players, 1999–2007

League/competition level (sex)	Number of players	Distance covered (m)					Reference
		total	fullback	central defender	midfielder	forward	
Manual video analysis							
International English (female)	30	11 979	12 636	11 099	12 971	11 804	63
Italian junior professionals (male)	29	9 890					17
English professionals (male)	24	11 264	11 433	10 650	12 075		13
Elite Danish (male)	24	10 330					15
Danish Premier League (male)	23	10 800					64
Swedish Premier League (male)	23	10 150					64
Italian professionals (male)	18	10 860	10 980[a]	9 740[a]	11 000[a]	10 480[a]	15
South American professionals (male)	17	8 638					65
Elite Danish (female)	14	10 300					16
English professionals (male)	12	10 274					58
Under 19 professionals (male)	12	9 741					58
International Swedish/Danish (female)	11	10 000					19
Elite Swedish/Danish (female)	11	9 700					19
English professionals (male)	6	10 104					65
Elite English (female)	5	12 400					61
Manual computer pen and tablet							
Professional Australians (male)	36	10 100	8 800[b]		10 100	9 900	38
Elite Norwegian juniors (male)	9	10 335					66
Automatic tracking on video							
Champions League matches (male)	791	11 010		10 020	11 570		67
Professional European leagues (male)	300	11 393	11 410	10 627	12 009[c]	11 254	43
Brazilian first division (male)	55	10 012	10 642	9 029	10 537[c]	9 612	25
European professionals (male)	18	10 864					44
Champions League matches (male)	18	10 461					68
Portuguese first division (male)	3	12 793	14 199[b]		12 958	11 224	46
French professional (male)	1	11 000			11 000		37
English professionals (male)	NP	10 659					69
Global positioning system							
International Australian (female)	6	9 140	9 010[b]		9 640	8 510	60
Triangulation/camera potentiometer							
Japanese professionals (male)	1	10 460					33

a Results for each playing position were calculated from a combination of data obtained for both groups of players.

b Results did not distinguish between fullbacks and central defenders.

c Combined results for central and external midfield players.

NP = not provided.

attacking (own team in possession) play. This comparison may help to determine whether players are working as much in a defensive role as they are in attack. At present, this factor has not been examined in the scientific literature. Results are likely to be affected by the tactical role of players, for example a ‘holding’ midfielder deployed on mainly defensive duties will no doubt cover less distance than other midfielders when his/her team is attacking. Another concern may be to identify whether physical demands are comparable between different levels within elite soccer, for example, between the various divisions in professional leagues. A comparison of professional Italian and elite Danish players showed that the former covered a significantly higher distance during games.[15] A motion analysis study of the total distance run by the same elite females competing at both national (for their clubs) and at international level (for their national team) established that these players ran significantly greater distances when competing at international level.[19] The observation highlights the need to take the level of competition, and perhaps the importance of the game, into consideration when interpreting data on motion analysis of match-play.

It is not feasible to use the total distance run to compare the overall physical contributions of players when there is a difference in the overall duration of games. For example, different categories of age in youth soccer generally play games of different durations, and other types of soccer such as futsal are limited to a total of 40 minutes play. An alternative means of comparing the overall physical contributions of players is to calculate a relative measurement of performance by correcting the absolute value (total distance covered) for the match to a minute-by-minute analysis of distance run. Recent studies have shown that the intensity of play in professional futsal[70] was higher than for elite players competing in the Australian National league.[38] The futsal players covered on average 117 m per minute compared with 111 m per minute for the Australian players, indicating that the intensity of the game of futsal may be higher than that for traditional soccer games, although analysis of data on players in professional European Laegues is needed to substantiate this claim.

3.2 Categories of Movements

In field sports such as soccer, movement activities are generally coded according to their intensity, which is determined by the speed of actions. When evaluating performance, the frequency of each type of movement and the time spent or distance run in each movement can be analysed. The main categories generally used to analyse soccer work rate are classed as standing, walking, jogging, cruising (striding) and sprinting. These categories have recently been extended to include other activities such as skipping and shuffling.[26] Most activities in soccer are carried out at a submaximal level of exertion, but there are many other game-related activities that must be taken into account such as alterations in pace, changes in direction, execution of specific game skills, and tracking opponents (which are examined later in this section). Elite players spend the majority of the total game time in the low-intensity motions of walking, jogging and standing.[13,15,43] In comparison, high-intensity efforts (cruising and sprinting) constitute around 10% of the total distance covered.[3,9] This finding compares with analysis of performance in professional futsal games where the percentage of the total distance covered spent in high intensity is almost one-quarter (22.6%) and can, on occasions, exceed one-third.[70] Research on female performance has shown that these players spend more time in lower intensity activities compared with males, which may be explained by biological differences such as endurance capacity.[71]

In soccer, activities at lower levels of intensity such as jogging and walking tend to dominate work rate profiles. However, the impact of high-intensity efforts in match-play cannot be over-emphasized, and it has been suggested that this feature may be the most appropriate means of evaluating and interpreting physical performance.[16,57] Measurement of high-intensity exercise, for example every 5 minutes during the course of the game, is an alternative way for coaches to evaluate overall work rate. High-intensity exercise is a constant feature across matches[9] and games are often won or lost on successful attempts at scoring carried out at high speed.[71] The high-intensity category of work rate includes the addition of cruising and sprinting actions, which are predetermined according to running speed. In elite soccer, players generally have to run at a high intensity every 60 seconds and sprint all-out once every 4 minutes.[13] However, Di Salvo and co-workers[43] presented evidence that the number of sprints made per player ranges greatly (3–40). These authors suggested that this finding strongly depended upon individual playing position.

Because of the intermittent nature of the game, performance can be enhanced through improving players' ability to perform high-intensity work repeatedly. The timing of anaerobic efforts, their quality (distance, duration) and the capacity to repeat these efforts, whether in possession of the ball or without, are crucial since the success of their deployment plays a critical role in the outcome of games.[8] Players in successful teams competing within the same elite league were reported to perform more high-speed running and sprinting in the most intense periods of the game and more sprinting over the whole 90 minutes than less successful teams.[64]

In elite soccer, the average distance and duration of sprints is short, as evidence has shown that these activities are rarely more than 20 m in length and tend to last around 4 seconds.[3,43,58] These findings imply that when a player is required to sprint, his or her acceleration capabilities may be of greater importance than their maximal running speed, as the tactical demands of the game probably render it unnecessary to attain maximal speeds. Improving performance in these actions will help players in many aspects of their game, such as being first to the ball or getting away from a marker. For example, if a player tends to lose out by poor acceleration or lack of speed over a short distance, the trainer could suggest an individual speed development programme. A more detailed motion analysis study on the characteristics of sprint patterns of players during competition could be beneficial. For example, no information is available on whether sprints commence from a variety of starting speeds such as a standing start or when jogging and, if so, does such differentiation also exist between playing positions. A recent study on elite rugby union players showed that forwards commenced these actions most frequently from a standing start (41%), whereas backs sprinted from standing (29%), walking (29%), jogging (29%) and occasionally striding (13%) starts.[72] Practitioners designing conditioning programmes would no doubt benefit from this information by ensuring that training sessions involve the actual movement patterns performed in matches. The programme can then provide sufficient overload through careful manipulations of the match demands in preparation for competition. This may involve alterations in playing time, size of pitch or number of players involved in order to increase the training intensity.

In soccer, only a small percentage of the total distance covered by players is with possession of the ball. Nevertheless, evidence from a field test of maximum oxygen consumption has shown that running with the ball significantly raises oxygen consumption and energy expenditure and should be taken into account when evaluating player efforts.[73] The vast majority of actions are 'off the ball', either in running to contest possession, supporting team-mates, tracking opposing players, executing decoy runs, making counter-runs by marking a player, or challenging an opponent. These actions often require frequent changes in movement activities, such as accelerations and decelerations, changes of direction, turns and unorthodox movement patterns (backwards and sideways runs), and contribute significantly to additional energy expenditure.[8] The latest GPS systems reportedly enable the quantification of the stress placed upon players from accelerations, decelerations, changes of direction and impacts, permitting the individualization and optimization of exercise and recovery programmes[48] – although this claim has yet to be scientifically validated. A challenge for future researchers is to investigate and combine data both on contacts, collisions and tackles and on motion analysis categories into a single index of training and competition loading.

Two studies have recently been undertaken to investigate deceleration[74] and turning[75] movements in professional soccer. Players were shown to perform an average of 54.1 deceleration movements and 558 turning movements during 'purposeful movement' passages from Premier League matches. The authors suggested that both these types of actions are a common and highly important part of the modern game, and there is a particular need for developing specific deceleration and turning exercises in strength and conditioning training sessions. An investigation into whether the inclusion of an enforced deceleration phase on repeated sprint efforts would cause greater fatigue and slower sprint times compared with efforts undertaken without this phase may be of interest in further understanding match performance and optimizing fitness training programmes.

The activity profile of players may be influenced by the style of play used by individual clubs and by regional differences. Such regional differences in performance are important because players moving between countries will probably need time to adapt both physically and tactically to the particular style of the different leagues. Nevertheless, there is still a lack of studies attempting to address either cultural or geographical differences in the work rate pattern,[27] especially at international level or between various professional leagues. Similarly, motion analysis research on the work rate performance characteristics of female and, in particular, younger players is still relatively limited in the literature. Results of a recent study on elite Brazilian youth players belonging to under 15, under 17 and under 20 age groups indicated significant differences in both overall workload and individual playing positions according to player age.[76] The age of players should therefore be a relevant factor when evaluating work rate profiles.

3.3 Determining Positional Demands

Understanding the workload imposed on top-level soccer players according to their positional role during competitive matches is necessary to develop a sport-specific training protocol.[43] Contemporary data[13,15,43] generally confirm the previously identified trend[11,20] that midfield players generally cover greater distances in a game than defenders or forwards. Goalkeepers usually cover much lower distances (around 4 km) per match. However, individual differences in the distance covered are not just related to a division into basic traditional team positions of defenders, midfielders and attackers. For each playing position, there may be a significant variation in the physical demands, depending on the tactical role and the physical capacity of the players. For example, Barros et al.[25] and Di Salvo et al.[43] showed that in professional Brazilian and European soccer, fullbacks ran significantly further than central defenders. Similar results between defensive positions have also been obtained for international female soccer players.[62] These results highlight that individual differences in playing style and physical performance should be taken into account when planning training and nutritional strategies.[77]

Again, marked differences in the intensity of various running activities exist across the various playing positions. A detailed analysis of English Premier League players showed that playing position (defender, midfielder and attacker) had a significant influence on the time spent sprinting, running, shuffling, skipping and standing still.[21] Rienzi et al.[65] observed that defenders perform more backward running than strikers. Similarly, it has been reported that Premier League midfielders and strikers engaged in significantly more of the ‘other’ type of movements (jumping, landing, diving, sliding, slowing down, falling and getting up) than the other positions.[21]

Analysis of work rate categories also suggests that training and fitness testing should be tailored specifically to positional groups (e.g. separation between central and external midfielders) rather than simply differentiating between forwards, midfielders and defenders because each positional group has its own unique physical demands. For example, a variation of 1.9 km in the distances covered at high intensities by midfield players in the same game has been observed.[15] Variations in work rate between players may imply that not all positions are taxed to full capacity in every game. Findings from a study comparing 123 professional European players showed that central defenders sprinted significantly less distance than fullbacks.[43] A large-scale study of professional Spanish soccer players reported a significant difference in the total distance sprinted by wide midfielders compared with central midfielders.[78] This research again demonstrates the need for a criterion model in order to tailor training programmes and strategies to suit the particular needs of individual playing positions. Research dividing the high-intensity efforts of players for defending and attacking play would be pertinent to determine whether positional role determines the physical contribution of players according to whether their team is in possession or not.

Motion analysis and its application to training must also take into account the relationship between the physical and technical demands of games. For example, match data on professional English players show that forwards tend to receive the ball more frequently when cruising and sprinting than defenders and midfielders, indicating that the ability required to implement technical skills at pace when attacking is important for this position.[79]

3.4 Use of Motion Analysis in Studies of Fatigue

In motion analyses of soccer, data may be split into distinct time-frames to help establish whether work rate varies with time or task. According to analyses and performance measures during elite match-play, fatigue manifested as a decreased performance seems to occur at three different stages in a game: (i) after short-term intense periods in both halves; (ii) in the initial phase of the second half; and (iii) towards the end of the game.[57] Simple comparisons of the overall work rate between first and second halves of matches can indicate the occurrence of fatigue, although it may be more closely identified if activities during the game are broken up into 5- or 15-minute segments.[8] Minute-by-minute analysis of work rate throughout a game has also been employed as a possible means of identifying a drop-off in physical performance.[25]

In soccer, the evidence of a difference in the total distance covered between halves is inconsistent and a significant decrement does not necessarily occur in all players, especially if players operate below their physical capacities in the first half. Therefore, a simple comparison of the overall distance run per half may not be a valid means to allow interpretation on whether or not a player has experienced fatigue. Nevertheless, table III presents data from various studies comparing the total distance run by elite soccer players for the two halves of the game. An average difference of −3.1% in the total distance run between halves (range −9.4% to +0.8%) can be observed across all studies on elite soccer. The largest difference between the total distance run in the first half compared with the second half was reported for players participating in the Australian National Football League.[38] Professional Brazilian players have also been reported to cover significantly more distance in the first half,[25] whereas more recent data showed no significant difference in work rates between halves for elite Spanish players and other European players participating in Spanish League and the Union of European Football Associations (UEFA) Champions League games.[43] In this latter study, the data may have been confounded, as no mention was made as to the inclusion of substitutes and the effect their work rates may have had on the results. Nevertheless, individual teams and players may pace their efforts in order to finish the game strongly. A comparison of total distance run between match halves of the winners (Barcelona) and losers (Arsenal) of the 2005–06 UEFA Champions League final showed that the Spanish players covered more distance in the second half than in the first half (5121 vs 5218 m).[68] In contrast, players belonging to the losing team who completed the whole match covered slightly less ground in the second half (5297 vs 5252 m) than in the first half, suggesting they may have been forced into a fatigued state. In this study, the data may have been confounded as Arsenal was forced to play with ten players for the majority of the game due to the dismissal of the goalkeeper.

Table III. Comparison of distances covered by elite soccer players during the first and second halves of competitive match-play

Study	Nationality	Distance run (m)			Difference (%)
		total	1st half	2nd half	
Barros et al.[25]	Brazilian	10 012	5173	4808	−7.1
Burgess et al.[38]	Australian	10 100	5300	4800	−9.4
Di Salvo et al.[43]	European	11 393	5709	5684	−0.4
Miyagi et al.[33]	Japanese	10 460	5315	5141	−3.3
Mohr et al.[15]	Italian	10 860	5510	5350	−2.9
	Danish	10 330	5200	5130	−1.3
Rienzi et al.[65]	South American/English	9 020	4605	4415	−4.1
Zubillaga et al.[68]	English	10 549	5297	5252	−0.9
	Spanish	10 339	5121	5218	+1.9

A 14% slower overall speed in the second half of the game when compared with the first half has been reported in elite Australian soccer players.[38] This result was attributed to fewer observations of the low-intensity movements (9.0% less walking and 12.4% less jogging) and more stationary periods. Engagement in game events such as kicking and passing was also 11.2% less frequent in the second versus the first half of games. Similarly, a recent study of work rates in professional Italian players examined the effects of fatigue on technical performance.[80] A significant decline between the first and second half was found for both physical performance and some technical scores (involvements with the ball, short passes and successful short passes). Minute-by-minute analysis of total distances covered by Brazilian players revealed significant differences after the fifth minute of the game, with highly significant differences after the eighth.[25] The authors suggested that this more detailed analysis may allow a better understanding of fatigue. However, these results should be treated with caution as it is highly unlikely that players experience fatigue so soon during a match. This reduction in performance is more likely to be linked to play settling down after the frantic first few minutes of the game where engagement is at its most intense. Indeed, a study by Rahnama et al.[67] yielded evidence that the majority of critical game incidents and the highest intensity of activities were observed in the first 15 minutes of the game.

A significant reduction in the distance run at medium[43] and high intensity[37,63] between halves has been reported in players competing in elite European soccer games and tournaments. In elite Scandinavian soccer players, the amount of high-intensity running was lower (35–45%) in the last 15 minutes than in the first 15 minutes of the game, with more than 40% of the players having their lowest amount of intense exercise in the last 15 minutes.[15] This trend was confirmed in a study of elite female players where a marked decrease in the amount of high-intensity running within each half was observed and 13 of 14 players did their least amount of high-intensity running in the last 15-minute period of the first or second half.[16] Similarly, GPS-based tracking of activity patterns in professional futsal players has shown that during the last period of the game, the number of bouts of high-intensity exercise significantly decreased.[81] However, the total distance covered or the amount of sprinting may be unaffected between playing halves in certain players,[25] and the distance covered in high-intensity activities may even increase between halves[82] and in the last few minutes of the game.[8] Players carrying out fewer actions at low or moderate intensity may be 'sparing' their efforts for the final few crucial actions as their energy levels become depleted. Some players demonstrating no decrease in performance between halves or in the final quarter of the match may have paced themselves in order to finish the game strongly. A pertinent study may be to examine whether the type of competitive match affects work rate and any subsequent reduction in performance. For example, it would be relevant to determine whether players tend to work harder or demonstrate greater fatigue during Cup games than during League games or when playing against teams from lower standards of play. In addition, research to investigate work rates in the extra-time period during Cup matches would provide useful information on the occurence of fatigue and which players tend to cope better.

Another method of examining fatigue may be to concentrate on the maximal speed or duration of individual sprints to determine whether a player's sprint performance is declining (e.g. is the player slower?) towards the end of the match. The maximal sprint speed of an international midfield soccer player averaged every 5 minutes throughout the match has been reported to decrease significantly towards the end of the match.[82] However, as the data were drawn from a case study of one player, it is difficult to draw conclusions about the relationship between maximal sprinting speed and fatigue. In addition, soccer players may not always reach maximal speed during sprinting actions, because of the tactical demands of the particular situations restricting the length of these runs. Work rate analysis to determine whether there is a decrease in the capacity to accelerate rather than in maximal sprint speed towards the end of a game may be a more pertinent means of evaluating the occurrence of fatigue, although no study has as yet examined this feature. Nevertheless, work rate information indicating fatigue towards the end of the game could lead the coach to change tactics or even make a substitution to avoid the opposition exploiting this emerging physical weakness. Substituting players before the onset of fatigue towards the end of the game may restore the imbalances in work rate. Substitute players have been shown to cover significantly more ground at high intensity during the final 15 minutes than the other players already present on the pitch.[15] The latest video-tracking systems allow coaches to analyse work rate in real-time and make objective evidence-based decisions when attempting to identify players who may need replacing.

Evaluating fatigue during match-play may lead coaches to examine whether the intensity of the following sprint is affected by the intensity of the previous sprint (e.g. if the sprint is long and at maximal speed). It may also be useful to look at the relationship between successive sprints and whether the intensity of the subsequent activities is affected, for example if moderate-intensity exercise has more of a negative impact on ensuing sprint performance than efforts at low intensity. Individual sprints often depend on the requirements of the game situation, and particularly the recovery allowed by the unpredictable nature of play. After the 5-minute period during which the amount of high-intensity running peaked in one study, performance was reduced by 12% in the following 5 minutes compared with the game average in elite players.[15] Further data on Fourth Division Danish players have shown that performance of the third, fourth and fifth sprints carried out after a period of intense exercise during the first half was reduced compared with before the game.[83] This finding together with the observation that sprint performance measured at the end of the first half was the same as before the match, provided direct evidence that fatigue occurs temporarily during a game.

Fatigue may be evident as a prolonged recovery during the game, for example increased time spent in low-intensity activities. The reason for this decline in performance could be repeated pressure from the opposition on an individual player, eventually leading to an inability to respond to game demands. Rampinini et al.[84] recently observed that the work rate of a team of professional soccer players was significantly influenced by the activity profile of opponents. Fatigue during match-play may be transient, the player recovering once there is respite from the opponents. In this instance, tactical support for the player targeted is vital so that the offence from the opponents is not relentless. However, the same study[84] showed that the total distance covered and the amount of high-intensity running during matches were higher against 'better' opponent teams than against 'lesser' opponent teams. This finding suggests that players can increase or decrease their work rate according to both the demands of individual matches and to the quality of the opposition.

A study of the relationship between match scoreline and work rate in soccer showed that players performed significantly less high-intensity activity when winning than when the score was level.[85] Players also performed significantly less high-intensity activity when losing than when the score was level. The authors suggested that players on teams that are winning relax their work rate, allowing opponents back into the game, and that players on teams that are trailing may lose the motivation to maintain a sufficient work rate. When a team is ahead, however, forward players perform significantly more exercise – although this only appears to relate to the ~10-minute period directly after a goal has been scored, and the elevated work rate is not ultimately sustained.[86] This phenomenon merits further investigation, together with the impact of the time in the match at which goals are scored, the actual score-line, the significance of goal to score-line, as well as the impact of dismissals, specific formations and tactics on the work rate of players.

Work rates may vary between successive matches and different phases of the season, with players periodically experiencing a possible decline in performance. Distance covered per match may vary, which again suggests that players may not always be fully utilizing their physical capacity.[8] Reasons may include the specific tactical role chosen by the coach for the player or the self-imposed physical demands chosen by the player. Analysis of the total distance run by top-level players has been shown to vary significantly for individual players at different stages of the season with players covering greater distances at the end of the season.[15] These discrepancies may be partly explained by changes in the physical condition of the players as the work rate profile fluctuates in conjunction with the amount of training that is completed by teams.[27] During an intense schedule of three competitive matches in 5 days in the English Premier League, total distance run did not vary significantly,[69] suggesting this measurement may not be always be a valid indicator of a drop-off in performance during the season.

Analysis of the physical efforts made in the various categories of movement may yield information on whether the performance of a player is decreasing across different games. A case report comparing the performance of an international French player over five successive weekend matches showed little variation in the distance covered within the different categories of running.[45] In top-class Danish soccer, the CV in high-intensity running has been shown to be 9.2% between successive matches, whereas it was 24.8% between different stages of the season.[15] The seasonal variation is most likely due to alterations in fitness as the competitive schedule reaches a peak. However, few reports have included the ambient conditions under which the games analysed were played.[27] As soccer is often played across all four seasons of the year, a future study to examine the relationship between physical performance and playing conditions is recommended. Similarly, a study comparing work rate performance between games played at varying times of the day would be pertinent.

Teams may be required to play several games within a very short time-frame and there is potential for residual fatigue and incomplete recovery to affect the movement patterns of players during subsequent games. English Premiership soccer players were reported to demonstrate a significant increase in recovery time between high-intensity efforts during an intense period of three matches in 5 days.[69] Further work is needed to identify whether performance is affected significantly between playing positions. Nevertheless, this finding indicates that motion analysis data can play an important role in the approach to training and preparation before and during intense playing schedules. A future study could be designed to look at a possible relationship between work rate and injury occurrence. For example, a decline in high-intensity performance over several consecutive matches may suggest that recuperation of a player is needed to avoid becoming susceptible to 'overtraining'. Similarly, players returning after injury could have their profiles scrutinized to see how they have recovered from intense periods of play, or have their performance compared against a benchmark profile obtained from previous matches.

Once a susceptibility to fatigue is identified in individual players, the possible reasons for its occurrence should be explored. A reduction in activity has been identified at the beginning of the second half compared with the first half.[57] During the break, players tend to rest, leading to a drop in muscle temperature and subsequently to reduced performance levels. Mohr and co-workers[87] presented evidence that undertaking a few minutes of low- to moderate-intensity exercise during the pause may help players to 'ready' themselves and to perform better physically straight after the break. As previously mentioned, fatigue can also occur as the end of a game draws near. Reduced exercise performance at the end of soccer games may be associated with lowered glycogen levels in individual muscle fibres.[77] Therefore, adequate attention to nutritional preparation (before, during and after matches) for competition is necessary. The effectiveness of nutritional interventions could be monitored using motion analysis in match-play. Monitoring efforts during training by means of heart rate monitors may also help coaches to avoid over-exerting players before matches and lowering their energy stores. This information can now be combined with motion analysis data from electronic transmitters worn by players to determine individual physiological workload during training.

3.5 Other Uses of Motion Analysis Research

Physiological studies and motion analysis research on elite soccer players have provided evidence that the total amount of work done during match-play is related to the maximal aerobic power of players, which underlines the need for a high level of aerobic fitness.[17,88] This fact is especially important for certain playing positions such as midfield players who are expected to work harder than the other outfield positions. Motion analysis studies may be employed to determine the effects of a training intervention on competition work rate. Evidence shows that improvements in maximal oxygen uptake after an 8-week period of aerobic interval training corresponded to significant increases in the total distance covered during a match in elite junior players.[66] Players who are aerobically well trained can maintain their work rates better towards the end of the game than those of poorer aerobic fitness.[9] Increasing maximal aerobic power may also aid recovery following successive bouts of high-intensity anaerobic efforts, which produce transient fatigue.[45] Its role is paramount because the recovery during repeated-sprint bouts in soccer is often of an active nature. A 6-week programme of aerobic interval training undertaken by a group of amateur senior players led to an 18% increase in high-intensity activities during competition.[17]

However, there is still a limited amount of knowledge on the effects of training programmes on actual performance of players in matches at elite level. In addition, no motion analysis study in elite soccer has as yet assessed the degree to whether the physical demands of the game are adequately replicated in training. For example, it may be worthwhile determining whether players undertake comparable amounts of high-intensity exercise (e.g. number and duration of sprints) in training as in match-play.

Over recent years, researchers have attempted to examine the validity of selected field tests by establishing links with on-field physical performance. The results from such tests can help to determine the physical capacity of players and whether they may be susceptible to experiencing fatigue during match-play. The results from a 'repeated sprint ability' test have been highly correlated to the total distance covered in competition when sprinting.[44] Similarly, a strong correlation has been observed between an intermittent recovery test and both total distance run and sprint performance in elite females.[16] Mohr et al.[15] assessed the relationship between physical fitness and match performance at two standards of soccer. They compared the performance of top class soccer players versus moderate level players both in an intermittent recovery test and in work rates in match-play. The top players demonstrated superior performance in the intermittent test and carried out significantly more high-intensity running and sprinting during match-play.

These results justify the use of field and laboratory fitness testing of players and linking the fitness data to work rate assessments. However, the majority of research has been carried out on top-level Scandinavian players and further research (and on a larger scale) is needed to test these relationships in higher level professional leagues and for differing age groups. Furthermore, although various tests have been related closely with the physiological load imposed through match-play, they still appear to lack ecological validity with respect to the motion types, directions, turns and intensities corresponding to the physical demands of the game and do not provide sufficiently adapted protocols for the individual playing positions within soccer.[21] These questions may be resolved using motion analysis methods for determining precise locomotor activities during matches.

Motion analysis data drawn from match-play have also been employed to help design laboratory-based protocols to simulate soccer-specific intermittent exercise and examine factors such as the effects of training interventions,[89] nutritional strategies,[90] temperature[91] and fatigue on performance. In the application to fatigue, an intermittent-exercise protocol was designed to simulate the exercise intensities associated with playing a match in order to monitor the functional characteristics of lower limb muscles at half-time and at the end of the 90 minutes.[92] Results showed a progressive increase in muscle fatigue due to a decline in muscle strength as exercise continued. Findings therefore had implications for competitive performance and further understanding of the reported increased risk of injury towards the end of the game. A future focus on the relationship between injury occurrence and fatigue during actual competitive match-play should be beneficial. For example, motion analysis techniques could be employed to examine whether players are more at risk of injury after periods of high-intensity exercise.

4. Conclusions

A thorough understanding of the physical demands of soccer via information on player work rates is required so that optimal training and preparation strategies can be constructed. As shown in the present review, an ever-increasing number of scientific investigations based on motion analysis techniques are providing important information on elite soccer play. These investigations have identified the activity profiles and physical requirements of contemporary elite soccer as well as the demands of individual playing positions. Motion analysis research has also allowed investigators to determine the extent of fatigue experienced by players during competition as well as variations in physical performance over the course of the season. There are also possibilities to link fitness data to work rate assessments and to determine the effects of training interventions on match performance.

Many of these investigations into work rate have been possible thanks to major advances in computer and video technology, which are providing more efficient ways of obtaining and analysing data, especially on a larger scale. A plethora of commercial analysis systems are now available, albeit with a price range varying by many thousands of dollars. The cost of many systems currently used in elite soccer is often prohibitive to all but the wealthiest clubs. Similarly, many researchers are still using older techniques, given that they do not have access to these more advanced technologies due to the large costs associated with using them.

Using information derived from these latest techniques, academics could start to test and build upon existing research by exploring some of the gaps and questions identified throughout this review. Furthermore, conducting research into how these technologies are actually being put into use within coaching contexts would be pertinent, as there is little appreciation about how effectively and efficiently they are being translated and adopted by practitioners to prepare and develop members of their squad. This reservation applies to both the operators' comprehension and the coaches' use of data derived from these tools. Additionally, the measurement precision and reliability of systems proven on the basis of sound scientific evidence has not always been satisfactorily demonstrated. No current method has been accepted as the 'gold' standard approach to work rate analysis, and few investigators have attempted to make comparisons between different methodologies and technologies. It is imperative that researchers investigate the scientific legitimacy of these systems so that applied practitioners and the academic community can be assured of their accuracy when employing these methods. Nevertheless, the perfecting of motion analysis technologies will no doubt continue as it has done over recent years, with real-time analysis and application becoming the norm.

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Appendix 2: Study theme 1, Characteristics and position-specific demands of physical performance.

Appendix 2a: Copy of Paper 2, Carling, C. (2010). Analysis of physical activity profiles when running with the ball in a professional soccer team. *Journal of Sports Sciences, 28,* 319-328.

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Analysis of physical activity profiles when running with the ball in a professional soccer team

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Abstract

In an analysis of the physical demands when running with the ball in professional soccer, this study (1) determined activity profiles during match-play, (2) examined effects of fatigue, and (3) investigated differences according to playing position. Thirty French League 1 matches from two competitive seasons (2007–2008, 2008–2009) were analysed using multi-camera computerized tracking. Players ($n = 28$) ran a mean total distance of 191 ± 38 m with the ball, of which 34.3% was covered at speeds > 19.1 km $\cdot$ h^{-1}, 25.6% between 14.1 and 19.0 km $\cdot$ h^{-1}, 12.5% between 11.1 and 14.0 km $\cdot$ h^{-1}, and 27.6% at < 11.0 km $\cdot$ h^{-1}. Mean distance covered per possession was 4.2 ± 0.7 m, speed at ball reception was 10.3 ± 0.9 km $\cdot$ h^{-1}, while mean and peak speed during runs was 12.9 ± 1.0 km $\cdot$ h^{-1} and 24.9 ± 2.4 km $\cdot$ h^{-1}, respectively. Mean time in possession, duration, and touches per possession were 53.4 ± 8.1 s, 1.1 ± 0.1 s, and 2.0 ± 0.2, respectively. There were differences across playing positions for all variables (P at least 0.017 and effect size at least 0.54). Total distance run did not differ between halves but varied over the course of matches ($P < 0.001$), decreasing just before half-time. These findings provide valuable information about the physical and technical requirements of running with the ball that could be useful in the prescription of general and individualized training programmes.

Keywords: *Fatigue, performance, football, locomotor activity, motion analysis*

Introduction

Recently, analyses of professional soccer have identified activity profiles and physical requirements of contemporary match-play (Carling, Bloomfield, Nelsen, & Reilly, 2008; Stølen, Chamari, Castagna, & Wisløff, 2005). Extensive research on the physical efforts of professional players across Europe and South America has shown that there are marked differences in the distances covered in various running activities according to playing position (Barros et al., 2007; Di Salvo et al., 2007; Di Salvo, Gregson, Atkinson, Tordoff, & Drust 2009; Mohr, Krustrup, & Bangsbo, 2003; Rienzi, Drust, Reilly, Carter, & Martin, 2000). Understanding the physical efforts at different speeds imposed during competition on players according to their positional role is necessary to develop and optimize physical preparation regimes to respond to the specific demands of elite match-play.

In professional soccer, only 1.2–2.4% of the total distance covered by players is in possession of the ball, with distances dependent on playing position (Di Salvo et al., 2007). Nevertheless, it has been shown that running with the ball increases physiological stress compared with normal running (Hoff, Wisløff, Engen, Kemi, & Helgerud, 2002; Reilly & Ball, 1984). The additional energy expenditure required for this match activity should therefore be taken into account when evaluating physical performance. Furthermore, research on professional soccer has identified substantial differences in the overall distance covered with the ball (Rampinini, Impellizzeri, Castagna, Coutts, & Wisløff, 2009) and in distances covered with the ball at high speeds across playing positions (Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007). In addition, players in highly ranked professional Italian soccer teams ran greater distances with the ball than their counterparts from lower-ranked teams (Rampinini et al., 2007). Finally, the physical efforts of professional players when in possession of the ball have substantially increased in the contemporary game compared with in previous decades (Di Salvo et al., 2007).

Motion-analyses of elite soccer have identified a reduction in high-speed efforts between playing

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halves and towards the end of matches (Carling et al., 2008; Mohr, Krustrup, & Bangsbo, 2005; Reilly, Drust, & Clarke, 2008). Match-related fatigue has also been shown to affect physical efforts with the ball (Rampinini et al., 2009), as elite Italian soccer players ran substantially less distance in possession during the second half of competition. However, no decline in performance between halves was reported in top Spanish and English players (Di Salvo et al., 2007), suggesting an additional need for research. Moreover, the authors did not determine if variations in performance between halves were specific to playing positions in a team. Similarly, no study has tried to determine whether physical performance with the ball varies over different match intervals and if variations depend on playing position. This discrepancy is important, as research in professional English players has shown that off-the-ball efforts during attacking play decrease as matches progress (Bradley et al., 2009). For example, the distance covered by players at high speeds during attacking play in the last 15-min period of the game was 23.0% less than in the first 15-min period.

Although research on variations in activity with the ball has important practical implications, there is no information on the range of speeds at which outfield players receive possession and subsequently run with the ball, including the length and duration of running actions and number of touches taken, and if performance in these areas depends on playing position. Information about these areas in an evaluation of the physical demands during possession in elite soccer would inform the design and prescription of fitness and technical training drills. Consequently, the aims of this study on the physical demands with the ball were to: (1) determine physical activity profiles in a professional soccer team when running with the ball; (2) examine effects of fatigue over matches; (3) investigate technical aspects of individual ball possession; and (4) determine whether there are differences in performance across playing positions.

Methods

Participants and match sample

With ethics approval from the internal review board of the sampled professional football club, physical demands in possession of the ball were analysed for 28 outfield players who competed in the French League 1 division (highest standard in French soccer). The players were fully informed of all experimental procedures before giving their informed consent to participate in the study. To ensure team and player confidentiality, all performance data were anonymized before analysis.

Players were categorized into one of five individual playing positions: full-backs ($n = 5$), central defenders ($n = 5$), wide midfielders ($n = 6$), central midfielders ($n = 6$), and centre-forwards ($n = 6$). The sample included only players that played in their customary position.

A total of 30 French League games over two seasons (from mid- to end-season 2007–2008 and from start- to mid-season 2008–2009) were included for analysis. The sample included 19 home and 11 away matches in which players completed the entire match. Altogether, 228 observations of match performance were obtained with a median of 6.5 games per player (range = 1–24). The total number of observations of match performance for each player is presented in Table I.

Data collection procedures and measures of competitive performance

A computerized player tracking system (AMISCO Pro®, Sport-Universal Process, Nice, France) was used to characterize activity profiles in the team. This multiple-camera system tracked the movements of every player over the course of matches. It provided information on running speeds, distances covered, time spent in different categories of movement, and the frequency of occurrence for each activity. Player movements were tracked at a sampling rate of 25.0 Hz providing approximately 2.5 million data points per match (Carling, Williams, & Reilly, 2005). Simultaneously, a trained operator coded each technical action involving the ball. The workings of the AMISCO Pro® system have been described in more detail elsewhere (Carling et al., 2005, 2008; Di Salvo et al., 2007).

Physical performance with the ball was determined automatically by computerized analysis of player movements and actions using match-analysis software (AMISCO Viewer®, Sport-Universal Process, Nice, France).

The measures of performance with the ball selected for the analyses were classified into four categories. The first category was match distances covered in individual possession of the ball, which included total distance covered and distance covered in four categories of movement speed based on a slightly modified version of the thresholds previously employed in other studies of performance in competitive elite soccer (Carling & Bloomfield, 2010; Di Salvo et al., 2007): 0.0–11.0 $km \cdot h^{-1}$ (light speed), 11.1–14.0 $km \cdot h^{-1}$ (low speed), 14.1–19.0 $km \cdot h^{-1}$ (moderate speed), and > 19.1 $km \cdot h^{-1}$ (high speed and sprinting combined).

Table I. Characteristics of physical efforts during possession of the ball across playing positions (mean ± *s*).

Match performance variables	All players (n = 228)	Fullbacks (FB) (*n* = 49)	Central-defenders (CD) (*n* = 59)	Wide-midfielders (WM) (*n* = 35)	Central-midfielders (CM) (*n* = 63)	Centre-forwards (CF) (*n* = 22)	Statistical difference	Post hoc (Bonferroni)
Distance covered (m) between 0.0-11.0 km/h	52.8 ± 25.1	55.9 ± 26.6	51.1 ± 2.6	55.2 ± 16.9	60.7 ± 28.3	41.3 ± 20.3	$P = 0.132$	
Distance covered (m) between 11.1-14.0 km/h	23.9 ± 15.2	18.3 ± 11.6	25.9 ± 17.9	28.9 ± 14.9	29.1 ± 13.8	17.3 ± 9.3	$P = 0.001$	CM > CF[b]; WM > CF[b]
Distance covered (m) between 14.1-19.0 km/h	48.9 ± 27.7	40.0 ± 20.5	48.4 ± 26.5	56.9 ± 25.3	56.6 ± 30.9	42.5 ± 16.9	$P = 0.009$	CM > FB[a]; WM > FB[a]
Distance covered (m) > 19.1 km/h	65.3 ± 45.2	56.4 ± 33.9	35.5 ± 26.5	111.8 ± 60.1	56.3 ± 35.9	66.1 ± 40.0	$P < 0.001$	CF > CD[a]; CM > CD[b]; FB > CD[b]; WM > CD[c], CF[c], CM[c], FB[c]
Total distance in possession (m)	191.0 ± 80.3	170.1 ± 63.6	162.3 ± 70.7	252.7 ± 81.6	203.2 ± 82.9	166.9 ± 55.3	$P < 0.001$	WM > FB[c], CD[c], CF[a]
% of total distance run	1.7 ± 0.7	1.5 ± 0.6	1.5 ± 0.6	2.2 ± 0.8	1.7 ± 0.7	1.5 ± 0.5	$P < 0.001$	WM > CD[c], CM[a], FB[c]
Mean distance per action (m)	4.0 ± 1.9	3.0 ± 0.9	4.0 ± 1.3	5.0 ± 1.2	3.8 ± 1.2	4.2 ± 1.9	$P < 0.001$	CD > FB[c]; CF > FB[b]; CM > FB[b]; WM > CD[b], CM[c], FB[c]

Note: FB = full-backs, CD = central defenders, WM = wide midfielders, CM = central midfielders, CF = centre-forwards; *n* = number of observations of match performance.
[a]$P < 0.017$, [b]$P < 0.01$, [c]$P < 0.001$.

Second, to investigate the effects of fatigue on this component of physical performance, measures of distance were compared between the two match halves and across six intervals in games (0′00–14′59 min, 15′00–29′59 min, 30′00–44′59 min, 45′00–59′59 min, 60′00–74′59 min, and 75′00–90′00 min). Third, running speeds in possession were analysed and included peak speed in possession, mean speed of all actions, and mean speed of the player at ball reception. Peak speed was considered to be maximum running speed in possession attained by each player during a match. Finally, analysis of technical skills included the mean number of ball possessions, mean time spent in ball possession, mean number of touches, mean time per possession, and mean distance from the nearest opponent when the player received the ball.

Statistical analyses

All statistical analyses were conducted using SPSS for Windows Version 14.0 (SPSS Inc., Chicago, IL, USA). All results are reported as means and standard deviations (mean ± *s*) calculated by conventional procedures unless otherwise stated. Before using parametric statistical test procedures, the normality of the data was verified. A one-way analysis of variance (ANOVA) was used to test for differences in means in performance measures between playing positions. A two-way ANOVA was used to explore differences in means for distance covered in each category of running speed between playing positions. To investigate fatigue across match halves, a three-way ANOVA was performed to examine the interaction between playing position and total distance covered and distance covered at four running speeds across match halves. To isolate any differences in total distance covered according to playing position between the three intervals across each half, a two-way ANOVA was used. Follow-up univariate analyses using Bonferroni-corrected pairwise comparisons were used where appropriate.

To control the Type I error rate, a pseudo-Bonferroni adjustment was applied according to previously outlined procedures for objective measures of physical performance in elite soccer (Rampinini et al., 2007, 2009). In the present study, these objective measures of ball possession included distances run, running speeds, and technical variables. Thus, an operational alpha of 0.017 ($P < 0.05/3$) was used. Effect sizes for these differences were also determined. Effect size values of 0.20–0.49, 0.50–0.79, and ≥0.8 were considered to represent small, medium, and large differences, respectively (Cohen, 1988). Values are reported as means ± standard deviations.

Results

Distances covered with the ball

During matches, the players covered a mean distance of 191.0 ± 80.3 m in possession of the ball (Table I). This figure accounted for 1.7 ± 0.7% of the total match distance covered. Altogether, 34.3% of distance in possession was covered at speeds > 19.1 km · h^{-1}, 25.6% between 14.1 and 19.0 km · h^{-1}, 12.5% between 11.1 and 14.0 km · h^{-1}, and 27.6% at < 11.0 km · h^{-1}. Differences were observed in the total distance run across the four categories of movement speed ($P < 0.001$). *Post-hoc* analyses revealed greater distances covered at speeds of 0.0–11.0 km · h^{-1}, 14.1–19.0 km · h^{-1}, and > 19.1 km · h^{-1} than at 11.1–14.0 km · h^{-1} (all $P < 0.001$). These differences were associated with large effect sizes (≥0.80).

Two-way ANOVA identified a main effect for total distance run with the ball across playing positions ($F_{4,12} = 17.47$; $P < 0.001$). The wide midfielders covered the greatest distances (see Table I). There were moderate-to-large effect sizes for the differences in wide midfielders compared with all other positions (0.60–1.22). In addition, the percentage of total distance covered over entire games when the player was in possession of the ball varied between positions ($P < 0.001$), being highest in wide midfielders and lowest in full-backs, central defenders, and centre-forwards (values identical for all three).

There was also an interaction between playing position and distance covered in each category of running speed ($F_{3,12} = 10.17$; $P < 0.001$). These differences were accompanied by moderate-to-large effect sizes (0.60–2.00). *Post-hoc* analyses showed that central midfielders covered the most distance at speeds of 11.1–14.0 km · h^{-1}, whereas wide midfielders did so at speeds of 14.1–19.0 km · h^{-1} and > 19.1 km · h^{-1}.

Distance covered per ball possession by players was 4.0 ± 1.9 m (Table I). Distance completed per ball possession differed among playing positions ($P < 0.001$; effect sizes 0.54–1.96) with the highest and lowest values being recorded in wide midfielders and full-backs, respectively.

Effect of fatigue on ball possession

Total distance covered in each match half and across the six intervals in all players is reported in Figure 1. Across all players, the three-way ANOVA revealed no main effect in total distance covered between the two game halves ($F_{1,4} = 0.07$; $P = 0.795$) or in the total distance covered at each running speed between halves ($F_{3,12} = 2.22$; $P = 0.085$). Although there was an interaction that approached significance between individual playing position and total distance covered in each match half ($F_{1,4} = 2.38$; $P = 0.050$), there was no interaction between playing position and distance covered in the four categories of running speed across each half ($F_{4,12} = 0.67$; $P = 0.785$).

Across all players, a two-way ANOVA identified a main effect for distance covered across six equal time intervals over the course of matches ($F_{4,20} = 15.88$; $P < 0.017$) (Figure 1). Players ran greater distances in the first interval of the first and second halves (effect sizes of 1.65 and 1.11, respectively) compared with the final interval in the first half. However, there was no interaction between playing position and distance run across match intervals ($F_{5,20} = 0.87$; $P = 0.757$).

Running speeds

Table II illustrates a running speed per ball possession of 12.9 ± 1.8 km · h^{-1} across all players with differences among positions ($P < 0.001$, effect sizes

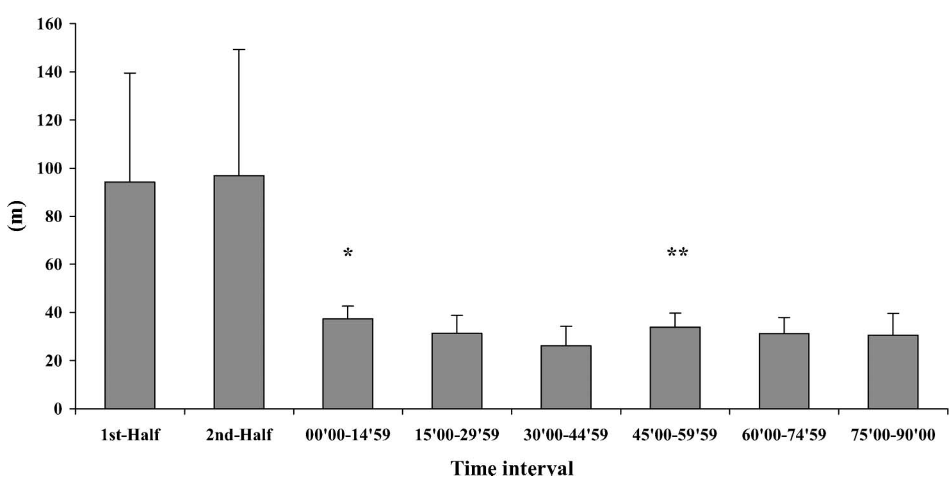

Figure 1. Comparison of the total distance covered with the ball between match halves and across six separate time intervals for all players. *$P < 0.01$: difference in distance covered with ball versus 30′00–44′59 min interval. **$P < 0.017$: difference in distance covered with ball versus 30′00–44′59 min interval.

1.01–1.30). Running speed in possession was highest in centre-forwards and lowest in full-backs.

Across all positions, speed on reception of the ball was 10.3 ± 1.8 km · h^{-1}. There were differences among playing positions ($P < 0.001$), with the highest speeds reported in wide midfielders and centre-forwards and the lowest values in full-backs. There were moderate-to-large effect sizes for the differences among positions (1.01–2.15).

In all players, peak speed in possession was 24.7 ± 6.1 km · h^{-1}, with differences among playing positions ($P < 0.001$). The highest and lowest values were reported in wide midfielders and central defenders, respectively. Effect sizes ranged from 0.59 to 1.26 for these differences.

Technical performance

Players had 46.7 ± 9.1 individual possessions per match, with differences among playing positions ($P < 0.001$) (Table II). There were substantially more ball possessions by full-backs, central midfielders, and wide-midfielders than central defenders and centre-forwards (effect sizes of 1.47–1.99).

The number of touches per possession across all players was 2.0 ± 0.2 and varied among playing positions ($P < 0.001$). Effect sizes for these differences across positions ranged from 0.97 to 2.02. The number of touches per possession was highest in wide midfielders and lowest in full-backs.

Players spent 53.4 ± 8.1 s per match in possession. There were differences among playing positions ($P = 0.002$), with wide midfielders spending more time in possession than centre-forwards ($P < 0.01$, effect size = 0.88).

Duration of possessions was 1.1 ± 0.1 s and values varied among playing positions ($P < 0.001$). Duration was greatest for wide midfielders and shortest for full-backs. There were moderate-to-large effect sizes (0.61–1.54) for these differences.

On reception of the ball, players were 4.0 ± 1.2 from an opponent, and distances differed among playing positions ($P < 0.001$). Full-backs and wide midfielders had the least and most space, respectively, on ball reception compared with the other positions. Effect sizes for these differences ranged from 0.65 to 1.86.

Discussion

In this study, a detailed investigation of the physical activity profiles of professional soccer players with the ball was conducted. The main finding is that total distance covered in possession at various movement speeds varied depending on playing position. The speed at which players were running when they received the ball was in the light-speed range

Table II. Movement speed and technical characteristics of individual possessions of the ball across playing positions (mean ± *s*).

Match performance variables	All players (n = 228)	Fullbacks (FB) (*n* = 49)	Central-defenders (CD) (*n* = 59)	Wide-midfielders (WM) (*n* = 35)	Central-midfielders (CM) (*n* = 63)	Centre-forwards (CF) (*n* = 22)	Statistical difference	Post hoc (Bonferroni)
Speed at reception (km/h)	10.3 ± 1.8	8.9 ± 0.9	10.3 ± 1.1	11.1 ± 1.0	10.1 ± 1.0	11.1 ± 1.4	$P < 0.001$	CD > FB[c]; CM > FB[b]; CF > FB[c], CM[c]; WM > FB[c], CM[c]
Speed in possession (km/h)	12.9 ± 1.8	12.0 ± 1.8	12.1 ± 1.6	14.0 ± 1.6	12.4 ± 1.6	13.9 ± 2.1	$P < 0.001$	CF > FB[b]; WM > CD[c], CM[c], FB[c]
Peak speed in possession (km/h)	24.7 ± 6.1	23.7 ± 5.7	21.6 ± 5.4	28.2 ± 4.1	25.2 ± 6.8	25.0 ± 5.0	$P < 0.001$	CM > CD[b]; WM > CD[c], FB[a]
Time spent in possession (s)	53.4 ± 8.1	51.4 ± 20.0	48.4 ± 19.4	64.3 ± 18.0	58.7 ± 22.6	44.1 ± 29.9	$P = 0.002$	WM > CF[b]
Time per possession (s)	1.1 ± 0.1	0.9 ± 0.3	1.2 ± 0.3	1.3 ± 0.2	1.1 ± 0.3	1.1 ± 0.4	$P < 0.001$	CD > FB[c]; CM > FB[a]; WM > FB[c]
Number of actions	46.7 ± 9.1	56.4 ± 11.6	39.4 ± 11.5	50.1 ± 10.5	52.5 ± 13.7	35.0 ± 10.3	$P < 0.001$	FB > CD[c], CF[c]; CM > CD[c], CF[c]; WM > CD[c], CF[c]
Number touches per possession	2.0 ± 0.2	1.8 ± 0.2	2.0 ± 0.3	2.2 ± 0.2	2.1 ± 0.3	2.0 ± 0.4	$P < 0.001$	CM > CD[a], FB[c]; WM > CD[c], FB[c]
Distance from opponent on ball reception (m)	4.0 ± 1.2	3.0 ± 1.0	4.0 ± 1.3	5.0 ± 1.2	3.8 ± 1.4	4.2 ± 1.8	$P < 0.001$	CD > FB[c]; CF > FB[b]; CM > FB[b]; WM > CD[b], CM[c], FB[c]

Note: FB = full-backs, CD = central defenders, WM = wide midfielders, CM = central midfielders, CF = centre-forwards; *n* = number of observations of match performance.
[a]$P < 0.017$, [b]$P < 0.01$, [c]$P < 0.001$.

($\sim$10.0 km $\cdot$ h^{-1}), although reception speed varied according to playing position. The mean distance, duration and speed of possessions, number of touches taken, and distance from nearest opponent when receiving the ball also varied across playing positions. Finally, the physical efforts in possession of the ball did not change between match halves but varied over the course of the game, notably decreasing just before the half-time interval.

The present results are in line with findings from previous studies (Di Salvo et al., 2007; Rampinini et al., 2009), which reported that only a small percentage of total distance run (1.7%) is with the ball. However, the analysis of efforts when running with the ball showed that actions are most commonly undertaken at high running speeds. Therefore, the ability to move at high speed with the ball seems to be an important facet of contemporary elite soccer and players across all positions should be able to carry out such actions. This statement is supported by findings from a recent study in professional Italian soccer, which showed that the most successful teams competing in the top League (five highest in ranking) covered substantially greater distances at high speeds with the ball than less successful teams (five lowest in ranking) (Rampinini et al., 2009). Furthermore, the change in tempo of matches over recent years through a marked increase in the number of actions with the ball (Di Salvo et al., 2007; Williams, Lee, & Reilly, 1999) lends further weight to the present findings.

Previous research has shown that for a given speed of locomotion, the training stimulus is higher when running with the ball than during normal running, suggesting benefits of soccer-specific routines wherever possible (Reilly, 2005). Indeed, high-standard Under-17 (McMillan, Helgerud, Macdonald, & Hoff, 2005) and senior professional soccer players (Hoff et al., 2002) used a circuit to test and subsequently develop endurance capacity based on dribbling actions with the ball. However, it is not clear if the circuit was designed using information on the physical demands of competition obtained from match analyses even if the test did include variations in running speed. The present results show that the highest percentage of movements with the ball was undertaken at high movement speeds ($>$19.1 km $\cdot$ h^{-1}). This suggests that aerobic training circuits using the ball should be based on movements carried out at high speeds to resemble the demands of the game. Nevertheless, including a range of movement speeds similar to those determined in the present study would be relevant, especially as actions undertaken at moderate speeds were also common. Furthermore, a large proportion of the actions with the ball were undertaken at speeds of less than 11.0 km $\cdot$ h^{-1}. This result probably reflects the fact that players make an immediate choice on whether to carry the ball or to release it quickly without attempting a run or dribble. In the latter case, the mean speed of the action would therefore be restricted. A future study that breaks down the speeds and distances of actions in which only a dribble or run with the ball was undertaken would be useful in aiding the design of precise testing and training prescriptions for this important aspect of soccer match-play.

Two recent reviews on physical activity profiles in elite soccer have confirmed the need for individualized training programmes, as the distances covered at different speeds vary according to playing position (Carling et al., 2008; Stølen et al., 2005). In the present report, a greater total distance with the ball was covered by wide midfielders, which is in line with findings from research in other professional European players (Di Salvo et al., 2007). However, unlike the present report, Di Salvo et al. (2007) did not provide any information on the different speeds at which players ran with the ball. In contrast, a recent study by Rampinini et al. (2007) in elite Italian soccer reported substantial differences in high-speed running with the ball across the playing positions, although players were grouped into four positional groups compared with five in the present study. The marked differences reported across these five playing positions in distance covered with the ball at several running speeds and especially at high speeds (notably in wide midfielders) is therefore noteworthy. In addition, the present results are the first to show that the mean distance of running actions with the ball is also dependent on playing position. These findings imply that fitness-training routines both with and without the ball should be based on the specific requirements of each individual playing position.

There were no differences between the two game halves among players in the distance covered in any of the four separate categories of running speed. This result suggests that this element of performance is not affected by game-related fatigue. During the second half total distance covered increased, although the magnitude of the change was small (effect size 0.10). Furthermore, in some playing positions, substantially greater distances were covered at certain running speeds during the second-half (e.g. a 35.30% increase in efforts at speeds $>$19.1 km $\cdot$ h^{-1} in central midfield players). Previous studies on differences in the physical efforts with the ball between game halves have provided conflicting evidence. Rampinini et al. (2009) reported a greater total distance covered in the first-half ($\sim$5.0%), whereas Di Salvo et al. (2007) reported a 4.6% increase in the second half, a result which is higher than the second-half increase (2.0%) observed in this study. It is difficult to provide valid reasons for an increase in second-half performance. One reason could be that players consider movements with the ball to involve risk and are therefore less willing to attempt such actions during the first half, especially as the match result is generally not yet decided. A study linking physical performance in possession of the ball with score-line is warranted.

Overall distance covered during different time intervals across the course of matches differed, with players running considerably less distance in the final interval of the first half. This result could again reflect that players are less willing to run with the ball in the first-half. A notable finding was the lack of a drop in overall physical performance observed during the final third of games. The distance run in this period was similar to that of the other match intervals, a result reflected by the low effect sizes associated with the differences (<0.30). This suggests that this aspect of physical performance was not affected by match-related fatigue, irrespective of playing position, because performance at the end of matches did not decrease among any of the positions. In contrast, other studies have demonstrated that distances covered at high running speeds by elite players decrease substantially in the final third of games (Bradley et al., 2009; Mohr et al., 2003). An exploration of variations in high-speed efforts with the ball across game intervals and their comparison between playing positions is warranted.

The novel approach to the evaluation of physical activity in ball possession using information on peak and mean running speed and speed at reception has led to several noteworthy findings, which provide valuable information for the design of realistic training drills notably from a technical standpoint. For example, speed on reception of the ball was $10.3\ \text{km} \cdot \text{h}^{-1}$, suggesting that realistic passing drills aimed at improving ball control should ensure that the player receiving possession is moving and not static. In addition, the mean and peak speeds of action imply that drills aimed at improving dribbling technique or general running with the ball should be carried out at minimum speeds of approximately $13.0\ \text{km} \cdot \text{h}^{-1}$ and include actions at high speeds ($\sim 25.0\ \text{km} \cdot \text{h}^{-1}$) regardless of playing position. The significantly higher mean speed ($14.0\ \text{km} \cdot \text{h}^{-1}$) and peak speed ($28.3\ \text{km} \cdot \text{h}^{-1}$) in possession by wide midfielders would, however, leads to the recommendation that these particular players follow individualized conditioning programmes based on the above information to help them meet the specific demands of this position.

The technical measures of physical activity with the ball demonstrate differences among playing positions in the total time spent in possession and the duration and number of touches in each possession. This finding could again encourage practitioners to create position-specific training drills. However, the results across all players generally show the short nature of actions in this component of physical activity (~ 1.0 s and 2.0 ball touches per action). These results could be related to a lack of time on the ball, as the player receiving possession was less than 4.0 m from an opposition player. Indeed, full-backs had fewest touches per possession and were frequently closer to an opposition player when receiving the ball than team-mates in other positions. These findings indicate the importance of creating space in which to make the most of the limited time in possession as well as good technique in controlling the ball.

The major limitations of this study were the low number of matches examined and that players played for only one club. Therefore, the patterns observed might be a reflection of this particular team. In addition, the techniques used to collect motion-analysis data must meet the criteria for quality control (Carling et al., 2008). These criteria include reliability, objectivity, and validity. There is a need for a detailed analysis of the errors associated with the analytical procedures in motion analysis (Drust, Atkinson, & Reilly, 2007). Although the present system has been widely adopted across professional European soccer and used in several recent scientific publications (Carling & Bloomfield, 2010; Carling, Espié, Le Gall, Bloomfield, & Jullien, in press; Di Salvo et al., 2007; Zubillaga, Gorospe, Hernadez-Mendo, & Blanco-Villanesor, 2008), its true scientific legitimacy has yet to be established.

In summary, the present study provides a comprehensive evaluation of physical activity profiles in an elite soccer team when players ran with the ball. In addition to identifying the general demands of soccer in terms of the distance covered at varying speeds and the speed of actions with the ball, the results demonstrate a large variation in efforts across playing positions. These findings have broadened the understanding of this key component of soccer match-play and could aid in developing subsequent training drills to optimize physical and technical performance as well as designing soccer-specific test protocols. However, further research is warranted to address other factors that may influence performance with the ball. Work could be extended to examine the effects of score-line, standard of opposition, match location, match type (domestic cup competitions vs. league games), and the influence of specific team formations (systems of play).

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Analysis of repeated high-intensity running performance in professional soccer

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Abstract

The aims of this study were twofold: (1) to characterize repeated high-intensity movement activity profiles of a professional soccer team in official match-play; and (2) to inform and verify the construct validity of tests commonly used to determine repeated-sprint ability in soccer by investigating the relationship between the results from a test of repeated-sprint ability and repeated high-intensity performance in competition. High-intensity running performance (movement at velocities >19.8 km $\cdot$ h^{-1} for a minimum of 1 s duration) was measured in 20 players using computerized time–motion analysis. Performance in 80 French League 1 matches was analysed. In addition, 12 of the 20 players performed a repeated-sprint test on a non-motorized treadmill consisting of six consecutive 6 s sprints separated by 20 s passive recovery intervals. In all players, most consecutive high-intensity actions in competition were performed after recovery durations $\geq$61 s, recovery activity separating these efforts was generally active in nature with the major part of this spent walking, and players performed 1.1 ± 1.1 repeated high-intensity bouts (a minimum of three consecutive high-intensity bouts with a mean recovery time $\leq$20 s separating efforts) per game. Players reporting lowest performance decrements in the repeated-sprint ability test performed more high-intensity actions interspersed by short recovery times ($\leq$20 s, $P < 0.01$ and $\leq$30 s, $P < 0.05$) compared with those with higher decrements. Across positional roles, central-midfielders performed more high-intensity actions separated by short recovery times ($\leq$20 s) and spent a larger proportion of time running at higher intensities during recovery periods, while fullbacks performed the most repeated high-intensity bouts (statistical differences across positional roles from $P < 0.05$ to $P < 0.001$). These findings have implications for repeated high-intensity testing and physical conditioning regimens.

Keywords: *Locomotor activity, physical performance, sprinting, football, soccer*

Introduction

The physical preparation of elite players has become an indispensable part of contemporary professional soccer due to the high fitness levels required to cope with the ever-increasing energy demands of match-play (Iaia, Rampinini, & Bangsbo, 2009). Sprint-type activities in particular are widely considered to be a crucial element of performance but only contribute a small proportion to the overall motion activity during competition; accounting for approximately 10% of the total distance covered over the course of matches (Carling, Bloomfield, Nelsen, & Reilly, 2008). However, evidence shows that, per game, top-class soccer players perform 150–250 intense actions (Mohr, Krustrup, & Bangsbo, 2003) and perform a high-intensity run (>19.8 km $\cdot$ h^{-1}) every 72 s (Bradley et al., 2009). Analyses of physical performance during short periods in match-play also show that players transiently perform substantially higher amounts of high-intensity running than the game average (Carling & Dupont, 2011). Consequently, short recovery intervals between consecutive intense actions occur on several occasions throughout competition. The ability to recover and subsequently reproduce these efforts (termed repeated-sprint ability) is widely accepted as a critical component of the high-intensity intermittent sport that is soccer (Gabbett & Mulvey, 2008).

The design of the conditioning elements of fitness training programmes requires detailed information on repeated high-intensity exercise profiles and the intensity and duration of recovery periods that occur during competition (O'Donoghue, 2002). However, there is limited information on the ability of soccer players to perform specific bouts of exercise during which players repeat several intense running actions of short duration or "repeated-sprint bouts" over short time intervals. Research in amateur male (Orenduff et al., 2010), international youth male (Buchheit, Mendez-Villanueva, Simpson, & Bourdon, 2010), and international female (Gabbett &

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Mulvey, 2008) soccer match-play has provided information on the frequency and characteristics of repeated-sprint bouts. Gabbett and Mulvey (2008) found that international female players performed repeated-sprint bouts (defined in their study as a minimum of three consecutive sprints, with recovery of less than 21 s between actions) almost five times per game and that recovery between sprints was generally active in nature (~93% of time). However, the specific nature and composition of repeated-sprint bouts performed in male professional soccer match-play are unclear. The frequency of bouts and the mean number of sprints, and the duration and intensity of recovery periods between sprints within these bouts warrant investigation. Furthermore, no information is available on the capacity of players in competition to maintain performance in consecutive sprints within repeated-sprint bouts (e.g. progressive decline in maximal and/or mean velocity across sprinting actions).

Measures of fitness obtained via field and laboratory testing of soccer players can be strongly associated with time–motion analysis assessments of match performance (Carling et al., 2008). Somewhat surprisingly, however, there is limited information on the relationship between match performance at the professional level and the results from tests of repeated-sprint ability. In a group of professional players, the total distance run and that covered in high-intensity movement were significantly related to performance in a field test of repeated-sprint ability (Rampinini et al., 2007). However, the association between performance in tests measuring repeated-sprint ability and other pertinent match-play measures such as the frequency of sprint efforts and recovery times separating these actions, the frequency of repeated-sprint bouts and changes in mean velocity of individual sprints within these bouts has yet to be explored. Furthermore, there is a need for appropriate repeated-sprint experimental protocols – ones that match the movement pattern in order to replicate the most intense physiological demands of the game (Meckel, Machnai, & Eliakim, 2009). To ensure that the construct validity of repeated-sprint tests is respected, protocols must measure match-related physical performance. However, many tests have inadequately assessed the repeated-sprint demands of competition in a game-specific manner by failing to take into account the most extreme demands of the sport (Gabbett, 2010). Additional information obtained from recent and more detailed analyses of repeated sprint exercise in professional soccer match-play could provide a more objective framework for the design of valid tests of repeated-sprint ability by determining the frequency and duration of sprints, and the intensity of recovery between these actions.

Consequently, the aims of this study were twofold: (1) to characterize repeated high-intensity movement activity profiles in official professional soccer match-play and determine the demands specific to positional role; and (2) to inform and verify the construct validity of tests commonly used to determine repeated-sprint ability in soccer by investigating the relationship between the results from a repeated-sprint ability test and repeated high-intensity running performance in match-play.

Methods

Participants and match sample

Physical performance in official competition was analysed for players in a professional soccer team that competed in the French League 1. While approval for the study was obtained from the present club, these data arose as a condition of employment in which player performance is routinely measured over the course of the competitive season (Winter & Maughan, 2009). Therefore, usual appropriate ethics committee clearance was not required. Nevertheless, to ensure team and player confidentiality, all physical performance data were anonymized before analysis.

Data on performance in 80 French League 1 games played over four seasons (2007/2008, 2008/2009, 2009/2010, and 2010/11) were collected for analyses. The sample included 20 players, with a total of four players in each of five positional roles: fullback, central-defender, central-midfielder, wide-midfielder, and centre-forward. Over the four-season study period, nine players participated in every season, seven in three seasons, three in two seasons, and one in a single season.

A total of 80 observations of physical performance for games in which players participated in at least 90 min of play were obtained for fullbacks and wide-midfielders, 73 for central-defenders, and 70 for central-midfielders. In centre-forwards, 50 observations of performance were obtained, of which 25 were for at least 90 min of play. The remaining observations ($n = 25$) were obtained from games in which the players completed a minimum of 75 min of play. On average, centre-forwards were substituted after approximately 83 min of play.

Data collection procedures and measures of competitive performance

A semi-automatic computerized player tracking system (AMISCO Pro®, Sport-Universal Process, Nice, France) was used to characterize match activity profiles in the team. The workings, accuracy, and reliability of this system in measuring player movements in elite soccer competition have been described in more detail elsewhere (Carling et al., 2008; Di Salvo et al., 2007; Randers et al., 2010).

In this study, repeated-sprint bouts and individual sprinting actions are referred to as ‘‘high-intensity’’ rather than ‘‘sprinting’’ movement. The speed threshold commonly used for the analysis of ‘‘sprint’’ actions in professional soccer match-play refers to 0.5 s runs performed at velocities above 25.0 $km \cdot h^{-1}$ (Bradley et al., 2009; Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Gregson, Drust, Atkinson, & Di Salvo, 2010). However, while soccer players perform numerous intense running actions during competition, there is large inter-individual variation in the velocities at which they begin to sprint. Therefore, some runs might not achieve the necessary velocity classification threshold for sprinting leading to underestimations in performance (Abt & Lovell, 2009). In addition, players frequently do not achieve their maximum running velocity in match-play (Rampinini et al., 2007). Thus, to analyse intense running efforts in the present players, high-intensity actions were defined as runs performed at velocities $>19.8 \ km \cdot h^{-1}$ over a minimum duration of 1 s. A similar definition was previously used to analyse competitive physical performance in the present professional soccer team (Carling, 2010). The mean distance and duration of high-intensity actions were analysed, together with the percentage of the total distance run that was covered by players in high-intensity activity.

The mean recovery time for consecutive high-intensity actions over the course of games was calculated from the time (in seconds) that elapsed between all performed runs (Bradley et al., 2009). High-intensity actions were classified according to the recovery duration between consecutive efforts (Buchheit et al., 2010): $\leq$30 s, 31–60 s, and $\geq$61 s. Consecutive efforts with very short recovery durations of $\leq$20 s were also analysed separately. Information on the peak number of high-intensity actions performed over 1, 3, and 5 min periods (e.g. 1–2 min, 6–9 min, and 10–15 min) was recorded.

The characteristics of physical activity during recovery periods in between consecutive high-intensity actions were analysed by calculating the proportion (%) of the overall time between actions spent in standing (0–0.6 $km \cdot h^{-1}$), walking (0.7–7.1 $km \cdot h^{-1}$), jogging (7.2–14.3 $km \cdot h^{-1}$), and running (14.4–19.7 $km \cdot h^{-1}$).

The extreme physical demands of match-play in team sports can be examined using information from analysis of ‘‘repeated high-intensity bouts’’ (Spencer, Bishop, Dawson, & Goodman, 2005). The definition of a repeated high-intensity bout was similar to that previously employed in analyses of play in international soccer (Gabbett, 2010) and field-hockey (Spencer et al., 2004) competition: a minimum of three consecutive high-intensity actions with a mean recovery duration equal to or less than 20 s between efforts. The number of individual high-intensity actions and recovery time between these efforts in each repeated high-intensity bout were measured. We also recorded the mean and peak speed and duration and distance of individual high-intensity actions making up each bout.

Repeated-sprint ability test

A laboratory test of repeated-sprint ability was performed on a Woodway Force non-motorized treadmill (Force 3.0, Waukesha, WI, USA). The non-motorized treadmill was set up with one horizontal load attached to the vertical strut and four individual vertical load cells under the running surface. The participant was attached to a horizontal rod by means of a hip-belt. The rod’s posterior end was fixed to the rear of the treadmill. The rod was serially connected to a force transducer permitting measurement of horizontal force. Vertically mounted force transducers recorded the vertical force applied to the treadmill bed. Power output was calculated from vertical force and horizontal force data. Both horizontal and vertical load cells were calibrated before and after each test using a range of known mass. Treadmill belt speed, distance, and horizontal forces were collected at a sampling rate of 10 Hz via the XPV7 PCB interface (Fitness Technology, Adelaide, Australia) and analysed using the Force 3.0 Software (Innervations Software, Joondalup, Australia).

Reliability trials of running performance in amateur soccer players during this repeated-sprint test using the same experimental set-up have been performed (Nédélec, Berthoin, & Dupont, 2011). The intra-class correlation coefficient, typical error of measurement, and coefficient of variation for peak power output was 0.91, 91 W, and 4.1%, respectively. The intra-class correlation coefficient, typical error of measurement, and coefficient of variation for mean power output was 0.99, 27 W, and 1.4%, respectively. Finally, the intra-class correlation coefficient, typical error of measurement, and coefficient of variation for percentage decrement score was 0.65, 3.3%, and 32.1%, respectively.

All participants were free from illness and injury and testing took place during the mid-season winter break. After one familiarization trial, 12 of the 20 players performed six consecutive 6 s sprints with each sprint separated by a 20 s passive recovery period. This mode of exercise, number and duration of sprint repetitions, and recovery duration and type are similar to those frequently employed in studies on field sports (Spencer et al., 2005). To ensure pacing did not occur, the participants completed a maximal single sprint test before the repeated-sprint test and were subsequently expected to achieve a time for their first sprint within 95% of that of their single maximal sprint performance (Castagna et al., 2008).

Mean running velocity was calculated over 6 s for each individual sprint effort. These individual mean values for velocity were subsequently averaged to obtain a mean value for all six sprints (mean velocity). Of the six individual mean velocity values obtained for the consecutive sprints, the fastest mean velocity value was identified (highest mean velocity). The peak running velocity attained over the six sprints was recorded (peak velocity). A performance decrement score (percent performance decrement) to evaluate declines in the mean velocity of consecutive sprints was calculated using the methodology described by Dupont and colleagues (Dupont, McCall, Prieur, Millet, & Berthoin, 2010).

Statistical analyses

Statistical analyses were conducted using SPSS for Windows v.14.0 (SPSS Inc., Chicago, IL, USA). Results are reported as means and standard deviations (mean $\pm$ *s*) unless otherwise stated. A one-way analysis of variance (ANOVA) was used to test for differences in means in match performance measures across positional roles. A two-way ANOVA was used to explore differences across positional roles in the mean time spent in different categories of running speed during the recovery periods between high-intensity actions. To isolate any differences in the frequency of recovery periods (classed according to the time duration) in between consecutive high-intensity actions across positional roles, a two-way ANOVA was also used. Where appropriate, follow-up univariate analyses using Bonferroni-corrected pair-wise comparisons were employed.

The known-group effect difference technique was used to assign participants into two groups (“highest” or “lowest” ranked performers) based on individual performances observed in the repeated-sprint test (Rampinini et al., 2007). These included mean velocity over the six sprints, fastest mean velocity, peak velocity, and percent performance decrement. Measures of match performance [percent of overall distance run covered in high-intensity running, frequency of and recovery time between high-intensity actions, percent of these actions interspersed by short recovery times ($\leq$20 s and $\leq$30 s), the frequency of repeated high-intensity bouts, and the mean and peak speed of individual actions within these bouts] in a minimum of five complete matches played during the same season were subsequently compared between the highest and lowest ranked groups using unpaired *t*-tests. Pearson’s product–moment correlations were also employed to examine relationships between repeated-sprint ability test scores and measures of match performance. The correlation coefficients (*r*) were interpreted in accordance with the following scale of magnitude (Hopkins, Marshall, Batterham, & Hanin, 2009): $\leq$0.1, trivial; $>$0.1–0.3, small; $>$0.3–0.5, moderate; $>$0.5–0.7, large; $>$0.7–0.9, very large; and $>$0.9–1.0, almost perfect. Finally, effect sizes (ES) for statistical differences were determined. Effect size was assessed using the following criteria: $\leq$0.2, trivial; $>$0.2–0.6, small; $>$0.6–1.2, moderate; $>$1.2–2.0, large; and $>$2.0, very large (Batterham & Hopkins, 2006). Statistical significance was set at $P \leq 0.05$.

Results

Match performance

In relation to the total distance covered, the percentage of distance run in high-intensity activities varied across positional roles ($P < 0.001$). The highest values were observed in fullbacks and lowest in central-defenders (fullback: 8.6 $\pm$ 1.2%; central-defender: 5.1 $\pm$ 1.4%; central-midfielder: 6.2 $\pm$ 1.3%; wide-midfielder: 8.3 $\pm$ 2.2%; centre-forward: 7.3 $\pm$ 1.6%; ES range = moderate 0.8 to very large 2.7). The mean recovery duration between high-intensity actions also varied across positional roles ($P < 0.001$, ES range = large 1.5 to very large 2.2) with the longest and shortest durations observed in central-defenders and fullbacks, respectively (Table I). For all positions, the most commonly observed recovery duration between consecutive high-intensity actions was $\geq$61 s (67.0 $\pm$ 9.6% of the total number of actions) with the highest frequency in central-defenders (76.5 $\pm$ 8.4% of the total). A statistical interaction was observed between recovery duration and positional role ($P < 0.001$). The lowest and highest frequencies of consecutive high-intensity actions separated by recovery durations $\leq$30 s and 31–60 s were observed in central-defenders and fullbacks, respectively. The lowest and highest frequency of very short recovery durations ($\leq$20 s) between high-intensity actions was observed in central-defenders and central-midfielders, respectively. Effect sizes for these statistical differences across positional roles ranged from moderate to large (0.6–1.8).

The highest number of high-intensity actions recorded in any single 1 min ($n = 5$) and 5 min ($n = 11$) period was observed in a fullback, and in a 3 min period ($n = 7$) jointly in a fullback and a central-midfielder.

The analysis of activity patterns in between consecutive high-intensity actions showed that

Table I. Frequency of recovery periods based on the time elapsed between consecutive high-intensity actions in relation to positional role (mean ± *s*).

Recovery duration (s)	All Players ($n=353$)	Fullback (FB) ($n=80$)	Central-defender (CD) ($n=73$)	Central-midfielder (CM) ($n=70$)	Wide-midfielder (WM) ($n=80$)	Centre-forward (CF) ($n=50$)	Bonferroni *Post-hoc* analysis
Mean recovery time (s)	139.0 ± 42.6	115.8 ± 18.6	194.6 ± 48.4	134.7 ± 28.5	120.5 ± 24.1	129.3 ± 27.6	CD > FB^a, CM^a, WM^a, CF^a; CM > FB^b
% < 20s	14.3 ± 6.0	16.1 ± 5.6	10.8 ± 5.3	16.4 ± 5.6	15.3 ± 5.7	12.4 ± 6.3	FB > CD^a, CF^b; CM > CD^a, CF^b; WM > CD^a
% <30s	18.9 ± 7.0	21.6 ± 6.3	14.0 ± 6.5	21.0 ± 6.4	20.2 ± 6.1	16.9 ± 6.6	FB > CD^a, CF^b; CM > CD^a, CF^c; WM > CD^a
%31–60s	14.1 ± 6.0	16.6 ± 5.6	9.5 ± 5.2	14.2 ± 5.5	15.2 ± 5.0	15.1 ± 6.0	FB > CD^a; CF > CD^a; CM > CD^a; WM > CD^a
% > 61s	67.0 ± 9.6	61.8 ± 7.6	76.5 ± 8.4	64.8 ± 8.1	64.6 ± 8.0	68.0 ± 8.2	CD > FB^a, CM^a, WM^a, CF^a; CF > FB^a

Post-hoc analysis: $^aP < 0.001$, $^bP < 0.01$, $^cP < 0.05$.

players across all positional roles spent the major part of recovery in walking and jogging activities (Table II). However, a statistical interaction was observed between positional role and recovery time spent in the four locomotor activities ($P < 0.001$). Substantial differences were observed in recovery activity profiles in central-defenders and centre-forwards compared with the other positional roles. Notably, centre-forwards spent more time in walking than all other positional roles (statistical differences from $P < 0.01$ to $P < 0.001$) but less time in the "running" threshold than fullbacks, central-midfielders, and wide-midfielders (statistical differences from $P < 0.01$ to $P < 0.001$). More time spent in "running" was observed for central-midfielders compared with all other positional roles (all statistical differences: $P < 0.001$). Effect sizes for these statistical differences ranged from small to very large (0.4–2.9).

Across all players, an average of 1.1 ± 1.1 exercise bouts that met the criteria for repeated high-intensity activity were performed per player per match with a statistical difference observed between positional roles ($P < 0.001$; ES range = moderate 1.0 to large 1.3) (Table III). On average, fullbacks performed approximately four times as many repeated high-intensity bouts per match than central-defenders. The mean number of individual high-intensity actions per bout was similar across positional roles ($P = 0.486$), whereas the mean duration ($P = 0.006$) and length of actions ($P = 0.002$) varied, with the highest values observed in fullbacks. Recovery duration also varied across positional roles ($P = 0.044$) with the shortest recovery times between bouts observed in central-defenders. Small to moderate (0.5–0.7) effect sizes for these statistical differences were observed.

The maximum number of repeated high-intensity bouts observed in any one match was six (in a wide-midfielder) and the peak number of individual high-intensity actions reported within any one single bout of repeated high-intensity activity was seven (in a centre-forward). Figure 1 presents a graphical representation containing quantitative and qualitative information on this intense bout of activity. The overall duration of this bout was 111.0 s, equating to one high-intensity action every 15.9 s. Maximum and minimum recovery times between individual high-intensity actions within this bout were 9.5 s and 40.0 s, respectively. The mean duration and length of these high-intensity actions was 3.1 ± 0.8 s (range 2.1–4.7 s) and 18.4 ± 4.8 m (range 12.1–27.4 m), respectively. The mean speed of actions was $25.0 \pm 1.9\ \text{km} \cdot \text{h}^{-1}$, with a peak speed of $28.2\ \text{km} \cdot \text{h}^{-1}$ observed in the final effort of the bout. Of the recovery activity between efforts, 69.1% was spent in walking, 22.3% in jogging, and 10.8% in running activities respectively.

Table II. Characteristics of running activities during recovery periods in between consecutive high-intensity actions in relation to positional role (mean ± *s*).

Running activity	All Players ($n = 353$)	Fullback (FB) ($n = 80$)	Central-defender (CD) ($n = 73$)	Central-midfielder (CM) ($n = 70$)	Wide-midfielder (WM) ($n = 80$)	Centre-forward (CF) ($n = 50$)	Bonferroni *Post-hoc* analysis
% Standing	1.7 ± 0.9	1.6 ± 0.8	2.0 ± 0.9	1.6 ± 1.0	1.7 ± 1.0	1.6 ± 0.9	
% Walking	61.3 ± 4.3	61.3 ± 3.6	62.7 ± 2.7	56.9 ± 3.0	62.2 ± 4.9	64.3 ± 2.4	CD > FB^b, CM^a; CF > FB^a, CD^b, CM^a, WM^a
% Jogging	30.3 ± 3.4	30.2 ± 3.2	30 ± 2.4	32.7 ± 2.3	29.4 ± 4.4	28.9 ± 2.3	FB > CF^c; CM > FB^a, CD^a, CM^a, CF^a
% Running	6.7 ± 1.7	6.9 ± 1.1	5.3 ± 0.9	8.9 ± 1.5	6.7 ± 1.2	5.2 ± 0.8	FB > CD^b, CF^b; CM > FB^a, CD^a, WM^a, CF^a; WM > CD^b, CF^b

Note: % = percentage of recovery time spent in each running activity.
Post-hoc analysis: $^aP < 0.001$, $^bP < 0.01$, $^cP < 0.05$.

Table III. Frequency of repeated high-intensity bouts and characteristics of high-intensity actions within these bouts in relation to positional role (mean ± *s*).

Repeated high-intensity bouts	All Players ($n = 353$)	Fullback (FB) ($n = 80$)	Central-defender (CD) ($n = 73$)	Central-midfielder (CM) ($n = 70$)	Wide-midfielder (WM) ($n = 80$)	Centre-forward (CF) ($n = 50$)	Bonferroni *Post-hoc* analysis
No. of bouts	1.1 ± 1.1	1.6 ± 0.8	0.4 ± 1.1	1.3 ± 0.6	1.4 ± 1.1	0.6 ± 0.8	FB > CD^a, CF^a; CM > CD^a, CF^b; WM > CD^a, CF^a
No. of HIA per bout	3.3 ± 0.5	3.4 ± 0.6	3.3 ± 0.5	3.2 ± 0.4	3.2 ± 0.4	3.3 ± 0.6	
HIA duration (s)	2.7 ± 0.7	2.9 ± 0.7	2.5 ± 0.8	2.5 ± 0.7	2.6 ± 0.6	2.8 ± 0.7	FB > CD^c
HIA distance (m)	16.5 ± 4.9	18.2 ± 4.6	15.0 ± 5.6	14.9 ± 5.0	16.2 ± 3.9	17.4 ± 4.4	FB > CD^b, CM^b
HIA recovery time (s)	13.6 ± 4.4	14.4 ± 5.2	11.4 ± 3.7	13.7 ± 4.7	13.6 ± 4.4	13.9 ± 4.4	FB > CD^c

Note: HIA = high-intensity actions.
Post-hoc analysis: $^aP < 0.001$, $^bP < 0.01$, $^cP < 0.05$.

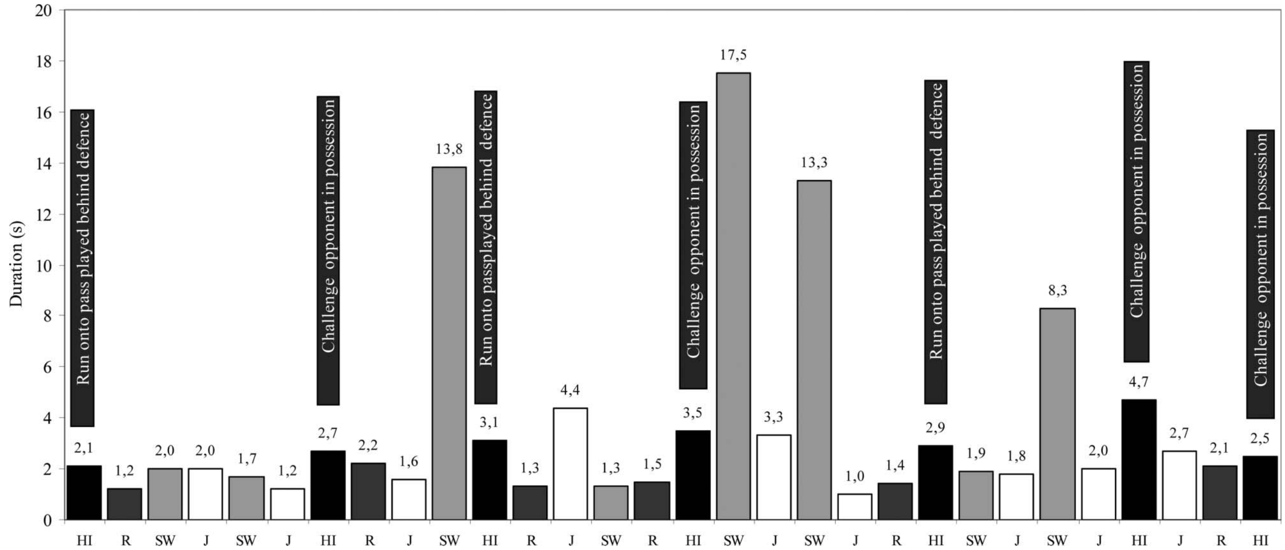

Figure 1. Descriptive characteristics of the most intense repeated high-intensity activity bout represented by the peak number of high-intensity actions performed by a centre-forward. Movement classification: HI = high-intensity, R = running, J = jogging, and SW = standing/walking.

Table IV. Comparison of mean and maximal running velocity of consecutive high-intensity actions in repeated high-intensity bouts characterized according to the number of consecutive actions observed within bouts.

	Repeated high-intensity bouts					
Number of consecutive HIA	HIA 1	HIA 2	HIA 3	HIA 4	HIA 5	HIA 6
Maximum velocity ($km \cdot h^{-1}$)						
3 consecutive actions	24.9	24.7	24.9			
4 consecutive actions	24.7	24.8	24.4	24.5		
5 consecutive actions	25.0	24.9	24.8	25.8	24.4	
6 consecutive actions	24.9	25.1	24.5	25.0	27.3	25.1
Mean velocity ($km \cdot h^{-1}$)						
3 consecutive actions	22.1	22.0	22.1			
4 consecutive actions	21.9	21.9	22.0	21.9		
5 consecutive actions	22.0	22.3	21.9	22.0	21.5	
6 consecutive actions	21.8	21.4	21.4	22.2	22.9	22.2

Note: HIA = high-intensity actions.

No significant decrements in the mean and maximum velocity of individual high-intensity actions performed during repeated high-intensity bouts were observed irrespective of the number of consecutive efforts (3, 4, 5, or 6) performed in each bout (Table IV).

Laboratory repeated-sprint ability test

In all players, analysis of performance across the six consecutive 6 s sprints showed a mean velocity of $15.8 \pm 1.1\ km \cdot h^{-1}$, a highest mean velocity of $17.3 \pm 1.4\ km \cdot h^{-1}$, and a peak velocity of $20.3 \pm 1.3\ km \cdot h^{-1}$. The performance decrement across sprints was $8.9 \pm 2.6\%$. Players assigned to the group ranked highest in the four scores in the treadmill test generally did not display better performance ($P > 0.05$) in any of the match activity parameters (Table V). In contrast, a higher frequency of high-intensity actions with recovery times ≤ 20 s ($P = 0.007$, ES = very large 2.0) and ≤ 30 s ($P = 0.028$, ES = large 1.5) was observed in players assigned to the group reporting the lowest percent performance decrement. Finally, no significant correlations were observed between any of the scores obtained in the repeated sprint ability test and measures of match-play performance ($P > 0.05$). The highest correlations (positive and negative) were observed between the mean velocity of treadmill sprints and recovery time between high-intensity actions ($r = 0.419$, considered moderate), and the percent decrement score and frequency of high-intensity actions interspersed by recovery times ≤ 20 s ($r = -0.507$, considered large).

Table V. Competitive high-intensity running activity profiles in two groups of professional soccer players (highest and lowest ranked performers) ranked according to performance measures of repeated sprint ability determined during a non-motorized treadmill test (mean ± *s*).

RSA treadmill test performance	Mean velocity ($km \cdot h^{-1}$)		Highest mean velocity ($km \cdot h^{-1}$)		Peak velocity ($km \cdot h^{-1}$)		Performance decrement (%)	
Match performance	Lowest ranked	Highest ranked	Lowest ranked	Highest ranked	Lowest ranked	Highest ranked	Lowest ranked	Highest ranked
High-intensity actions								
% Total distance covered	7.1 ± 1.5	6.4 ± 1.2	7.1 ± 1.5	6.4 ± 1.2	6.8 ± 1.5	6.7 ± 1.4	6.5 ± 1.5	7.0 ± 1.3
Mean number	40.0 ± 5.2	40.2 ± 6.6	40.0 ± 5.2	40.2 ± 6.6	40.7 ± 5.4	39.6 ± 6.3	39.0 ± 6.4	41.2 ± 5.1
Mean recovery time (s)	141.6 ± 20.5	147.0 ± 29.3	141.6 ± 20.5	147.0 ± 29.3	141.1 ± 20.8	147.4 ± 29.0	148.7 ± 28.3	139.7 ± 20.5
% Recovery time < 20 s	15.3 ± 4.2	13.6 ± 5.3	15.3 ± 4.2	13.6 ± 5.3	15.6 ± 4.2	13.3 ± 5.1	11.2 ± 3.7	17.7 ± 3.0*
% Recovery time < 30 s	18.6 ± 4.9	17.9 ± 6.1	18.6 ± 4.9	17.9 ± 6.1	19.0 ± 4.8	17.5 ± 6.1	15.1 ± 4.7	21.5 ± 3.8#
Repeated high-intensity bouts								
Mean number	1.1 ± 0.9	1.1 ± 0.9	1.1 ± 0.9	1.1 ± 0.9	0.9 ± 0.9	1.4 ± 0.9	1.0 ± 1.0	1.3 ± 0.7
Mean velocity	21.9 ± 0.1	21.9 ± 0.2	21.9 ± 0.1	21.9 ± 0.2	21.9 ± 0.1	21.9 ± 0.2	22.0 ± 0.1	21.9 ± 0.1
Maximum velocity	27.2 ± 2.2	27.2 ± 2.1	27.2 ± 2.2	27.2 ± 2.1	27.4 ± 2.3	27.0 ± 1.9	27.9 ± 0.5	26.8 ± 2.5

Note: RSA = repeated sprint ability.
*$P < 0.01$: difference between lowest and highest ranked group. #$P < 0.05$: difference between lowest and highest ranked group.

Discussion

This study is the first to investigate in detail the characteristics of repeated high-intensity movement activity patterns in professional soccer match-play and the demands specific to positional role. The major findings were that mean recovery time between high-intensity actions varied substantially in relation to positional role with the longest and shortest values observed in central-defenders and fullbacks, respectively. While the majority of consecutive high-intensity actions were interspersed by recoveries > 61 s, those performed following a very short recovery time (≤20 s) were more frequently observed in central-midfielders. The majority of recovery time in between high-intensity actions in players across all positional roles was active in nature, with the major part of this activity spent in walking. However, central-midfielders spent significantly more recovery time moving at higher intensities compared with the other positional roles. The frequency of repeated high-intensity bouts (a minimum of three consecutive high-intensity actions with a recovery period ≤20 s between actions) varied across positional roles and was highest in fullbacks. While no significant relationships were generally observed between performance measures obtained in a treadmill repeated-sprint ability test and those in match-play, players with the lowest performance decrement performed a higher frequency of high-intensity actions interspersed by short recovery times (≤20 s and ≤30 s).

Information regarding the mean recovery durations between high-intensity actions is valuable for estimating the average work-to-rest ratios during soccer match-play (O'Donoghue et al., 2005). In this study, a mean recovery duration of 139 s across all players was observed, with the shortest and longest values observed in fullbacks (116 s) and in central defenders (194 s), respectively. Unfortunately, such information does not provide insights into repeated intense movement patterns commonly known as repeated-sprint activity (Spencer et al., 2005). The majority of consecutive high-intensity actions (67.0%) observed in the present players were performed after a recovery period ≥61 s. Research in international youth soccer match-play has also reported recovery times between high-intensity actions generally greater than 60 s in duration (Buchheit et al., 2010). Although approximately one-fifth of consecutive high-intensity actions performed were interspersed by short recovery durations (≤30 s), the present results nevertheless suggest that these players had sufficient time to completely recover "physiologically" from the majority of high-intensity actions. A 120 s recovery period between short bouts of high-intensity activity has been shown not to lead to a decrement in running performance, even when 15 sprints were performed in succession (Balsom, Seger, Sjodin, & Ekblom, 1992). In addition, the present players performed an average of 1.1 repeated high-intensity bouts per match, with these comprising only three consecutive high-intensity actions. This result is substantially lower than the 4.8 repeated sprint bouts per match observed in international women's soccer (Gabbett & Mulvey, 2008). This discrepancy may be explained by differences in respective methods employed to collect movement data as manual coding techniques are known to lead to overestimations in high-intensity running performance (Carling et al., 2008). It may also be due to the strict inclusion criteria employed here to define high-intensity movements (runs performed at velocities >19.8 km $\cdot$ h^{-1} and minimum 1 s duration). In comparison, Bradley et al. (2009) defined high-intensity work as any movement performed at velocities >19.8 km $\cdot$ h^{-1} but for a minimum of 0.5 s in English Premier League players. Use of this latter definition might have led to identification of more repeated high-intensity bouts in the present group of players. These discrepancies in definitions across studies suggest a need for consensus to ensure standardization in the classification of movement thresholds (according to speed and duration) for time–motion analyses of professional soccer match-play.

The low frequency of repeated high-intensity bouts observed in the present team nevertheless suggests that this specific fitness component might not play as crucial a role in elite match performance as commonly believed. Alternatively, the prescription of supplementary specific conditioning programmes to improve performance in the present group of elite soccer players could be warranted. However, a low occurrence of repeated high-intensity running sequences was also reported in international youth soccer competition (Buchheit et al., 2010). Additional analyses not reported here showed that an international wide-midfielder playing in the present team did not record a single repeated high-intensity bout in 35% (7 of 20) of matches analysed. These results therefore lend support to other research findings in that the need to frequently reproduce highly intense efforts is perhaps not central to success. Indeed, high-ranked teams in the English Premier League (top 10) were shown to perform less high-intensity running than low-ranked teams (Di Salvo et al., 2009). Over the four seasons studied, qualification for European competition was successfully achieved on three occasions by the present team, who also won its National Championship in the final season.

Despite the overall low frequency of repeated high-intensity bouts, performance demands differed significantly across positional roles, with fullbacks performing the most bouts. In addition, consecutive high-intensity actions with recovery duration $\leq$20 s between efforts were more common in central midfielders. When rest periods between high-intensity actions are below 30 s in duration, subsequent sprint performance can deteriorate due to decreases in adenosine triphosphate concentration and intramuscular pH slowing phosphocreatine resynthesis (Spencer et al., 2005). Therefore, players in these positional roles potentially experienced transient fatigue during certain phases of match-play. However, analysis of the maximum and mean running velocity of the individual efforts performed in repeated high-intensity bouts showed in general that players were able to maintain performance even when six high-intensity actions were performed successively with $\leq$20 s rest between runs. Analysis of data on mean and maximum velocity of consecutive high-intensity actions demonstrated no significant changes between the first and final effort across repeated high-intensity bouts. In addition, analysis of the most intense repeated high-intensity bout performed by a centre-forward showed that the mean and maximal speed of the final high-intensity actions (7th action) was higher than corresponding measures for the previous six individual efforts. However, the possible occurrence of fatigue patterns in repeated high-intensity performance as matches progressed (e.g. towards the end of games) was not examined here and warrants inclusion in future research.

Overall, the present results suggest that the players studied were able to reproduce performance when called upon to perform sporadic but extreme sequences of high-intensity running in match-play. A reasonable explanation for this lack of a decline in velocity across multiple high-intensity efforts may be due to the relatively short length of runs ($\sim$16 m), which allowed adequate replenishment of the phosphocreatine system between efforts (Abt, Siegler, Akubat, & Castagna, 2011; Bishop, Spencer, Duffield, & Lawrence, 2001). Indeed, resynthesis of phosphocreatine stores appears to be related to the distance of efforts, as stores are more adequately replenished following repeated 15 m sprints than repeated 40 m sprints (Balsom et al., 1992).

The mode of recovery (passive or active) and, to a lesser extent, the intensity of active recovery, can potentially affect subsequent high-intensity performance (Spencer et al., 2005). Oxygen uptake and phosphocreatine resynthesis during repeated high-intensity exercise are notably restricted by active recovery (Dupont, Moalla, Guinhouya, Ahmaidi, & Berthoin, 2004). The analysis of running activities in between high-intensity actions showed that the majority of recovery was active in nature (98%) and that majority of this time was spent in lower intensity movement (< 14.3 km · h^{-1}). In comparison, 93% of recovery time between sprints in international women's soccer competition (Gabbett & Mulvey, 2008) was active in nature. Importantly, statistical differences in recovery intensity were reported here with respect to positional role. Central-midfielders performed substantially more movement at higher intensities (speeds of 14.3–19.8 km · h^{-1}) between consecutive high-intensity actions compared with other positional roles, a finding that is in accordance with a report on amateur soccer (Orendurff et al., 2010). Therefore, practitioners might aim to specifically develop the capacity of central-midfielders to recover actively at higher levels of intensity.

In the repeated-sprint ability treadmill test, players who reported the lowest percent performance decrement reported a greater frequency of high-intensity actions interspersed with recovery times $\leq$20 s and $\leq$30 s in duration. This result suggests that those with a greater resistance to fatigue in a treadmill test of repeated-sprint ability are able to perform a greater frequency of high-intensity actions with short rest intervals in competition. In contrast, no association was observed between test scores and the percent of the overall distance run that was covered in high-intensity exercise or the frequency of high-intensity actions and recovery time between efforts. Related research in professional soccer showed that players who performed better in a repeated-sprint ability field test of similar intensity performed more high-intensity running in competition, although the performance decrement across sprints was unrelated to this aspect of match performance (Rampinini et al., 2007). However, the authors did not investigate the relationship between running performance in a repeated-sprint ability test and the frequency and characteristics of repeated high-intensity bouts as done here. Therefore, the general lack of an association here between the frequency of, and mean and peak velocity of repeated high-intensity bouts in match-play and treadmill measures of repeated-sprint ability is of note. On the whole, these results might suggest a lack of empirical support for the construct validity of the present and similar tests of repeated-sprint ability as predictors of high-intensity match performance in professional soccer. However, additional research is required to determine the reliability of the present test and its applicability for use in professional soccer, and further studies using both laboratory and field tests of repeated-sprint ability to evaluate performance in a larger and wider sample of professional teams are warranted to verify the present findings.

Tests of repeated-sprint ability in field sports are generally designed to replicate a highly stressful period of play during a match and measure the ability to resist fatigue and maintain high performance levels (Oliver, Armstrong, & Williams, 2007). Current tests are generally short in duration (< 3 min) and involve repetition of 6–7 sprints over a distance of 30 m with an active recovery period between sprints lasting 25 s (Carling, Reilly, & Williams, 2009; Reilly, 2005). Results from this study tend to support this consensus as the maximum number of high-intensity actions observed across 3 min and 5 min periods equalled 7 and 11, equating to one action per 26 s and 27 s, respectively. In contrast, a mean recovery time of 13.6 s was observed between consecutive high-intensity actions recorded in repeated high-intensity bouts, and analysis of the most extreme demands of match-play showed that players performed up to five high-intensity actions within a 1 min period (one bout every 12.0 s) and seven efforts within a period of 111 s (one run every 15.9 s). In addition to recovery periods between these high-intensity actions being generally active in nature, the duration of these intervals is towards the lower end of the scale for those typically used in tests to assess repeated-sprint ability in soccer players (Spencer et al., 2005).

The present findings therefore suggest that fitness personnel might employ repeated-sprint ability tests with a maximum active recovery period of 15 s between consecutive efforts. A repeated-sprint test specific to the most intense period of soccer play identified in this study and potentially sufficient to elicit an overload stimulus might require seven high-intensity actions (running speed > 19.8 km · h^{-1} maintained over $\sim$20 m) with 15 s active recovery intervals between efforts and inclusion in the latter of running activities at both low and moderate intensities. In addition, large oscillations within these extreme bouts of exercise in the length and duration of individual high-intensity actions and in the recovery duration between efforts were reported in this study. As observed in the most intense bout of activity performed by a forward player (Figure 1), the characteristics of high-intensity actions are probably linked to the tactical requirements of the game situations. The length of efforts and the recovery periods in between these determine the physiological responses to high-intensity exercise (Svensson & Drust, 2005). Therefore, future tests of repeated-sprint ability might be designed to take into account such variations to provide a more ecologically valid assessment of players' ability to perform repeated high-intensity exercise.

In summary, this study has provided an insight into repeated high-intensity activity profiles and the extreme demands of match-play in professional soccer. A methodological limitation, however, was the relatively small number of players included for analysis and that they came from only one club. Therefore, the patterns observed might be a reflection of only this particular team and/or the League in which it competes. Nevertheless, these results have implications for the design and validity of tests of repeated-sprint ability in terms of the frequency, distance, and duration of high-intensity actions and the nature of recovery between efforts. In contrast, doubts might be raised on current evidence on the validity of the present and potentially other laboratory repeated-sprint ability tests to predict competitive physical performance. These results may also cast doubt on the relative importance of repeated high-intensity activity and therefore the need for conditioning programmes in an attempt to improve the general and/or position-specific ability of professional soccer players to perform repeated high-intensity work. While such fitness training interventions can induce substantial improvements in football-specific endurance (Ferrari Bravo et al., 2008), the relative importance of repeated-sprint ability to team performance in professional soccer and notably the outcome of matches remains unexplored.

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Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play?

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Abstract

The aim of this study was to determine whether declines in physical performance in a professional soccer team during match-play were associated with reductions in skill-related performance. Computerized tracking of performance in midfield players (n = 11) showed that total distance and distance covered in high-speed running (>14.4 km · h^{-1}) were greater in the first versus second half of games (both $P < 0.001$) and in the first versus the final 15 min of play ($P < 0.05$). Analysis of high-speed running across 5-min periods showed that more distance was covered in the first versus the final game period, and in the peak period of activity compared with the following period and game mean for other periods (all $P < 0.05$). Analysis of skill-related measures revealed no significant decline between halves, across 15-min intervals or in the 5-min period following that of peak high-speed activity compared with the game mean for other 5-min periods. In contrast, frequencies of passing, ball possessions, and duels were greater in the first 5-min than in the final 5-min period ($P < 0.05$). Neither physical nor skill-related performance was affected across three consecutive games within a period of $\leq$7 days. The results suggest that the players were generally able to maintain skill-related performance throughout games and when competing in successive matches within a short time.

Keywords: *Fatigue, football, locomotor activity, technique*

Introduction

Computerized motion analyses of contemporary professional soccer performance have identified the activity profiles of players and the physical requirements of competition (Carling, Bloomfield, Nelsen, & Reilly, 2008). Motion analyses also provide information on the extent of fatigue experienced by players at the highest level of competition. It is widely recognized that there is a decline in physical efforts across playing halves and notably towards the end of matches (Mohr, Krustrup, & Bangsbo, 2005; Reilly, Drust, & Clarke, 2008). For example, the distance covered at high running speeds in professional players decreases substantially in the final third of games (Mohr, Krustrup, & Bangsbo, 2003). Similarly, players also experience temporary fatigue in match-play, as research has shown that the amount of high-intensity running performed by FA Premier League players declined by ~50% to levels below the game mean after the most intense 5-min period of activity (Bradley et al., 2009). High aerobic requirements throughout a game and extensive anaerobic demands during certain intense periods of exercise lead to major metabolic changes and contribute to the observed development of fatigue during and towards the end of matches (Bangsbo, Iaia, & Krustrup, 2007). There is also potential for players to experience residual fatigue during intense competitive schedules over the playing season. Research has shown that physical performance in professional soccer players was adversely affected across an intense period of three official games in 5 days (Odetoyinbo, Wooster, & Lane, 2008). Indeed, 96–120 h of rest are necessary for elite players to achieve pre-match values for sprint running performance as well as to normalize blood markers of muscle damage (creatine kinase) and inflammation (uric acid) (Ispirlidis et al., 2008).

Thus, while other factors such as changes in tactics, playing formation or score line may be linked to variations in the physical efforts of players during match-play, the evidence from motion analyses indicates that declines in physical performance are generally linked to match-related fatigue. Research has also investigated the relationship between variations in physical and skill-related performance in soccer as many game skills are performed in a

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fatigued state (Lyons, Al-Nakeeb, & Nevill, 2006). In junior soccer players, a decline in passing precision directly after completion of a 90-min game and after an isolated 5-min period of high-intensity exercise that simulated the most demanding phase of a match has been observed (Rampinini et al., 2008). Similar findings have been reported in adult semi-professional soccer players (Stone & Oliver, 2009). The speed and accuracy with which players completed soccer-specific skills were significantly affected after a 45-min period of intermittent shuttle running replicating one half of a soccer match. Finally, soccer skill performance measured by the time taken to complete a passing test, including penalty time accrued for inaccurate passing or poor control, declined during the final 15 min of exercise within a 90-min intermittent running test (Ali & Williams, 2009). Changes in arousal (Ali & Williams, 2009), decreased neuromuscular and cognitive function (Rampinini et al., 2008), glycogen depletion and dehydration (McGregor, Nicholas, Lakomy, & Williams, 1999) are possible candidate factors for impaired skill-related performance during and/or towards the end of such exercise.

Although these findings have provided useful information on variations in skill-related performance, the studies were frequently performed in controlled laboratory or field environments using simulated soccer activity and non-elite participants. In the only related study conducted during match-play, a concomitant decline in measures of physical and skill-related performance was observed in the second half of games (Rampinini, Impellizzeri, Castagna, Coutts, & Wisløff, 2009). From these results, the authors suggested that the onset of fatigue over the course of games in professional soccer players was accompanied by a drop in skill-related performance. However, no study has investigated whether the proficiency and frequency of soccer-specific skills in professional match-play (e.g. passing completion rates, frequency of possessions) are affected in the same way as physical performance towards the end of games, following short periods of intense physical activity, or when participating in several matches during a tight time-frame.

Consequently, the aim of this study was to determine whether declines in physical performance in professional soccer match-play are associated with a reduction in skill-related performance. With this in mind, we analysed data collected from computerized motion analyses and match analyses of physical performance and soccer-specific skills respectively. These data were subsequently used to explore the relationship between in- and end-game measures of physical and skill performance and those across multiple games within a short time-frame.

Methods

Participants and match sample

Physical and skill-related performance in official competition was analysed for players from a professional soccer team that competed in the French League 1 (highest standard in French soccer). While approval for the study was obtained from the club involved, these data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season (Winter & Maughan, 2009). Therefore, usual appropriate ethics committee clearance was not required. Nevertheless, to ensure team and player confidentiality, all performance data were anonymized before analysis.

Altogether, 35 French League 1 games and two UEFA Europa League games over three seasons (2007–2008, $n = 16$; 2008–2009, $n = 15$; 2009–2010, $n = 6$) were used for analysis. The sample included 25 home and 12 away matches in which players completed the entire match. Altogether, 60 observations of match performance were obtained with a median of nine games per player (range = 2–24). A total of 11 midfield players (central- and wide-players) were included in the analyses. Only midfielders (and those that played in their customary midfield role) were selected for analysis due to the continuous demands from both an attacking and defensive point of view that are placed on players in this position. In comparison, the main roles of defenders and forward players are to contribute to defending and attacking play respectively. Therefore, in these latter positions, game contributions and variations in performance across different time periods within matches will depend strongly on ball possession.

Data collection procedures and measures of competitive performance

A semi-automatic computerized player tracking system (AMISCO Pro®, Sport-Universal Process, Nice, France) was used to characterize match activity profiles in the team. This multiple-camera system passively tracks the movements of every player using a sampling rate of 10.0 Hz over the entire course of matches (Carling, Williams, & Reilly, 2005). An operator simultaneously codes each player action involving the ball and the decisions of the referee. Physical and skill-related performances from the raw data file were determined automatically by computerized analysis of player movements and actions using match-analysis software (AMISCO Viewer®, Sport-Universal Process, Nice, France). The workings, accuracy, and reliability of the AMISCO Pro® system in measuring player movements and coding game-specific events in elite soccer competition have been described in more detail elsewhere (Carling et al., 2008; Di Salvo et al., 2007; Randers et al., 2010; Zubillaga, Gorospe, Hernadez-Mendo, & Blanco-Villanesor, 2008).

The measures of performance selected for the analyses were classified into two categories:

1. *Physical performance*: Total distance covered, distance covered in high-speed running, and total distance covered in individual possession of the ball. All movements at speeds $\geq 14.4 \text{ km} \cdot \text{h}^{-1}$ were considered to be high-speed running (Abt & Lovell, 2009; Bradley et al., 2007; Gregson, Drust, Atkinson, & Salvo, 2010). The peak period of high-speed running distance represented the 5-min period that contained the most high-speed running in a match and was specific for each player profiled (Bradley et al., 2007; Mohr et al., 2003).
2. *Measures of skill-related performance* defined in the AMISCO® Pro system and coded internally by trained company match analysts included the total number of passes, percentage of completed or uncompleted passes, number of ball possessions and possessions gained or lost, number of touches per possession, number of duels and percentage of duels won or lost.

To investigate the relationship between physical and skill-related performance, measures of both were compared across 15- and 45-min intervals. Data collected in injury time or extra time were not included for analysis. This was done to facilitate comparison, as the duration of the respective match halves was never identical. End-game performance was also analysed by comparing distance covered in high-speed running and skill-related measures in the first 5-min period with those in the final 5-min period (85–90 min) and the mean 5-min period (mean of all periods minus first and final 5-min periods). In-game performance for the same data was compared between that observed during the peak 5-min period of high-speed running versus the subsequent 5-min period and the mean of all 5-min periods (minus peak and subsequent 5-min periods).

To examine the effects of playing multiple matches within a tight time-frame, physical and skill-related performances in midfield players ($n = 7$) who participated in a sequence of three successive games over a short time period ($\leq$7 days) were analysed. Of these players, four participated in one single sequence of three games while three players participated in two sequences of three games. The first match in the sequence generally took place on a Sunday, followed by the second on either Wednesday or Thursday, and the third on the following Sunday. All of these games were played in December during the 2009–2010 season. The variation in overall performance data collected over 90-min was compared between matches. In addition to the aforementioned skill-related variables, the total number of shots and percentage of shots on target were also compared across games.

Finally, measures of the time the ball was in play over the aforementioned match periods were included. This analysis was done to take into account the possible influence that the time the ball was in play might have had on variations in physical and skill-related performance.

Statistical analyses

All statistical analyses were conducted using SPSS for Windows Version 14.0 (SPSS Inc., Chicago, IL, USA). Results are reported as means and standard deviations (mean $\pm s$) unless otherwise stated. To investigate differences between match halves, Wilcoxon's signed rank test was performed. Friedman's repeated-measures analysis of variance on ranks test was used to assess differences in means in performance measures across separate time intervals. Follow-up univariate analyses using Tukey pairwise multiple comparison procedures were performed where appropriate. Statistical significance was set at $P < 0.05$. Confidence intervals (CI) for significant differences in means are reported. Effect sizes (ES) for statistical differences were also determined. Effect size values of 0.2, 0.5, and > 0.8 were considered to represent small, medium, and large differences respectively (Cohen, 1988).

Results

Physical performance

Players covered a greater total distance (5694 ± 287 m vs. 5432 ± 252 m, $P < 0.001$; mean difference = 262 m, CI = 162 to 362, ES = 1.1) and distance in high-speed running (1404 ± 252 m vs. 1273 ± 217 m, $P < 0.001$; mean difference = 131 m, CI = 54 to 208, ES = 0.6) in the first versus second half of games. In contrast, the distance covered in individual ball possession did not differ between halves (99 m vs. 96 m, $P = 0.973$).

A statistical difference was observed for the total distance run and distance covered in high-speed running (both $P < 0.001$) across 15-min intervals (Table I). A greater overall distance was covered in the first versus the fifth ($P < 0.05$; mean difference = 118 m, CI = 73 to 164) and sixth ($P < 0.05$; mean difference = 144 m, CI = 86 to 200) intervals. A greater overall distance was also covered in the second interval versus the fifth ($P < 0.05$; mean difference = 122 m, CI = 80 to 166) and sixth

Table I. Comparison of physical and skill-related performance across six 15-min match intervals in professional midfield soccer players (mean ± *s*).

	Interval 1 (I1) (0–15 min)	Interval 2 (I2) (16–30 min)	Interval 3 (I3) (31–45 min)	Interval 4 (I4) (46–60 min)	Interval 5 (I5) (61–75 min)	Interval 6 (I6) (76–90 min)	*P*-value	*Post hoc* difference ($P < 0.05$)
Physical performance								
Total distance (m)	1919 ± 125	1923 ± 124	1852 ± 156	1856 ± 124	1801 ± 118	1775 ± 158	$p<0.001$	I1 vs. I5 and I6; I2 vs. I5 and I6
High-speed distance (m)	468 ± 103	491 ± 105	444 ± 106	442 ± 105	420 ± 97	411 ± 88	$p<0.001$	I1 vs. I5 and I6; I2 vs. I5 and I6
Distance with ball (m)	30 ± 21	37 ± 27	31 ± 22	33 ± 20	31 ± 20	33 ± 25	P = 0.821	
Technical Performance								
Passes	7.1 ± 2.7	7.5 ± 3.5	7.3 ± 3.2	7.4 ± 3.7	6.8 ± 3.3	6.9 ± 3.8	P = 0.792	
Successful passes (%)	66.3 ± 21.2	70.6 ± 23.2	66.0 ± 21.7	66.4 ± 22.7	69.7 ± 23.6	70.2 ± 21.5	P = 0.640	
Possessions	8.3 ± 3.1	8.5 ± 3.8	8.6 ± 3.4	8.3 ± 4.0	7.8 ± 3.4	7.9 ± 4.0	P = 0.788	
Possessions gained	1.8 ± 1.5	1.8 ± 1.4	1.7 ± 1.3	1.7 ± 1.6	2.0 ± 1.4	1.6 ± 1.5	P = 0.670	
Possessions lost	2.4 ± 1.5	2.1 ± 1.5	2.8 ± 2.0	2.7 ± 2.0	2.5 ± 1.8	2.1 ± 1.6	P = 0.294	
Touches per possession	2.1 ± 0.7	2.2 ± 0.7	2.1 ± 0.5	2.0 ± 0.5	2.2 ± 0.7	2.2 ± 0.5	P = 0.619	
Duels	3.3 ± 2.0	2.5 ± 1.9	2.3 ± 1.7	3.0 ± 5.6	2.2 ± 1.5	2.3 ± 1.9	P = 0.106	
Duels won (%)	54.9 ± 30.3	52.9 ± 38.2	47.8 ± 37.5	53.0 ± 38.8	46.2 ± 34.0	48.2 ± 36.1	P = 0.831	
Time ball in play (s)	512.5 ± 62.4	485.8 ± 52.9	470.6 ± 52.2	486.3 ± 58.9	483.1 ± 62.1	474.6 ± 61.7	P = 0.097	

($P < 0.05$; mean difference = 148 m, CI = 95 to 207) intervals. Effect sizes ranged from 0.9 to 1.0 for these differences in total distance covered. In addition, a greater distance in high-speed running was covered in the first interval versus the fifth ($P < 0.05$; mean difference = 48 m, CI = 10 to 86) and sixth ($P < 0.05$; mean difference = 57 m, CI = 21 to 93) intervals. Similarly, more distance in high-speed running was covered in the second interval versus the fifth ($P < 0.05$; mean difference = 71 m, CI = 36 to 106) and sixth ($P < 0.05$; mean difference = 80 m, CI = 47 to 113) intervals. Effect sizes ranged from 0.5 to 1.0 for these statistical differences in high-speed running. Again, the distance covered in individual ball possession did not vary across 15-min intervals ($P = 0.821$).

Analysis of the distance covered in high-speed movement across three selected 5-min periods (first, final, mean of all other periods) revealed a significant difference ($P < 0.001$) (Table II). Players ran a greater distance in the first 5-min period versus both the final period (mean difference = 43 m, CI = 27 to 59) and mean of all other 5-min periods (mean difference = 37 m, CI = 24 to 50) ($P < 0.05$, ES = 0.9 and 1.9 respectively). Similarly, distance covered at high speed differed between the peak 5-min period, the following period, and the mean of all other periods ($P < 0.001$) (Table II). Efforts during the peak 5-min period were greater than those in the following 5-min period (mean difference = 99 m, CI = 89 to 109) and the mean of all other 5-min periods (mean difference = 103 m, CI = 96 to 110) ($P < 0.05$, ES = 2.2 and 4.2 respectively).

The analysis of physical performance when competing in three successive matches within a time frame of $\leq$7 days is presented in Table III. No differences across consecutive games were observed for the total distance run ($P = 0.385$), distance covered in high-speed running ($P = 0.249$) or that covered in individual possession ($P = 0.347$).

Skill-related performance

Analysis of all skill-related performance revealed no significant differences between match halves or 15-min intervals for any of variables. (Table I). Similarly, the time the ball was in play did not differ across halves or 15-min intervals.

Due to low numbers, the variables analysed across 5-min periods were restricted to total passes, completion rates in passing, and number of possessions and duels (Table II). Analysis of these factors showed a statistical difference across the three selected 5-min periods (first, final, and mean of all other periods) for total passes ($P = 0.010$), number of possessions ($P = 0.007$), and duels ($P = 0.016$). No difference was observed for completion rate in

Table II. Physical and skill-related performance across selected 5-min periods in matches in professional midfield soccer players (mean ± *s*).

End-game performance	First period (0–5 min)	Final period (86–90 min)	Mean of other 5-min periods*	*P*-value	*Post hoc* difference ($P < 0.05$)
High-speed distance (m)	182 ± 65	139 ± 50	145 ± 20	p < 0.001	1st period > Final and Mean
Passes	2.8 ± 1.7	2.1 ± 1.6	2.4 ± 0.6	p = 0.010	1st period and Mean > Final Period
Successful passes (%)	71.9 ± 33.8	69.4 ± 29.2	69.3 ± 13.0	p = 0.075	
Possessions	3.1 ± 1.8	2.4 ± 1.6	2.7 ± 0.7	p = 0.007	1st period and Mean > Final Period
Duels	1.1 ± 1.1	0.7 ± 0.9	0.7 ± 0.3	p = 0.016	1st period > Final period
Ball in play (s)	198.8 ± 32.2	175.3 ± 33.7	173.3 ± 13.1	p < 0.001	1st period > Final and Mean
In-game performance	**Peak 5-min period**	**5-min period following peak**	**Mean of other 5-min periods#**	***P*-value**	***Post hoc* difference ($P < 0.05$)**
High-speed distance (m)	242 ± 41	143 ± 45	139 ± 25	p < 0.001	Peak period > Following and Mean
Passes	2.5 ± 1.6	2.1 ± 1.6	2.3 ± 0.7	p = 0.117	
Successful passes (%)	72.0 ± 31.2	68.9 ± 38.3	69.3 ± 12.9	p = 0.242	
Possessions	2.9 ± 1.8	2.5 ± 1.8	2.7 ± 0.7	p = 0.279	
Duels	0.8 ± 0.9	0.6 ± 0.9	0.7 ± 0.3	p = 0.137	
Ball in play (s)	194.6 ± 34.9	174.9 ± 37.3	172.9 ± 14.0	p < 0.001	Peak period > Following and Mean

*Mean of 5-min periods: Mean of all 5-min periods minus first period in first half and final period in second half.
#Mean of 5-min periods: Mean of all 5-min periods minus peak and following period.

Table III. Comparison of physical and skill-related performance in professional midfield soccer players when competing in three successive matches within a time-frame of ≤7 days (mean ± *s*).

Performance across matches	Consecutive matches 1	2	3	*P*-value
Physical performance				
Total distance (m)	10494 ± 514	10949 ± 853	10795 ± 618	p = 0.385
High-speed distance (m)	2667 ± 200	2629 ± 398	2414 ± 145	p = 0.249
Distance with ball (m)	153 ± 41	210 ± 95	203 ± 68	p = 0.347
Technical performance				
Shots	2.0 ± 1.8	1.3 ± 1.2	2.5 ± 2.2	p = 0.565
Shots on target	66.1 ± 30.3	23.5 ± 20.8	25.2 ± 21.3	p = 0.086
Passes	41.7 ± 11.0	50.8 ± 22.4	52.3 ± 23.9	p = 0.723
Successful passes (%)	69.1 ± 14.0	77.5 ± 13.4	73.4 ± 16.5	p = 0.522
Possessions	47.3 ± 10.1	52.5 ± 26.2	56 ± 15.1	p = 0.441
Possessions gained	9.7 ± 3.4	9.0 ± 5.3	10.8 ± 5.6	p = 0.847
Possessions lost	13.7 ± 4.0	12.7 ± 6.9	13.8 ± 9.2	p = 0.860
Touches per possession	2.1 ± 0.3	2.2 ± 0.3	2.0 ± 0.3	p = 0.302
Duels	6.7 ± 2.9	5.7 ± 3.1	8.2 ± 3.8	p = 0.421
Duels won (%)	46.5 ± 26.7	31.8 ± 23.6	52.8 ± 22.0	p = 0.422

passing, although the result approached significance ($P = 0.075$). The time the ball was in play also varied across these three periods ($P < 0.001$). The frequency of passes performed in the first 5-min period (mean difference = 0.7, CI = 0.3 to 1.2) and for the mean of all other 5-min periods (mean difference = 0.4, CI = 0.1 to 0.8) was greater than that for the final 5-min period ($P < 0.05$; ES = 0.4 and 0.5 respectively). Similarly, the frequency of possessions in the first 5-min period (mean difference = 0.7, CI = 0.3 to 1.2) and for the mean of all other 5-min periods (mean difference = 0.3, CI = 0.1 to 0.6) was greater than that for the final 5-min period ($P < 0.05$; ES = 0.4 and 0.2 respectively). Finally, the frequency of duels was lower in the final 5-min period versus the first 5-min period (mean difference = 0.4, CI = 0.1 to 0.7) ($P < 0.05$; ES = 1.4). The time the ball was in play was greater in the first 5-min period than in the final 5-min period (mean difference = 24 s, CI = 14 to 34) and mean of all other 5-min periods (mean difference = 26 s, CI = 19 to 32) ($P < 0.05$; ES = 0.7 and 1.1 respectively).

No differences were observed for any of the skill-related measures during the period of peak intensity compared with the following 5-min period and for the mean of all other 5-min periods. In contrast, the time the ball was in play varied across the same periods ($P < 0.001$), with more play being observed during the peak period versus the following 5-min period (mean difference = 20 s, CI = 10 to 30) and the mean of all other 5-min periods (mean difference = 22 s, CI = 14 to 29) ($P < 0.05$; ES = 0.5 and 1.6).

The analysis of skill-related performance when competing in three successive matches within a time-frame of ≤7 days is presented in Table III. No differences across games were observed for any of the variables.

Discussion

In this study, computerized motion analysis was used to explore the effects of physical efforts on skill-related performance in professional soccer match-play. The major findings were that while a decline in physical performance was observed during the second half and the final third of games, this was not accompanied by a drop in skill-related performance. In addition, unlike high-speed running performance, skill-related measures were not affected in the 5-min period following the most intense 5-min period of high-speed exercise. In contrast, a reduction in the distance covered in high-speed exercise was accompanied by a drop in the frequency of some skill-related variables during the final 5 min of games. None of the physical or technical measures of performance were affected when competing in three successive matches within a short time-frame (≤7 days).

Resistance to fatigue is a key factor in the effectiveness of a player's ability to continually perform efficient and precise movements within soccer (Stone & Oliver, 2009). In the players in the present study, physical performance manifested by distance covered in high-speed running declined between halves and during the final third of matches. This finding is in agreement with the general consensus that fatigue accumulated throughout a match has a deleterious effect on end-game physical performance (Bradley et al., 2009; Mohr et al., 2003). Decrements in running performance in the latter stages of games have been linked to a depletion of muscle glycogen in individual muscle fibres (Reilly et al., 2008). However, the present observed decline in physical performance was not accompanied by a reduction in the frequency or proficiency of any of the skill-related performance measures. This result suggests that skill-related contributions of the present players in terms of technical actions and ball involvements were not affected by end-game fatigue. This observation is partly at odds with the results of a test of soccer skill in which passing performance declined during the final 15 min of exercise in a 90-min intermittent running simulation (Ali & Williams, 2009). The authors suggested a possible link with changes in arousal, which led to lapses in concentration. The discrepancy between these study findings may be due to the gross nature of the present measures and therefore a lack of sensitivity in detecting changes in skill performance compared with those investigated in controlled field and/or laboratory studies. In related research by Rampinini et al. (2009) on performance in professional Italian soccer match-play, there was a significant drop in the number of ball involvements in the second half although proficiency in technical actions (e.g. percentage of completed passes) was generally similar between halves. However, Rampinini et al. (2009) did not differentiate between playing positions, whereas the present study concentrated solely on midfield players, which may partly explain this discrepancy between findings. While a decline in physical performance in the present players was observed, the higher aerobic fitness generally observed in elite midfield players (Stølen, Chamari, Castagna, & Wisløff, 2005) may have offered them greater protection against a diminution in skill-related performance in the second half of matches, especially towards the end of play. Indeed, related research in junior soccer players has shown that fatigue-related decline in technical proficiency for a given intensity is closely associated with the fitness of the players (Rampinini et al., 2008). Furthermore, attenuated declines in passing performance were observed in soccer players who had undertaken a post-season period of aerobic interval training (Impellizzeri et al., 2008). Finally, another reasonable explanation may be that the present players employed an efficient pacing strategy to retain sufficient energy reserves to respond to match demands until the end of the game (Edwards & Noakes, 2009).

In contrast to the above findings on soccer-specific skills during the second half and final third of matches, the present players were observed to have significantly fewer involvements with the ball (number of passes, possessions and duels) during the final 5-min period of matches compared with the first 5-min period and the mean of all other 5-min periods. A concomitant reduction in high-speed running during the final 5 min was also observed in the present players, a result that is in accordance with the findings of a study on physical performance in players of the FA Premier League (Bradley et al., 2009). While proficiency in passing was unaffected, this result suggests that both physical performance and skill-related involvements of the present players were affected at the end of games. Local muscular fatigue and declines in cognitive function, strength, and endurance capacity have been suggested as possible reasons for decrements in skill-related performance towards the end of matches (Rampinini et al., 2009). Previous research has shown that the ingestion of a carbohydrate-electrolyte solution during exercise can help maintain soccer skill performance towards the end of a 90-min simulation of soccer activity (Ali & Williams, 2009). Such nutritional strategies may have positive implications in offsetting the effects of fatigue observed in the present players. However, caution is needed when comparing performance at the beginning and end of the present games, as the time the ball was in play in the first 5 min of play was significantly greater than that in the final 5-min period. This reduced duration may have led players not only to work less physically but also provided them with fewer opportunities to play the ball compared with at the beginning of matches.

Research in elite soccer match-play has shown that the amount of high-speed running decreases significantly after the most intense periods of exercise (Mohr et al., 2003). Analysis of high-speed running performance in the present group of players confirms this trend and suggests that they experienced transient fatigue in match-play. This temporary fatigue after periods of intense exercise in match-play may be related to disturbances in muscle ion homeostasis and an impaired excitation of the sarcolemma (Mohr et al., 2005). However, caution is once again needed, as the time the ball was in play during the 5-min period in which the most high-speed activity occurred was significantly longer than in the subsequent 5-min period. Therefore, this temporary reduction in physical performance may be linked not only to the occurrence of transient fatigue but also to reduced playing opportunities as the ball was more often out of play.

In contrast to physical efforts, skill-related performance (frequency and proficiency) was not affected after an intense 5-min period of physical activity compared with during an average 5-min period over games, although the time the ball was in play was lower for this 5-min period. This result suggests that an intense 5-min period of physical activity did not affect the frequency of game involvements or proficiency in various skills during the subsequent 5-min period. This finding is in contrast to that observed by Rampinini et al. (2008), in that a simulation of a typical 5-min phase of high-intensity running performed by young soccer players significantly affected subsequent passing proficiency. Similarly, work by McMorris and Rayment (2007) in semi-professional soccer players showed that short-duration, intermittent bouts of high-intensity activity had a negative effect on passing accuracy. Again, caution is required when interpreting the present results, as only gross measures of skill-related actions (e.g. number and completion rate of passes) were examined. More appropriate methods may be needed to accurately control and detect changes in skill (e.g. modified neuromuscular and cognitive function) in individual players within the context of a match. However, the present results suggest that there is a large disparity between controlled methods for testing decrements in skill-related performance actions and the actual requirements of match-play. This lack of a decline in performance may also be linked to the time interval between the end of the peak period of intense activity and the performing of subsequent game skills. The effects of fatigue on soccer skills from high-intensity exercise are immediate but these effects dissipate very quickly (within 2 min) following cessation of exercise (Lyons et al., 2006). Therefore, in future work, it would be worthwhile examining the frequency of and/or proficiency in skill-related actions that fall within the first 2 min following the most intense 5-min period of high-speed activity.

Previous research using motion-analysis techniques has reported a substantial but non-significant drop in the high-speed efforts of FA Premier League professional soccer players when competing in the final game compared with the first game during an intense competitive schedule of three games over a 5-day period (Odetoyinbo et al., 2008). A similar finding was observed in the present study, as the distance covered in high-speed running did not vary significantly across a dense competitive schedule of three games in $\leq$7 days. Nevertheless, the distances covered at high speeds by the present players dropped in the final versus the first game but to a lesser extent than in the FA Premier League players (-9.5% vs. -13.5%). The slightly longer interval between matches in the present study may have provided the players with more time to recover thereby reducing the effects of residual fatigue on physical performance.

This decline albeit non-significant in physical performance was generally not accompanied by a drop in skill-related performance across successive matches. Somewhat surprisingly, improvements were observed in the proficiency and frequency of which some skill measures were performed in the final match. While the reason for this discrepancy is unclear, the interval between games may have sufficed for full recovery thereby reducing the possibility for residual fatigue to affect skill-related performance. The use of evidence-based post-match recovery procedures recently described by Dupont et al. (2010) at the present club may also partly explain the lack of a significant drop observed between games for the match-related measures of physical and skill-related performance. Further research on physical and skill-related performance during a tighter time-frame (e.g. $\leq$5days) may be merited. In addition, the physical and skill demands imposed by differing opposition over the three games may have influenced the performance of the present team and merit inclusion in a future study.

Indeed, comprehensive research in Italian professional soccer has identified a strong link between physical and technical performance of teams and the quality of opposition (Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007; Rampinini et al., 2009).

The limitations of this study included the relatively low number of players included for analysis ($n = 11$) and that they all played for the same club. Therefore, the patterns observed might be a reflection of this particular team only and a larger and wider sample size is recommended. In addition, a larger sample size could allow for analysis of more skill-related variables. For example, the effects of temporary and end-game fatigue on completion rates in making passes of varying length and direction may be useful. In addition, analysis of the context of the skill-related measures examined in this study may be necessary. For example, variations in proficiency observed in technical actions such as passing or shooting may frequently be linked to the game situation (e.g. more intense pressure on a ball-carrier in deep attacking positions). In addition, these results raise questions about the definition and analysis of "skill" and whether this is simply the pure technical ability to make a pass or a context-specific match quality that encompasses both pure technical ability and the capacity to use that technique within ever-evolving game and pressure situations. Future ecologically sound studies are needed to examine the effects of soccer-specific fatigue on the performance of different skills during matches using tests that demonstrate high reliability and good ecological validity (Lyons et al., 2006). Furthermore, the in-game variations in performance may have been either under- or over-estimated, as pre-defined 5-min periods (e.g. 0–5 min, 5–10 min) were used in this study. Further research to identify peak periods of high-speed activity and their subsequent effect on skill performance is merited. Finally, as the analyses were completed on players during competitive matches, the present results may simply reflect the interaction between all the players involved in the games (Carling et al., 2005; Rampinini et al., 2009).

In conclusion, this study has presented for the first time the association between physical and skill-related performance in professional soccer match-play. Results show a drop in skill-related involvements during the final 5 min of games probably as a consequence of fatigue manifested by a decline in high-speed work. In contrast, a decline in physical performance between halves and in the final 15 min of games did not lead to a reduction in either skill-related involvements or proficiency. Similarly, neither physical nor skill-related performance declined across multiple games within a tight time-frame. It is hoped that the present findings will broaden the body of research on fatigue in elite soccer match-play as well as informing the development of preparation strategies to aid players in maintaining performance in soccer-specific skills throughout a game by helping them to become better accustomed to cope with the demands of the game. Further research is nevertheless warranted to address other factors that may have influenced performance, such as the effects of score line, changes in tactics or playing formation, and standard of opposition.

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Appendix 2d: Copy of Paper 5, Carling, C., Le Gall F., & Reilly, T. (2010). Effects of physical efforts on injury in elite soccer. *International Journal of Sports Medicine, 31*, 181-185.

Effects of Physical Efforts on Injury in Elite Soccer

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- injuries
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- football incident analysis
- fatigue

Abstract

In this study, the influence of physical efforts on occurrence of match injury in a professional soccer club was investigated. Computerised motion-analysis was used to measure the physical efforts of players during 10 injury situations. Total distance and those covered at different movement intensities were measured across the 5-min period preceding injury. If the final run preceding injury involved a high-intensity action (HIA), the distance, duration and speed of the effort and the recovery time between this and the penultimate HIA were measured. To determine the influence of these physical efforts, the results were compared to a normative profile for players computed from data across 5 games for the same variables; habitual distances covered over a 5-min period and characteristics of and recovery time between HIA. Compared to the normative profile, no differences were reported in physical characteristics during the period leading up to injury or for HIA although the latter were substantially higher in intensity (duration and distance). A lower than normal recovery time between HIA prior to injury was observed (35.6 ± 16.8 s vs. 98.8 ± 17.5 s, $p = 0.003$). Within the limitations of the small sample, these findings may aid in further understanding injury and physical performance in elite soccer.

Introduction

Soccer (Association Football) is a complex contact sport with high physical, technical, tactical, and physiological demands at the elite level [10], and the risk of injury is considerable [26]. In order to suggest preventive strategies specific to soccer, it is necessary to have detailed information on the injury mechanisms involved. Previously, analysis of soccer incidents that combines game-specific and medical information has been employed to describe how injuries and high-risk situations of injury occur in match-play [1–3, 5, 23]. Examination of the playing situation, athlete-opponent interaction, and refereeing has highlighted the importance of tackling duels and heading duels as high risk situations. In addition, a critical incident technique was designed to identify behaviour with potential injury risk [32]; the findings emphasised tackling, receiving a tackle and charging an opponent as the circumstances with the highest injury potential.

A precise description of the inciting event is a key component in understanding the causes of injuries in sport [7]. In soccer, there is a need to investigate the effects of the physical efforts of players on the occurrence of injury [9]. The physical demands of match-play can now be easily and accurately investigated via information collected using computerised motion-analyses of player movements. Yet, to date, the effects of movement intensity when injuries are incurred has received scant attention. Furthermore, in the studies that have touched on this area [1–3, 5], movement intensities were recorded subjectively and no comprehensive data were provided on specific running characteristics such as starting, average or maximal running speed or on the length or duration of actions. Similarly, no study has examined the possible effects of physical efforts prior to the injury situation. Related research by Rahnama et al. [32] reported an increase in critical incidents and injury risk in the first 15-min and in the last 15-min compared to other periods of the game. The presumption was that injury risk was associated to the periods in which exercise intensity was highest when players were fresh and lowest when players experience fatigue during the game, but there were no measurements of players' movements recorded. As play-

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ers commonly experience transient fatigue in match-play notably after periods of intense exercise [8,28], motion analysis techniques could be used to determine whether greater than usual periods of intense exercise or inadequate recovery time between high-intensity efforts predispose a player to injury [9,10].

Therefore, the aim of this investigation in an elite soccer club was to examine the physical efforts of players in the period leading up to and for the final running action in occurrences of injury in professional match-play.

Methods

In the present study, injuries sustained during competitive matches (a total of 54 League matches from mid-season 2007–2008 to end of season 2008–2009) in players belonging to a 1st Division French League Club had been prospectively diagnosed and documented by the team's physician in a sports injury database (TeamSanté, Enora Technologies, Paris, France). Player consent and local ethics committee approval were obtained.

The methodologies and definitions of injury used in the present study closely follow those recommended by International Soccer Injury Consensus Groups [16,22]. A total of 47 injuries forcing a layoff of over 48 hours not including the day of injury [24,29] were available for analysis. Information including the type, location and cause of injury and the match period during which each injury occurred (matches were divided into six 15-min periods, i.e., 0–15-min, 15–30-min and 30–45-min for each respective half) was available. Also stored in the database was information on whether the player was forced to leave the field due to injury and the total number of days the player could not participate fully in training and competition. This latter number was used to calculate the severity of injury [16]. The severity of each injury was defined as slight, minor, moderate, or major depending on whether the player was absent from training or competition for two to three days, four to seven days, one to four weeks, or more than four weeks, respectively [24,29]. Finally, descriptive information on the final action at the time the injury was sustained and whether contact had occurred between players was recorded.

The occurrence of injuries in soccer match-play cannot always be clearly identified on video recordings [27]. Often there is no stoppage in play and players do not go down on the pitch to receive treatment and are subsequently substituted at half-time or receive treatment after the match [1]. Therefore, only injuries that had forced the player to immediately leave and not return to the field of play were included for investigation. This process also helped avoid the inclusion of situations where players intentionally lay down either to rest, feign injury or delay playing time [17]. To reduce the effects of opposition behaviour, only injury incidents where no foul-play was observed (decision by referee to award a free-kick) were considered. These strict inclusion criteria limited the total number of injuries to 17 (36.2 % of the total injury sample obtained over the two seasons).

After retrospective review of the medical records by the same club physician who had diagnosed the injuries, each injury incident was cross-referenced to determine whether the match had been recorded and analysed by the multiple-camera player tracking system (AMISCO Pro, Sport-Universal Process, Nice, France) used by the club to evaluate physical, technical and tactical performance in competition. A validation of this system has demonstrated high-levels of validity, accuracy and reliability in measuring player movements in elite soccer play [41]. If information from the system was available, the physical performance data were then used to measure the efforts of players over 5-min leading up to and during the injury situation. To obtain the time of injury, the club physician and the injured player reviewed the digital video recording of the injury incident and the time corresponding to the incident was obtained from the digital time code. Altogether, data were available for a total of 10 of the injuries (21.3 % of the total injury sample).

To investigate the effects of physical performance prior to injury, the total distance and distance covered in four categories of movement intensity were measured over the 5-min period preceding the time of injury: 0–11 km/h (walking, jogging or WJ); 11.1–14 km/h (low-intensity running or LI); 14.1–19 km/h (moderate-intensity running or MI); >19.1 km/h (high-intensity running or HI) [11]. To determine whether performance over this 5-min period may have influenced injury, data across five completed matches were used in an attempt to establish a normative physical performance profile for each player [11,12]. For this profile, the total distance covered in each category of movement intensity was calculated for entire games. To calculate the distance covered over a 5-min period, the total distance covered was divided by the match duration (in minutes) and then multiplied by 5. This figure was considered to be the player's habitual match-play activity level over a 5-min period. The physical performance data used for the normative profile were based on information during the same season in which the injury occurred. The normative profile was subsequently compared to the physical efforts over the 5-min period prior to injury.

The characteristics of the final running action in each injury situation were investigated. The starting and maximal running speed of actions and speed at time of injury were documented as were the duration, distance covered and average speed of the movement.

It has been suggested that players may be more at risk of incurring injury during HI activities [9]. If the player reached a speed >19.1 km/h for a minimum of 1 s duration at any time during the final running action, then the effort was considered to be a high-intensity run. Therefore, those injuries that had been identified as occurring during a HI exercise bout were investigated to determine whether the characteristics of these running actions differed from the player's habitual HI profile for this form of game activity. For this purpose, a normative profile was created for the speed, distance and duration of HI actions for five 90-min games for each player and in which the player did not incur an injury. This result was compared to the same data obtained from each individual injury action.

Finally, to determine whether recovery time may have played a part in injury, the time between the penultimate HI effort and the HI action leading to injury was determined. Again, this result was compared to a normative profile for each player created from the calculation of the average recovery time between HI actions over five full games.

Statistical analyses of the dataset were performed using paired t-tests to test for differences in physical activity profiles prior to and during the injury situation and those obtained from the normative profiling of the same player's performances. The level of accepted statistical significance was set at $p<0.05$. To control the Type-I error rate observed in multiple measures of physical performance in competitive soccer, a pseudo-Bonferroni's adjustment is used through dividing the alpha level by the number of categories in which objective measures of physical performance are classified [12,35,36]. In this case, the three normative profiles were utilised to compare performance: physical efforts over a 5-min period, characteristics of HI actions and recovery time between bouts of HI exercise. Thus, an operational alpha level of 0.017 ($p<0.05/3$) was used. Effect sizes for these differences were also determined. Effect size values (using Hedge's adjustment for small sample sizes) of 0.2, 0.5 and above 0.8 were considered to represent small, intermediate and large differences, respectively (13).

Results

Information on the characteristics of injuries and the final running action in each injury situation is reported in **Table 1**.
Out of the 10 injuries, 60% were diagnosed as sprains while strains (20%), bruising (10%) and a combined fracture/dislocation (10%) were also recorded. Injuries to the ankle region were more common (50%) while the upper leg (30%) knee (20%) were also affected. Altogether, 80% of injuries were considered to be of moderate severity while the remaining part (20%) was classed as major injuries. Finally, only two injuries (20%) were sustained in the second half and a greater proportion of injuries (60%) involved physical contact between players.
The starting speed in all but one action was observed to be at low exercise intensity. Altogether, 8 out of 10 of the final running efforts before the injury was incurred involved a HI run (>19.1 km/h) and the average speed of movement of these final actions was within the moderate-intensity range (~17 km/h). In a third of the movements (33.3%), the speed at the time the injury was sustained corresponded to moderate intensity.
The total distance and the distance covered at different intensities of movement in the 5-min prior to injury compared to the habitual physical performance profile of players are presented in **Table 2**. The lack of significant differences reported for any of these measures of physical performance were accompanied by insignificant to intermediate effect size differences. However, players covered around a third more distance (35%) at high running intensities before sustaining an injury compared to typical performance over a 5-min period.
Also presented in **Table 2** is information on the average speed, length, duration and recovery time of the eight HI actions that led to injury compared to the habitual characteristics of HI efforts in the same players. While no significant differences were obtained, results showed that these final HI actions leading to injury were almost double the length and duration of usual actions. These differences in action length and duration were accompanied by intermediate effect sizes (>0.5). In contrast, the recovery time between the penultimate HI effort and the HI action leading to injury was shown to be significantly shorter compared to the habitual recovery time between HI bouts ($p=0.003$). This difference was accompanied by a large effect size (>0.8).

Discussion

The aim of this first study was to analyse the physical performance of elite soccer players in competition prior to and during actions leading to injury using motion analyses. Within the limitations of the small sample, the running actions in the injury cases indicated that at the time of injury, players were generally moving at moderate speeds after having started their final run at low speeds before attaining high intensities and then reducing speed. Analysis of the characteristics of high-intensity bouts in the injury situation showed that these actions were greater in both distance and duration, albeit non-significantly, compared to the player's usual efforts. While the players' overall efforts in the 5-min period leading up to injury did not seem to play a direct part in the injury, a significantly lower than normal recovery time between high-intensity actions prior to sustaining injury was observed.
A large proportion of injuries sustained in professional soccer players are sustained during running actions [24] but little is known about the characteristics of these movements. In the present study, analysis of the running actions in the match injury situation showed these involved relatively high movement speeds (~17 km/h). Review of the injury situations showed that games skills, physical contact and injury avoidance behaviours were also superimposed on the locomotor activities leading to injury. The majority of the final running actions initially involved an acceleration phase from low to high running intensities, attaining speeds of over 23 km/h (for example to create space or close a player down), before the player decelerated to moderate speeds (generally when attempting to gain possession) at which the injury occurred. These acceleration and deceleration characteristics of running actions are highly common to the game of soccer. In the latter, impairments in the eccentric muscle contractions involved in such phases may be linked to an increased risk of joint and muscle injury [21]. Indeed, a recent review on soccer performance has identified a need for specific deceleration exercises in strength and conditioning training sessions [9] which could have some relevance for preventing some of the injuries identified in this and other reports [24,29,40] on soccer match-play.
In elite soccer match-play, high-intensity actions are rarely more than 20 metres in length and greater than 4 s in duration [14,18]. The present results from the normative analysis of player performance confirm this trend. While no significant differences were reported in distance or duration for the high-intensity run that led to injury, values for these measures were almost twice that of the normative profile. This finding suggests that players may be more at risk of injury when subjected to high-intensity bouts of exercise that are greater than usual in intensity. This observation could have important implications for the design of high-intensity running regimens. However, in the majority of the high-intensity actions that led to injury, players were in situations where they were challenging for possession. Further work combining injury and physical performance data is needed to examine whether the risk of injury is greater in situations where the player is tackling or being tackled which simply happen to be accompanied by high-intensity activities.
The physical efforts in the five minutes prior to the injury situation did not seem to play a role in causing injury. While players covered a slightly higher overall distance (+4%) than they would during a typical five-minute period of play, this result was not significant implying that fatigue was not a contributing factor to injury. However, the players had covered 35% more distance at high-intensities than usual before sustaining injury. Previous research in soccer match-play has shown that sprint performance is significantly reduced after the most intense periods of exercise indicating that players experience temporary fatigue [9,28,30]. The present players may have been experiencing

Table 1 Descriptive characteristics of injuries and movement data for the final running action leading to the injury.

	Injury			Layoff time	Speed (km/h)				Duration	Length	In ball	Contact	Qualitative description of game incident
Position	**Type**	**Location**	**Time in match**		**Start**	**At injury**	**Maximal**	**Average**	**(s)**	**(m)**	**Possession**		
defender	sprain	ankle	73rd min	> 1 month	0.6	8.0	12.1	9.0	1.6	4.0	no	no	run then jump to head ball and injured when taking off
defender	sprain	ankle	36th min	1–4 weeks	12.7	17.5	19.2	18.0	2.0	10.0	no	yes	run to intercept ball and injured during challenge for possession
defender	sprain	knee	7th min	1–4 weeks	8.0	16.4	23.7	18.6	8.8	45.5	no	no	run to close down opposition player followed by turn and injured during ensuing run
defender	sprain	knee	85th min	1–4 weeks	5.3	11.7	21.2	18.0	2.0	10.0	no	yes	run to intercept ball and injured during landing after challenge for possession
defender	sprain	ankle	7th min	1–4 weeks	10.9	11.0	11.3	11.0	2.5	11.0	no	yes	run to cover space and injured while challenging for possession
defender	strain	groin	32nd min	1–4 weeks	1.8	16.9	30.0	20.9	11.4	66.4	no	no	run to meet pass and injured when controlling ball
centre-forward	sracture/ dislocation	ankle/ lower leg	25th min	> 1 month	5.0	12.8	22.0	16.1	5.6	25.1	no	yes	run to close down opposition player followed by turn and injured during ensuing tackle
centre-forward	bruising/ hematoma	thigh	24th min	1–4 weeks	5.4	9.4	26.6	21.2	11.0	64.7	no	yes	run to meet pass and injured during challenge for possession
centre-forward	sprain	ankle	16th min	1–4 weeks	9.2	19.3	30.2	16.9	5.1	24.0	no	yes	run into space and injured during challenge for possession
centre-forward	strain	hamstring	23rd min	1–4 weeks	2.9	18.7	22.4	16.2	6.5	29.2	yes	no	run into space to collect possession and injured when passing
Mean ± SD					6.2 ± 4.0	14.2 ± 4.2	23.0 ± 6.5	16.6 ± 3.8	5.7 ± 3.7	29.0 ± 22.7			

Mean ± SD.

Table 2 Comparison between the players' normative physical performance profile over a typical 5-min game period and the 5-min period leading up to the injury; and comparison between the normative physical performance profile for a typical high-intensity action and the high-intensity action during which injury occurred.

	Normative	Injury Action	Mean difference	Effect Size
distance covered in 5-min period leading to injury (m)				
total	569.2 ± 28.2	594.5 ± 88.3	25.3 ± 84.8	0.36
high-intensity	44.2 ± 11.2	67.0 ± 57.3	22.8 ± 61.9	0.53
moderate-intensity	82.0 ± 14.0	84.8 ± 45.5	2.8 ± 47.3	0.06
low-intensity	81.7 ± 15.2	87.1 ± 31.4	5.4 ± 30.6	0.19
walking/jogging	361.4 ± 6.0	355.6 ± 59.9	−5.8 ± 59.9	0.08
characteristics of final high-intensity runs leading to injury (n = 8)				
length (m)	15.7 ± 0.4	27.6 ± 18.7	10.9 ± 18.8	0.71
duration (s)	2.5 ± 0.1	4.2 ± 2.7	1.7 ± 2.7	0.50
speed (km/h)	22.2 ± 0.2	22.0 ± 1.7	−0.2 ± 1.8	0.00
recovery time after previous high-intensity run (s)	98.8 ± 17.5*	35.6 ± 16.8	−63.2 ± 26.6	3.50

* Significantly greater recovery time (p = 0.003)
Mean ± SD

some degree of fatigue due to their increased efforts notably at high-intensities thereby affecting their capacity to perform maximally during the injury action.

These findings are supported by a significantly shorter than usual recovery time (~36 s vs. ~99 s in typical performance) observed between the penultimate high-intensity action and the one that led to injury. During multiple sprint work, fatigue is manifested as a progressive decline in functional performance, the magnitude of which is largely determined by the duration of the intervening recovery periods [18]. Therefore, at the time of injury, the present players may have experienced transient fatigue due to incomplete recovery between high-intensity bouts increasing their susceptibility to injury. This reduction could have affected functional performance in areas such as proprioceptive ability [37], dynamic joint stability [25], force production [4], neuromuscular responses [19] or running mechanics [38]. However, caution is required when interpreting these results as to the validity of the method employed for determining a normative profile for each player over a 5-min period. The work-rate pattern in soccer is random, can vary greatly across match periods and between games and depends on many factors such as scoreline or opposition standard. Nevertheless, researchers should be encouraged on the basis of the present study design and results to explore other means for creating a normative profile for work rate over pre-defined match periods.

These results may have important implications for the design of conditioning regimes to improve the player's fitness in an attempt to reduce the risk of injury. For example, high-intensity fitness training in soccer traditionally aims to improve the player's ability to recover quickly following successive bouts of high-intensity anaerobic efforts. This effect is achieved through an increased aerobic response, improved lactate removal, and enhanced phosphocreatine regeneration [18]. Specific high-intensity training regimens are traditionally based on work-rest ratios involving the repetition of runs over a set distance and with fixed recovery times [15]. However, the intensity of actions and recovery periods can alternate at any time according to the demands of the match which was the case during the injury incidents reported in this study. Therefore, to optimise player fitness and reduce the chance of injury, practitioners could consider constructing high-intensity training programmes on the repetition of runs that vary in both intensity (duration, distance) and in recovery time.

These preliminary findings may also be pertinent for constructing exercise protocols to simulate the exercise intensities experienced during match-play to investigate the effects of fatigue on injury risk in muscle and joints. Previous experiments have successfully used soccer-specific exercise within the laboratory setting [20, 21, 31, 33, 34, 39] to monitor changes in performance. However, these protocols tend to measure fatigue after fixed durations (e.g., start, middle and end of exercise) and use a 90-min exercise period divided into 15-min normative activity profiles that are identical in terms of intensity. These exercise protocols therefore do not represent the random nature of activity in soccer and on the basis of the present findings; we suggest that future research using such protocols should also investigate impairments in performance after periods of higher than average exercise intensity.

A major limitation of this study was the small number of injury cases examined. In studies of risk factors for sports injuries, a minimum of 20–50 injury cases is recommended [6]. It is inevitable though through comparisons with the low sample sizes obtained in other studies [2, 4], that identifying large numbers of real time-loss injuries on video during elite soccer competition is difficult. This limitation of the low sample size is partly countered by the strict injury inclusion criteria combined with the simultaneous access to medical information from team medical staff resulting in a less biased description of how soccer injuries occur [3]. A further limitation was the cohort included players from only one soccer club (as detailed medical information on opposition injuries and physical performance was not available) and the patterns observed may only be a reflection of this particular team. Furthermore, the proportion of injury types (for example, 60 % of injuries were sprains) investigated may not fully represent the patterns of injury habitually reported in elite soccer match-play [24, 40]. Investigations involving a substantially larger sample of clubs and injury cases are therefore warranted. However, obtaining confidential information and in sufficient quantities on both physical performance and player injury during match-play from elite clubs is difficult. Similarly, no single research approach to identifying the reasons for injury is adequate in terms of completeness of information provided and it is necessary to combine a number of different approaches to describe the mechanisms fully [27]. For example, the impact of extrinsic factors such as the playing situation, game context and opponent behaviour could have affected the present findings. Nevertheless, important practical insights can be gained from studying the events preceding injury and this first investigation is a first step in identifying and understanding the relationship between physical performance and injury in elite soccer competition. It is hoped that similar research on injury data will be done in other professional clubs and associations to build upon the present findings by exploring some of the gaps and questions identified in this report.

Conclusions
▼
The physical demands of contemporary professional soccer match-play are high and players are subjected to fatigue and risk of injury. The present study is the first to have shown that information on physical performance obtained from motion analyses of match-play may be valuable in increasing knowledge about the events involved in the occurrence of injury. These preliminary findings suggest that when there is inadequate time for recovery between high-intensity exercise bouts and the distance and duration of these actions are substantially higher than usual, players may be at increased risk of sustaining injury. Also, analysis of injuries showed that running actions involved both an acceleration phase to achieve high speeds as well as a deceleration phase during which injuries were sustained. Whilst further research is evidently necessary, the findings from this and future studies may eventually be employed in injury prevention strategies by informing the prescription of specific fitness training protocols.

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Appendix 3: Study theme 2, Factors potentially affecting physical performance.

Appendix 3a: Copy of Paper 6, Carling, C., & Bloomfield, J. (2010). The effect of an early dismissal on player work-rate in a professional soccer match. *Journal of Science & Medicine in Sport*, *13*, 126-128.

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Original paper

The effect of an early dismissal on player work-rate in a professional soccer match

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Abstract

The aim of this study was to examine the effects of an early dismissal (after 5-min play) on work-rate in a professional soccer match. A computerised player tracking system was used to assess the work-rates of seven players who completed the match on a team with 10 players. A minute-by-minute analysis of the remaining 91 min following the dismissal was performed for the total distance covered, the distance covered in five categories of movement intensity and the recovery time between high-intensity efforts for each player. The data were calculated for each half and for three equal intervals within each half and profiled against normative data for the same players obtained from the analysis of 15 games in the same season. Following the dismissal, the players covered a greater total distance than normal ($p < 0.025$), particularly in moderate-intensity activities ($p < 0.01$) and had shorter recovery times between high-intensity efforts ($p < 0.025$). In contrast, there was a significant reduction between game halves for total distance covered at both the highest ($p < 0.025$) and lowest running intensities ($p < 0.01$). However, there were no differences in high-intensity activities across the three intervals in the second-half. These findings suggest that in 11 vs. 11, players may not always utilise their full physical potential as this match illustrated an increase in overall work-rate when reduced to 10 players. However, as a team with 10 players is likely to incur higher levels of fatigue, tactical alterations may be necessary and/or players may adopt a pacing strategy to endure the remainder of the match.

Keywords: Fatigue; Football; Performance; Locomotor activity; Sprinting

1. Introduction

A thorough understanding of the physical demands of elite soccer via information on work-rates is required so that optimal training and preparation strategies can be constructed to respond to the demands of match-play. Recently, research on elite soccer has furthered our understanding of the fitness requirements and position-specific work-rate profiles of players[1] as well as identifying the occurrence of a reduced work-rate notably in the later stages of match-play.[2]

While this research has important practical implications, a recent review on motion-analysis studies in soccer[3] has identified several areas that require further exploration and especially the impact of dismissals on work-rate. Consequently, this case-study aims to explore the effects of an early dismissal on work-rate in a professional soccer match.

2. Methods

A multiple-camera player tracking system (AMISCO Pro, Sport-Universal Process, Nice, France) was used to record work-rates in 1st Division French League Games during the 2007/2008 season. In one match, an individual player belonging to the away team was dismissed after 5-min play. This provided a rare opportunity to analyse the work-rate in a team reduced to 10 players for over 90 min as there were 41 remaining minutes of the first-half and 50 min were played in the second-half. A total of seven outfield players (three defenders and four midfielders) from the away side who completed the entire game were included for analysis to establish a dismissal match work-rate profile (DWP).

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The objective measures of work-rate performance selected for the analyses were classified into two categories: (1) match distances covered including the total distance and distance covered in five categories of movement intensity[1]: 0–11 km/h (walking/jogging); 11.1–14 km/h (low intensity); 14.1–19 km/h (moderate intensity); 19.1–23 km/h (high intensity) and >23.1 km/h (sprinting). The absolute data were corrected to a minute-by-minute analysis of the distance covered to enable equal comparison of performance between the halves (as these were of differing duration) and three equally divided intervals in each half. (2) The average time spent in recovery between sprinting and high-intensity actions for each half.[3]

The DWP was then profiled against a normative data profile (NWP) for the same players during 15 matches randomly chosen from the start, middle and end of the season to explore any differences as a result of the sending-off. The sample included 10 home and 5 away matches in which the players completed the full match.

Statistical analyses (SPSS Science Inc, Chicago, IL) were performed using paired *t*-tests to test for differences between game profiles and compare playing halves. One-way repeated-measures analysis of variance tests with Bonferroni's post-hoc tests were conducted to isolate any differences between intervals across each half. A pseudo-Bonferroni's adjustment was applied according to previously outlined procedures for objective measures of work-rate.[4] Thus, an operational alpha level of 0.025 ($p < 0.05/2$) was used.

3. Results

Overall, the DWP for the seven players on this occasion was higher than the NWP. This result was observed through a greater total distance covered ($p < 0.025$), particularly in the first-half ($p < 0.025$), and throughout the match with more moderate-intensity activity ($p < 0.01$) and shorter recovery times between high-intensity efforts ($p < 0.025$). In the second-half, the distance covered at moderate intensities was higher in the DWP ($p < 0.025$) whereas distance covered in the walking/jogging category was higher in the NWP ($p < 0.025$).

One similarity observed across both profiles was that the total distance covered in the second-half was lower than in the first-half in both the NWP ($p < 0.025$) and DWP ($p < 0.01$). In the NWP this was due to a decrease in low-intensity activity ($p < 0.025$) whereas in the DWP, the distance covered in sprinting ($p < 0.025$) and walking/jogging ($p < 0.01$) was reduced in the second-half. While further analysis of the DWP across the three intervals of the second-half showed a difference ($p < 0.01$) in both total distance covered and walking/jogging with work-rate significantly dropping in the final interval, no significant difference was observed across intervals in distance covered at high intensities (Table 1).

4. Discussion

In this relatively unique match, there are two major findings that merit discussion. First, the result showing a higher work-rate of players during the game in which the dismissal occurred compared to their habitual performances recorded over a series of matches. This finding, albeit only from one match, suggests that elite soccer players may not always utilise their full potential and partly confirms previous speculation[3] that work-rate is self-chosen. In this match,

Table 1
Comparison of work-rate in elite soccer players across three intervals in the first- and second-half after a player was dismissed 5 min into the match (mean ± S.D.).

Distance run (m)	1st period	2nd period	3rd period	Significance	Post-hoc
Total					
1st half	126.8 ± 6.1	127.6 ± 8.1	121.7 ± 3.9	$p = .063$	
2nd half	123.1 ± 4.7	124.0 ± 6.0	115.8 ± 9.9	$p = .003$	3 < 1, 2
Sprint					
1st half	6.0 ± 3.8	4.5 ± 4.0	3.8 ± 3.5	$p = .503$	
2nd half	2.5 ± 0.9	1.4 ± 1.2	3.3 ± 3.2	$p = .267$	
High intensity					
1st half	7.0 ± 2.3	7.1 ± 2.1	7.6 ± 3.0	$p = .664$	
2nd half	6.7 ± 3.1	6.3 ± 2.0	6.6 ± 3.6	$p = .876$	
Moderate intensity					
1st half	25.4 ± 6.8	21.4 ± 3.8	19.6 ± 6.3	$p = .157$	
2nd half	23.5 ± 5.2	24.3 ± 4.0	22,8 ± 9.0	$p = .254$	
Low intensity					
1st half	20.5 ± 4.1	20.8 ± 6.0	16.6 ± 2.3	$p = .099$	
2nd half	19.9 ± 2.8	19.9 ± 4.7	18.3 ± 4.6	$p = .242$	
Walking/jogging					
1st half	68.6 ± 6.1	73.9 ± 2.0	74.2 ± 2.7	$p = .026$	
2nd half	70.6 ± 4.8	71.8 ± 3.0	64.2 ± 9.0	$p = .008$	3 < 1, 2

Data represent a minute-by-minute analysis of distance covered.

players may not have had the same opportunities to determine their efforts and were forced to work harder due to the tactical implications of the dismissal.

Second, in the dismissal work-rate profile there was a significant reduction in distance covered per minute in sprinting between halves, a result that did not occur in the normative game profile. This finding suggests either a different strategy of play and/or an earlier or higher occurrence of fatigue in players who perform for 90 min whilst participating in a team reduced to 10 players. The former theory may be supported by the lack of a statistical difference observed in high-intensity activities across three intervals in the second-half in this match when compared to the reduction in high-intensity running in elite soccer players at the end of the second-half reported in multiple matches without a dismissal.[2] In this respect, it could be suggested that the players may have either consciously applied a pacing strategy or changed tactics at half-time. The players carried out less actions especially at lower intensities and particularly during the final stages of the second-half potentially to 'spare' their efforts for the most crucial game actions as sprinting actually increased (albeit non-significantly) in the final interval when compared to the previous second-half intervals.

Although interestingly, it is only possible to postulate on theory from this single performance and research using a larger sample of matches combined with information on technical performance as well as the work-rate of opponents is necessary. A recent investigation on elite match-play has notably shown that work-rate is significantly related to that of opponents as well as their competitive level.[4] In addition, it would be useful to establish normative values for various team formations and tactics in order to examine the relative work-rate subsequent to a dismissal if match tactics are modified. Furthermore, seasonal variations in work-rate as well as the effects of score-line should be taken into account when interpreting match performance.[3]

Practical implications

- The present findings are a first step in understanding how elite soccer teams cope physically with a dismissal and could aid in developing subsequent recovery strategies.
- A team with 10 players is likely to incur higher levels of fatigue. Tactical alterations may be necessary and/or players may adopt a pacing strategy to endure the remainder of the match.

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Original paper

Work-rate of substitutes in elite soccer: A preliminary study

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Abstract

The aim of this study was to investigate the work-rate of substitutes in professional soccer. A computerised player tracking system was used to assess the work-rates of second-half substitutes (11 midfielders and 14 forwards) in a French Ligue 1 club. Total distance, distance covered in five categories of movement intensity and recovery time between high-intensity efforts were evaluated. First- and second-half work-rates of the replaced players were compared. The performance of substitutes was compared to that of the players they replaced, to team-mates in the same position who remained on the pitch after the substitution and in relation to their habitual performances when starting games. No differences in work-rate between first- and second-halves were observed in all players who were substituted. In the second-half, a non-significant trend was observed in midfield substitutes who covered greater distances than the player they replaced whereas no differences were observed in forwards. Midfield substitutes covered a greater overall distance and distance at high-intensities ($p < 0.01$) and had a lower recovery time between high-intensity efforts ($p < 0.01$) compared to other midfield team-mates who remained on the pitch. Forwards covered less distance ($p < 0.01$) in their first 10-min as a substitute compared to their habitual work-rate profile in the opening 10-min when starting matches while this finding was not observed in midfielders. These findings suggest that compared to midfield substitutes, forward substitutes did not utilise their full physical potential. Further investigation is warranted into the reasons behind this finding in order to optimise the work-rate contributions of forward substitutes.

Keywords: Fatigue; Football; Substitutions; Motion analysis

1. Introduction

Research in elite soccer has identified the occurrence of a reduced work-rate between playing halves and in specific relation to high-intensity efforts towards the end of matches.[1] There is a need therefore for countermeasures to fatigue and it has been suggested that the strategic use of substitute players during the second-half of matches could reduce the effects of fatigue across the team.[2]

However, only one study has examined the work-rate of substitutes in elite soccer.[3] The work-rate of substitutes was shown to be superior to that of players in the starting 11 over the same time period. While this investigation had useful practical implications, there is need for further research into the physical contributions of replacements notably in comparison to players they replace and to their habitual performances when starting games.

In this preliminary study, we tested four hypotheses: (i) players who are substituted demonstrate a reduction in work-rate. (ii) Substitutes have higher work-rates than the player they replace. (iii) Substitutes have higher work-rates in the time they played than other players in the same position. (iv) The work-rate of substitutes does not differentiate to that when starting games.

2. Methods

A multiple-camera player tracking system (AMISCO Pro, Sport-Universal Process, Nice, France) was used to analyse the work-rates of outfield substitute players belonging

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Table 1
First- versus second-half performance in substituted players and comparison with the second-half performance of their direct replacements.

Variable	Replaced midfielders		Replacement midfielders	Replaced forwards		Replacement forwards
	1st half	2nd half	2nd half	1st half	2nd half	2nd half
Average time played (min)	45.5 ± 0.2	26.0 ± 8.0	22.5 ± 8.1	45 ± 0.3	23.0 ± 7.1	24.8 ± 7.4
Total distance (m)	129.3 ± 3.6	130.0 ± 7.3	136.6 ± 9.1	119.6 ± 9.0	121.7 ± 10.2	121.1 ± 9.9
Sprint distance (m)	5.1 ± 2.0	5.5 ± 3.9	6.4 ± 4.5	5.1 ± 2.0	5.9 ± 3.5	5.3 ± 2.4
Recovery time between efforts (s)	296.2 ± 108.3	297.4 ± 164.1	315.5 ± 198.9	263.8 ± 84.1	282.3 ± 126.4	270.4 ± 151.0
High-intensity distance (m)	7.0 ± 2.1	7.3 ± 3.1	9.8 ± 3.6	6.7 ± 1.5	6.7 ± 3.2	6.7 ± 1.7
Recovery time between efforts (s)	117.8 ± 34.8	117.7 ± 31.5	95.1 ± 38.5	127 ± 24.7	125.6 ± 44.0	122.5 ± 34.0
Moderate-intensity distance (m)	23.6 ± 2.4	23.0 ± 3.8	28.6 ± 3.9	16.1 ± 4.3	17.5 ± 5.5	18.3 ± 4.6
Low-intensity distance (m)	21.7 ± 2.8	19.5 ± 3.4	21.8 ± 4.5	14.8 ± 3.5	16.7 ± 5.5	15.1 ± 3.6
Walking/jogging distance (m)	72.0 ± 2.2	74.1 ± 3.6	72.4 ± 3.4	76.2 ± 4.4	75.7 ± 5.3	75.3 ± 3.4

Unless stated, data represent a minute-by-minute analysis of distance covered (all data are mean ± S.D.).

to a French 1st Division professional soccer team during the 2007/2008 season. A total of 18 matches (15 home and 3 away games) were examined. Altogether, 11 midfield and 14 centre-forward second-half substitutes who played a minimum of 10-min per game were included for analysis. Defenders were excluded due to a low number of substitutions.

The objective measures of work-rate performance selected for the analyses were classified into two categories: (1) Match distances covered including the overall distance and distance covered in five categories of movement intensity: 0–11 km/h (walking and jogging); 11.1–14 km/h (low-intensity running); 14.1–19 km/h (moderate-intensity running); 19.1–23 km/h (high-intensity running) and >23.1 km/h (sprinting).[4] The absolute data were corrected to a minute-by-minute analysis of the distance covered in each category (distance divided by time played) to enable equal comparison of work-rate over the time period played by each player.[1] (2) The average time spent in recovery between sprinting and high-intensity actions.

To test hypothesis 1, the first- and second-half performance of the replaced players was compared. For hypothesis 2, the performance over the time played by the substitute was compared to that during the second-half by the player he replaced. This analysis only included players who were directly substituted into their usual positional roles (i.e. a midfielder replaced another midfielder). Hypothesis 3 was tested by comparing the performance of the substitute to that of players in the same position who remained on the pitch over the same time period. The performance of forward substitutes could not be compared to that of other forwards as this team employed a 4-5-1 playing system and only one forward was ever present on the pitch. For hypothesis 4, the performance of the substitute over the first 10-min of competition (i.e. from 75 to 85 min) was compared to his habitual performance over the opening 10-min of play when starting games. To determine the habitual work-rate profile of the player, analyses were undertaken across five matches from the same season in which the player completed the entire 90-min.

Statistical analyses were performed using Bonferroni-adjusted paired *t*-tests (same-participant) or unpaired *t*-tests (between-participant) to test for differences in work-rate (SPSS Science Inc., Chicago, IL). Bonferroni's adjustment was applied according to previously outlined procedures for objective measures of work-rate.[5] Thus, an operational alpha level of 0.025 ($p < 0.05/2$) was used.

3. Results

No differences in work-rate between the first- and second-halves were observed in forwards and midfielders who were substituted (Table 1). Similarly, no differences were reported in work-rate in either forward or midfield substitutes compared to the players they replaced. However, the greater overall distance covered by the latter approached significance ($p = 0.044$).

A greater minute-by-minute overall distance ($p = 0.006$), distance in high-intensity activity ($p = 0.008$) and a shorter recovery time between high-intensity efforts ($p = 0.003$) was reported in midfield substitutes compared to other midfielders who remained on the pitch after the substitution.

Forwards covered less distance ($p = 0.004$) as a substitute in their first 10-min when compared to their habitual work-rate profile over the opening 10-min of matches while this was not observed in midfielders.

4. Discussion

In this preliminary study of work-rate in substitutes in elite soccer, several hypotheses were tested and are discussed in turn.

Firstly, no decline in work-rate in substituted players was observed. This result supports previous speculation in that the majority of substitutions are probably for tactical reasons rather than fatigue.[2] Nevertheless, we suggest that further research on a larger sample of players combined with an analysis of technical performance is necessary to support the present findings.

Secondly, forward substitutes did not demonstrate a higher work-rate than the forward player they replaced whereas the trend, albeit non-significant, was for midfield substitutes to work harder. This observation in forward substitutes may have been influenced by factors such as the specific tactical requirements of their position.[4] It may also be linked to an inability of these players to 'get into the game'. This latter suggestion may be confirmed by the dismissal of the fourth hypothesis in forwards as a significantly lower work-rate was observed in these players when introduced as substitutes compared to when starting matches. Further investigation is warranted into the reasons behind this finding in order to optimise the physical contributions of forward substitutes.

Thirdly, the overall work-rate and exercise at high-intensity in midfield substitutes was superior to that of players who had started the game, a result in accordance with previous findings in elite soccer.[3] In addition, the work-rate of these players during their first 10-min as a substitute was similar to their performances recorded during the opening 10-min when starting matches. This finding is noteworthy as the highest intensity of game activities in elite soccer is generally observed in the opening 15-min period of competition.[1] Therefore, these observations on the physical contribution of midfield substitutes indicate the value of replacing players in this position when an increase in work-rate is required.

Practical implications

The present findings are a first step in identifying and eventually optimising the work-rate contributions of substitutes in elite soccer.

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ORIGINAL ARTICLE

Influence of opposition team formation on physical and skill-related performance in a professional soccer team

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Abstract

This study examined the influence of opposition team formation on physical and skill-related performance in a professional soccer team. Performance in 45 French League 1 matches played over three competitive seasons (2007–2008, 2008–2009, and 2009–2010) was analysed using multi-camera computerized tracking. Players ($n = 21$) in the reference team (using a 4-3-3/4-5-1 formation) were analysed in matches against three opposition team formations: 4-4-2 (11 games), 4-3-3/4-5-1 (16 games), and 4-2-3-1 (18 games). Performance was compared for defending and midfield units as a whole and individually across four positions: full backs, central defenders, central midfielders, and wide midfielders. Collectively, players covered a greater total distance ($P < 0.05$) and distance in low- to moderate-intensity running (0–14.3 $km \cdot h^{-1}$) ($P < 0.05$) in matches against a 4-2-3-1 compared with a 4-4-2 formation. Distance covered in high-intensity (14.4–19.7 $km \cdot h^{-1}$) and very high-intensity running ($\geq$19.8 $km \cdot h^{-1}$) was not affected by opposition formation. In contrast, players covered more distance in total high-intensity performance ($\geq$14.4 $km \cdot h^{-1}$) when the reference team was in possession against a 4-4-2 compared with a 4-2-3-1 formation ($P < 0.05$), while a greater distance was run at these speeds when the reference team was not in possession against a 4-2-3-1 ($P < 0.01$) and a 4-3-3 ($P < 0.05$) compared with a 4-4-2 formation. Players ran less distance at low-to-moderate intensities in the second- versus first-half of matches against all three formations ($P < 0.01$ to $P < 0.05$), whereas total distance and high-intensity performance were unaffected. None of the measures of physical performance across the individual playing positions were affected by opposition team formation. Skill-related performance varied according to opposition formation: players as a whole performed more passes versus a 4-4-2 than a 4-2-3-1 formation ($P < 0.01$); ground and aerial duels versus a 4-2-3-1 compared with a 4-4-2 formation (both $P < 0.01$); one-touch passes versus a 4-2-3-1 compared with a 4-4-2 formation ($P < 0.01$) and a 4-3-3/4-5-1 formation ($P < 0.05$). The mean number of touches per possession was highest versus a 4-4-2 compared with a 4-3-3/4-5-1 ($P < 0.01$) and a 4-2-3-1 formation ($P < 0.01$). While skill-related performance across the four individual playing positions was generally unaffected by opposition team formation, mean pass length was greater for central midfielders against a 4-4-2 compared with a 4-3-3/4-5-1 ($P < 0.05$) and a 4-2-3-1 formation ($P < 0.01$). In general, the findings suggest that physical performance in the reference team was not greatly affected by opposition team formation. In contrast, skill-related demands varied substantially according to opponent formation and may have consequences for tactical and technical preparation and team selection policies.

Keywords: *Playing system, football, motion analysis, technical performance*

Introduction

A thorough understanding of the physical demands of professional soccer is required so that optimal training and preparation strategies can be constructed to respond to the demands of match-play. Recently, advanced computerized motion analyses of performance in contemporary match-play have provided comprehensive insights into the activity profiles of professional soccer players and the physical requirements of competition (Drust, Atkinson, & Reilly, 2007). Motion analyses have also been used to investigate a myriad of variables that affect the physical performance profile of players in competition. These include the positional roles of players

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(Barros et al., 2007; Di Salvo et al., 2007), cultural differences (Rienzi, Drust, Reilly, Carter, & Martin, 2000), standard of play (Mohr, Krustrup, & Bangsbo, 2003), team quality (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007; Rampinini, Impellizzeri, Castagna, Coutts, & Wisloff, 2009), match congestion (Odetoyinbo, Wooster, & Lane, 2008), score line (Bloomfield, Polman, & O'Donoghue, 2004), player dismissals (Carling & Bloomfield, 2010), substitutes (Carling, Espié, Le Gall, Bloomfield, & Jullien, 2010), and the physical condition (Krustrup et al., 2003) and age (Pereira Da Silva, Kirkendall, & Leite De Barros Neto, 2007) of players.

There is also speculation that the physical efforts of players in match-play are influenced by team formation (Bradley et al., 2009b; Carling, Bloomfield, Nelsen, & Reilly, 2008; Drust et al., 2007). Indeed, the choice of team formation should take into account individual physical abilities such as endurance and speed (Bauer, 1993). Furthermore, the interaction between physical, tactical, and technical skills should also be considered when evaluating performance according to team formation (Carling, Williams, & Reilly, 2005). Yet to date, only one preliminary study using a relatively small sample size (19 matches) has examined the effects of team formation on physical and skill-related (tactical and technical) performance (Bradley et al., 2009a). The performance of teams adopting 4-4-2, 4-3-3, and 4-5-1 formations was compared. The results showed that teams using a 4-4-2 performed more high-intensity running and passes than those using a 4-5-1 formation. Furthermore, no study has investigated the direct influence of opposition team formation on physical and skill-related performance in a reference soccer team. Related research in professional Italian soccer has shown that physical performance in a reference team was directly related to the physical activity completed by opponent teams (Rampinini et al., 2007). However, no information was provided as to the possible influence on findings of the respective team formations used by opponents.

Further research using match analyses into the influence of opposition team formation on physical and skill-related performance is therefore warranted. This information may have implications for aiding team selection and optimizing physical and tactical preparation strategies for matches against different formations. It may also be useful in identifying a link between match-related decrements in physical performance and opposition team formation. Declines in physical performance in competition can occur directly after intense periods of activity and during the later stages of games, suggesting temporary and permanent fatigue (Mohr, Krustrup, & Bangsbo, 2005). The identification of reduced physical performance in competition that occurs specifically against certain team formations would be beneficial in informing strategies to aid teams to maintain performance throughout such matches.

Consequently, the aim of this study was to investigate the effect of opposition team formation on physical activity profiles and skill-related (tactical and technical) performance in a reference team during professional soccer match-play.

Methods

Participants and match sample

With ethics approval from the internal review board of the sampled football club, physical, tactical, and technical demands of match-play were analysed for outfield soccer players in a professional soccer team that competed in the French League 1 division (highest standard in French soccer). To ensure player confidentiality, all performance data were anonymized before analysis.

A total of 45 official games over three seasons (2007–2008, $n = 15$; 2008–2009, $n = 18$; 2009–2010, $n = 12$) in which players completed the entire match were used for analysis. Performance in the reference team was analysed in matches against three team formations commonly used in professional soccer: 4-4-2 (11 games, 9 teams), 4-3-3/4-5-1 (16 games, 12 teams), and 4-2-3-1 (18 games, 13 teams). The reference team recorded two top-ten finishes (9th and 5th) in the first two seasons and was placed 5th at the moment the final game was analysed in the current season. The standard of the sample of opponent teams analysed for each formation was: 4-4-2 = 4 top-ten and 7 bottom-nine placed teams; 4-3-3/4-5-1 = 9 top-ten and 7 bottom-nine placed teams; and 4-2-3-1 = 9 top-ten and 9 bottom-nine placed teams. The interaction between opposition standard (based on League position) and team formation was verified for the performance measures. Two- and three-way analyses of variance showed no significant interactions between factors ($P > 0.05$), indicating that the standard of opposition did not confound the results.

To determine opponent team formations, two UEFA-qualified coaches (one from the reference club's coaching staff and one independent observer) observed video recordings of the sampled games. These observers subjectively determined team formations at the start of games and also verified that the formations were consistent throughout the games. Games in which a dismissal occurred were not included for analysis. Teams that played a 4-3-3 formation were combined with those using a 4-5-1 system. Distinction between these two systems was deemed to be difficult by the observers, as teams often played a 4-3-3 when in possession and reverted to a 4-5-1 when out of possession. The reference team was generally organized in the 4-3-3/4-5-1 format and only games in which this formation was used were included for analysis.

Altogether, 21 players participated with a median of 15.5 matches (in which the full 90 min were played) per player (range 1–38). This sample led to a total of 297 observations of match performance. Of this total, the number of observations for each position was respectively: full backs, $n = 82$; central defenders, $n = 80$; central midfielders, $n = 78$; and wide midfielders, $n = 57$. Forward players were excluded due to a low number of observations in both the reference and opposition teams.

Data collection procedures and measures of competitive performance

A computerized player tracking system (AMISCO Pro®, Sport-Universal Process, Nice, France) was used to characterize activity profiles in the reference team. This multiple-camera system tracks the movements of every player at a sampling rate of 10 Hz over the course of matches and provides data on the distances covered at different movement speeds (Carling et al., 2005). A trained operator simultaneously codes technical actions involving the ball according to a pre-defined classification. The workings, accuracy, and reliability of the AMISCO Pro® system in measuring player movement and coding match-specific events in elite soccer competition have been described in more detail elsewhere (Carling et al., 2008; Di Salvo et al., 2007; Randers et al., 2010; Zubillaga, Gorospe, Hernadez-Mendo, & Blanco-Villanesor, 2008).

Physical and technical performance was determined automatically from the raw data files by computerized analysis of player movements and actions using match-analysis software (AMISCO Viewer®, Sport-Universal Process, Nice, France). To avoid the potential effect of variations in duration across games, information obtained in injury time or extra time was not included for analysis. Performance data for each game were therefore analysed over 90 min (two halves of 45 min each).

The performance measures selected for the analyses were classified into three categories:

(1) *Physical performance* – total distance covered and distance covered in three categories of movement speed (Bradley et al., 2009b): 0.0–14.3 $km \cdot h^{-1}$ (low-to-moderate intensity); 14.4–19.7 $km \cdot h^{-1}$ (high intensity); and ≥ 19.8 $km \cdot h^{-1}$ (very high intensity). Total high-intensity performance was defined as movement performed at speeds ≥ 14.4 $km \cdot h^{-1}$ (high-intensity and very high-intensity running combined). The distance covered in total high-intensity performance was measured for players when in individual possession of the ball and when their team was in (attacking play) and out (defensive play) of possession. In addition, both the mean time spent in recovery between actions performed in the total high-intensity performance category and the mean length of these efforts were calculated.

(2) *Declines in physical performance* – all measures of physical performance were compared across match halves. End-game performance was also analysed by comparing the percentage change in distance covered in total high-intensity performance. For this, the distance run in the final 15-min period was compared with that for the first 15-min period and the mean of other 15-min periods (mean of all periods minus final 15-min period).

(3) *Skill-related performance measures* defined and calculated in the AMISCO® Pro system included: frequency of passes and forward passes, mean length of passes, percentage of passes played with one touch, frequency of ball possessions, mean time and number of touches per possession, and frequency of ground and aerial duels. Finally, measures of the total time the ball was in play and the percentage of time spent in possession were measured across games for the team as a whole.

Statistical analyses

All statistical analyses were conducted using SPSS for Windows Version 14.0 (SPSS Inc., Chicago, IL, USA). Data are presented as means and standard deviations unless otherwise stated. Before using parametric statistical test procedures, the normality of the data was verified. Two-way analysis of variance (ANOVA) was used to test for differences in means for all players in performance measures against the three opposition formations and to examine the interaction between playing position and opposition formation. To investigate declines in performance, a three-way ANOVA was performed on each category of physical performance to examine the interaction between performance across match halves, opposition formation, and playing position. To study end-game decrements in performance, a two-way ANOVA was used to compare the interaction between percentage decline in physical performance (efforts in end 15-min period compared with first and mean 15-min periods), opposition formation, and playing position. Follow-up univariate analyses using Bonferroni-corrected pair-wise comparisons were used where appropriate.

Effect sizes for statistical differences were also determined. Effect size (ES) values of 0.20–0.49, 0.50–0.79, and ≥ 0.8 were considered to represent small, medium, and large differences, respectively (Cohen, 1988).

Results

Physical performance

Data on each category of performance against the three opposition team formations are presented in Table I. The total distance run for players in all positions combined varied when performing against the three opposition team formations ($P = 0.026$). Players covered greater total distances against a 4-2-3-1 compared with a 4-4-2 formation ($P < 0.05$, ES $= 0.32$).

The distance covered in low-/moderate-intensity running also varied when competing against the three opposition team formations ($P = 0.007$). Players ran more distance at low/moderate intensities against a 4-2-3-1 compared with a 4-4-2 formation ($P < 0.01$, ES $= 0.49$).

Distance covered in total high-intensity running by all players when their team was in possession varied when competing against the three formations ($P = 0.032$). Players covered more distance when their team was in possession against a 4-4-2 compared with a 4-2-3-1 formation ($P < 0.05$, ES $= 0.30$). Similarly, the distance covered in total high-intensity running when out of possession differed ($P = 0.004$) according to opposition team formation. Players ran significantly more distance against a 4-2-3-1 ($P < 0.01$, ES $= 0.40$) and 4-3-3 formation ($P < 0.05$, ES $= 0.37$) compared with a 4-4-2 formation.

No differences were observed in the following variables in matches against the three opposition team formations: distance covered in high-intensity ($P = 0.476$) and very high-intensity movement ($P = 0.411$); total high-intensity performance – mean recovery time between ($P = 0.230$) and mean length of ($P = 0.667$) actions; distance run in individual ball possession ($P = 0.307$).

Finally, no significant interaction was observed in any of the measures of physical performance for efforts across the individual playing positions against the three opposition team formations.

Declines in performance

The formation used by opponent teams affected the distance covered by the reference team in low-/moderate-intensity running across the two halves of matches ($P = 0.005$). Players in all positions combined performed less running at low/moderate intensities in the second versus the first half of matches against the three formations: 4-4-2, first half $= 4267 \pm 201$ m vs. second half $= 4046 \pm 191$ m, $P < 0.01$, ES $= 1.20$; 4-3-3/4-5-1, first half $= 4281 \pm 191$ m vs. second half $= 4142 \pm 190$ m, $P < 0.05$, ES $= 0.71$; 4-2-3-1, first half $= 4280 \pm 198$ m vs. second half $= 4199 \pm 220$ m, $P < 0.05$, ES $= 0.40$. The total distance run and distance covered at other movement speeds across match halves were unaffected by opposition team formation. Similarly, total high-intensity performance across match halves (recovery time between and length of actions; and the percentage decrement during the final 15-min period of matches) was unaffected by opposition team formation (Table II). Finally, performance in none of the physical performance measures across game halves within the four playing positions was affected by opposition team formations.

Skill-related performance

A significant difference was observed for players in all positions combined in the following skill-related performance variables when playing against the three formations (Table III): passing frequency ($P = 0.007$) with players performing more passes versus a 4-4-2 than a 4-2-3-1 ($P < 0.01$, ES $= 0.50$); mean number of ball touches per possession ($P = 0.003$) with players taking more touches versus a 4-4-2 compared with a 4-3-3/4-5-1 ($P < 0.01$, ES $= 0.67$) and a 4-2-3-1 ($P < 0.01$, ES $= 0.63$); frequency of ground duels ($P = 0.022$) with players performing more duels versus a 4-2-3-1 compared with a 4-4-2 ($P < 0.01$, ES $= 0.57$); frequency of aerial duels ($P = 0.004$) with players performing more duels versus a 4-2-3-1 than a 4-4-2 ($P < 0.01$, ES $= 0.56$); percentage of passes played with one touch ($P < 0.001$) with players performing more passes versus a 4-2-3-1 compared with a 4-4-2 ($P < 0.01$, ES $= 0.59$) and 4-3-3/4-5-1 ($P < 0.05$, ES $= 0.44$) formation. No difference was observed in the mean length of passes against the three formations for players in all positions combined ($P = 0.884$). While skill-related performance was generally unaffected across playing positions against the different team formations, mean pass length varied ($P = 0.018$), as this was greater in central midfielders against a 4-4-2 compared with a 4-3-3/4-5-1 ($P < 0.05$, ES $= 0.50$) and 4-2-3-1 ($P < 0.01$, ES $= 0.57$).

The time the ball was in play (4-4-2 = 50 min 40 s vs. 4-3-3/4-5-1 = 49 min 29 s vs. 4-3-2-1 = 49 min 0 s, $P = 0.419$) was similar against all formations. In contrast, the percentage of time spent in possession by the reference team varied against the three formations (4-4-2 = 55% vs. 4-3-3/4-5-1 = 5 2.4% vs. 4-2-3-1 = 50.3%, $P = 0.035$) with more

Table I. Comparison of distances covered at different intensities in a reference team against three opposition team formations

Position	4-3-3/4-5-1 vs.	Low/moderate (0–14.3 km·h^{-1})	High (14.4–19.7 km·h^{-1})	Very high (≥19.8 km·h^{-1})	Total distance (m)	Total ≥14.4 km·h^{-1} (individual Possession)	Total ≥14.4 km·h^{-1} (team in possession)	Total ≥14.4 km·h^{-1} (team out of possession)
Full back	4-4-2	8270 ± 260	1542 ± 279	843 ± 128	10655 ± 497	97 ± 53	965 ± 281	1222 ± 179
Full back	4-3-3/4-5-1	8323 ± 292	1590 ± 207	911 ± 153	10824 ± 473	96 ± 48	1002 ± 182	1289 ± 243
Full back	4-2-3-1	8404 ± 334	1592 ± 266	848 ± 158	10844 ± 513	86 ± 36	916 ± 183	1308 ± 225
Central defender	4-4-2	8246 ± 348	1288 ± 177	470 ± 108	10004 ± 469	77 ± 43	471 ± 135	1017 ± 97
Central defender	4-3-3/4-5-1	8414 ± 247	1269 ± 191	477 ± 112	10161 ± 404	79 ± 45	480 ± 124	1021 ± 168
Central defender	4-2-3-1	8431 ± 325	1264 ± 185	497 ± 141	10192 ± 466	69 ± 51	430 ± 119	1061 ± 234
Central midfielder	4-4-2	8518 ± 267	2001 ± 297	658 ± 151	11177 ± 549	99 ± 61	1172 ± 336	1343 ± 293
Central midfielder	4-3-3/4-5-1	8545 ± 228	2029 ± 319	704 ± 188	11278 ± 446	95 ± 48	1098 ± 316	1466 ± 291
Central midfielder	4-2-3-1	8587 ± 263	1985 ± 308	678 ± 195	11250 ± 510	99 ± 69	1051 ± 387	1430 ± 233
Wide midfielder	4-4-2	8221 ± 410	1478 ± 270	844 ± 260	10543 ± 656	202 ± 47	1537 ± 279	652 ± 223
Wide midfielder	4-3-3/4-5-1	8413 ± 426	1633 ± 236	869 ± 201	10916 ± 546	157 ± 66	1372 ± 254	915 ± 184
Wide midfielder	4-2-3-1	8495 ± 480	1591 ± 263	861 ± 174	10948 ± 650	168 ± 70	1336 ± 231	905 ± 267
Mean all positions	4-4-2	8314 ± 329	1577 ± 373	704 ± 219	10594 ± 681	119 ± 65	1036 ± 448***	1058 ± 307
Mean all positions	4-3-3/4-5-1	8424 ± 301	1630 ± 376	741 ± 236	10795 ± 624	107 ± 57	988 ± 392	1172 ± 314****
Mean all positions	4-2-3-1	8479 ± 350**	1608 ± 374	721 ± 222	10808 ± 661*	106 ± 67	933 ± 409	1176 ± 310****

*Significantly more distance covered against a 4-2-3-1 compared with a 4-4-2 formations ($P < 0.05$).
**Significantly more distance covered against a 4-2-3-1 compared with a 4-4-2 formations ($P < 0.01$).
***Significantly more distance covered against a 4-4-2 compared with a 4-2-3-1 formations ($P < 0.05$).
****Significantly more distance covered against a 4-3-3/4-5-1 ($P < 0.05$) and 4-2-3-1 ($P < 0.01$) compared with a 4-4-2 formation.

Table II. Characteristics of total high-intensity performance (≥ 14.4 km $\cdot$ h^{-1}) of a reference team against three different opposition team formations

		Recovery time (s)			Length (m)			Performance decrement (%)	
Position	4-3-3/4-5-1 vs.	First half	Second half	Mean	First half	Second half	Mean	First vs. end 15 min	Mean vs. end 15 min
Full back	4-4-2	26.8 ± 5.2	29.0 ± 4.8	27.9 ± 4.0	13.1 ± 0.7	13.1 ± 1.3	13.1 ± 0.6	15.3 ± 26.7	6.2 ± 26.8
Full back	4-3-3	25.2 ± 5.0	27.4 ± 3.7	26.3 ± 3.5	12.7 ± 1.0	13.3 ± 1.2	13.0 ± 0.8	14.0 ± 30.8	4.7 ± 28.8
Full back	4-2-3-1	25.5 ± 4.5	27.8 ± 4.3	26.7 ± 3.6	13.0 ± 0.8	12.7 ± 0.9	12.8 ± 0.7	7.0 ± 34.7	3.1 ± 22.5
Centre defender	4-4-2	36.4 ± 5.9	38.8 ± 6.7	37.6 ± 5.3	12.6 ± 1.1	13.0 ± 1.5	12.8 ± 1.2	12 ± 23.7	0.2 ± 25.8
Centre defender	4-3-3	35.3 ± 5.4	38.4 ± 6.7	36.8 ± 4.6	12.3 ± 1.2	12.4 ± 1.1	12.4 ± .9	18.0 ± 25.0	8.2 ± 24.9
Centre defender	4-2-3-1	35.1 ± 6.3	37.8 ± 7.0	36.5 ± 5.8	12.4 ± 0.9	12.2 ± 1.2	12.3 ± 0.8	14.6 ± 38.0	5.8 ± 36.6
Central midfielder	4-4-2	22.9 ± 4.7	25.4 ± 4.4	24.1 ± 4.2	12.7 ± 0.9	12.9 ± 0.7	12.8 ± 0.5	6.7 ± 25.2	0.5 ± 24.4
Central midfielder	4-3-3	22.2 ± 4.1	24.3 ± 4.5	23.2 ± 3.9	12.6 ± 0.9	12.7 ± 0.9	12.6 ± 0.8	6.2 ± 43.3	10.2 ± 22.8
Central midfielder	4-2-3-1	24.0 ± 4.9	25.2 ± 5.1	24.6 ± 4.1	12.9 ± 0.8	13.0 ± 1.01	12.9 ± 0.7	7.0 ± 36.7	6.8 ± 25.0
Wide midfielder	4-4-2	28.2 ± 5.1	29.3 ± 6.5	28.7 ± 5.3	13.5 ± 0.6	12.6 ± 0.8	13.0 ± 0.6	18.9 ± 18.3	12.2 ± 23.8
Wide midfielder	4-3-3	26.0 ± 3.7	28.0 ± 4.8	27.0 ± 2.8	13.1 ± 1.1	13.8 ± 1.1	13.4 ± 0.9	4.5 ± 31.6	3.7 ± 22.1
Wide midfielder	4-2-3-1	27.6 ± 6.1	27.7 ± 3.2	27.6 ± 3.8	13.6 ± 0.9	13.0 ± 1.1	13.3 ± 0.7	12.3 ± 37.7	10.8 ± 34.3
Mean all positions	4-4-2	28.6 ± 7.4	30.6 ± 7.6	29.6 ± 7.0	13.0 ± 0.9	12.9 ± 1.1	13.0 ± 0.8	12.4 ± 23.9	3.7 ± 24.9
Mean all positions	4-3-3	27.2 ± 6.9	29.5 ± 7.5	28.3 ± 6.6	12.7 ± 1.1	13.0 ± 1.2	12.9 ± 0.9	10.9 ± 33.7	7.1 ± 24.6
Mean all positions	4-2-3-1	28.0 ± 6.9	29.6 ± 7.1	28.8 ± 6.4	13.0 ± 0.9	12.7 ± 1.0	12.9 ± 0.8	10.2 ± 36.5	6.6 ± 29.5

Note: First vs. end 15 min = distance covered in the first 15-min period versus that covered in the final 15-min period.
Mean vs. end 15 min = distance for the mean of all 15-min periods (minus final period) versus that covered in the final 15-min period.

Table III. Comparison of skill-related performance in a reference team against three opposition team formations

Position	4-3-3/4-5-1 vs.	Passes (*n*)	Forward passes (*n*)	Mean pass distance (m)	One-touch passes (%)	Individual possessions (*n*)	Mean touches per possession (*n*)	Mean time per possession (s)	Ground duels (*n*)	Aerial duels (*n*)
Full back	4-4-2	53.1 ± 12.3	38.9 ± 8.4	19.6 ± 2.5	49.7 ± 12.4	57.1 ± 12.2	1.8 ± 0.3	0.9 ± 0.9	6.7 ± 2.4	4.7 ± 2.5
Full back	4-3-3/4-5-1	53.8 ± 16.6	41.3 ± 11.4	19.2 ± 3.4	49.5 ± 12.7	57.8 ± 17.1	1.8 ± 0.3	1.0 ± 0.3	7.0 ± 3.4	4.3 ± 1.7
Full back	4-2-3-1	49.5 ± 12.0	38.7 ± 9.8	19.0 ± 2.9	52.6 ± 11.8	53.6 ± 11.8	1.8 ± 0.3	1.0 ± 0.3	7.6 ± 3.2	4.8 ± 3.5
Centre defender	4-4-2	44.1 ± 11.2	35.4 ± 10.6	22.4 ± 2.1	37.9 ± 8.6	44.2 ± 15.0	2.1 ± 0.3	1.3 ± 0.4	3.7 ± 2.1	5.9 ± 2.8
Centre defender	4-3-3/4-5-1	39.7 ± 9.4	31.8 ± 7.2	24.0 ± 3.1	40.6 ± 9.5	41.0 ± 9.6	1.9 ± 0.3	1.2 ± 0.4	4.3 ± 2.3	6.8 ± 3.3
Centre defender	4-2-3-1	37.1 ± 10.7	30.6 ± 8.5	24.4 ± 3.7	45.8 ± 9.7	39.2 ± 11.4	1.9 ± 0.2	1.1 ± 0.3	4.5 ± 3.3	7.2 ± 4.1
Central midfielder	4-4-2	56.2 ± 13.8	35.6 ± 10.2	23.3 ± 15.6#	34.9 ± 11.6	57.9 ± 17.5	2.1 ± 0.3	1.0 ± 0.3	6.6 ± 3.0	1.7 ± 1.0
Central midfielder	4-3-3/4-5-1	49.0 ± 16.6	31.8 ± 11.4	18.7 ± 3.4	33.8 ± 12.6	53.9 ± 17.1	2.1 ± 0.3	1.1 ± 0.3	7.9 ± 3.4	2.1 ± 1.7
Central midfielder	4-2-3-1	45.1 ± 11.8	29.1 ± 8.0	18.1 ± 3.2	36.7 ± 9.8	51.4 ± 13.2	2.1 ± 0.3	1.1 ± 0.3	8.9 ± 4.9	3.9 ± 2.9
Wide midfielder	4-4-2	42.7 ± 13.1	23.8 ± 9.6	17.4 ± 5.2	27.3 ± 8.2	54.9 ± 11.9	2.7 ± 0.7	1.6 ± 0.4	7.3 ± 2.5	2.1 ± 0.8
Wide midfielder	4-3-3/4-5-1	43.3 ± 11.8	25.6 ± 7.9	19.4 ± 2.9	34.0 ± 9.1	52.4 ± 11.7	2.2 ± 0.3	1.3 ± 0.4	8.8 ± 4.9	3.9 ± 2.9
Wide midfielder	4-2-3-1	41.0 ± 8.8	24.8 ± 9.1	19.8 ± 4.4	38.5 ± 10.5	52.1 ± 8.6	2.3 ± 0.4	1.3 ± 0.4	9.6 ± 4.6	4.6 ± 2.9
Mean all positions	4-4-2	49.0 ± 13.4*	33.4 ± 10.7	20.7 ± 8.6	37.5 ± 12.9	53.5 ± 15.4	2.2 ± 0.5**	1.2 ± 0.4	6.1 ± 2.8	3.6 ± 2.7
Mean all positions	4-3-3/4-5-1	46.4 ± 13.7	32.6 ± 10.3	20.3 ± 3.8	39.5 ± 11.7	51.3 ± 14.4	2.0 ± 0.3	1.2 ± 0.3	7.0 ± 3.8	4.3 ± 3.1
Mean all positions	4-2-3-1	43.2 ± 11.9	30.8 ± 9.9	20.3 ± 4.3	44.7 ± 11.6****	49.0 ± 12.9	2.0 ± 0.3	1.1 ± 0.3	7.7 ± 4.5***	5.1 ± 3.6***

*Significantly more passes versus a 4-4-2 compared with a 4-2-3-1 formation ($P < 0.01$).
**Significantly more touches per possession versus a 4-4-2 than a 4-2-3-1 ($P < 0.01$) and 4-3-3 formation ($P < 0.01$).
***Significantly more duels against a 4-2-3-1 than a 4-4-2 formation ($P < 0.01$).
****Significantly higher percentage of one-touch passes versus a 4-2-3-1 than a 4-4-2 ($P < 0.01$) and 4-3-3 formation ($P < 0.05$).
#Mean pass distance significantly greater in central-midfielders versus a 4-4-2 compared with a 4-3-3/4-5-1 ($P < 0.05$) and 4-2-3-1 formation ($P < 0.01$).

possession observed against a 4-4-2 compared with a 4-2-3-1 ($P < 0.05$, ES $= 0.67$) formation.

Discussion

This study was a detailed investigation of the physical and skill-related activity profiles of a professional soccer team when competing against three common team formations. The major finding is that certain aspects of physical and skill-related performance in defensive and midfield units as a whole are affected when competing against different opposition team formations. In contrast, opposition team formation generally did not influence physical and skill-related performance across four individual playing positions. Similarly, physical performance across halves and towards the end of matches was generally unaffected by opposition team formation.

The total distance covered in elite soccer match-play provides a global indication of the intensity of exercise. Contemporary outfield male professional soccer players cover on average 9–13 km per match (Stølen, Chamari, Castagna, & Wisløff, 2005). In this study, players across the defensive and midfield positions ran distances within this range. However, the overall distance covered and distance covered at low/moderate intensities by players as a whole (attacking and midfield roles combined) were influenced by opposition formation and notably increased when performing against a 4-2-3-1 formation. The small effect sizes observed for these data, however, may indicate that these differences, though statistically significant, may have limited practical relevance (Di Salvo et al., 2009). Nevertheless, this finding tends to confirm previous speculation (Carling et al., 2008; Drust et al., 2007) that opposition team formations govern player efforts, as these determined the overall physical demands of elite soccer match-play. However, opposition team formation did not influence physical performance when the effect of individual playing position was taken into account. These results suggest that while the team as a whole may have needed to adjust its efforts against different team formations, the individual demands across playing positions did not vary according to opposition formation. Caution is required, however, when interpreting these findings, as information on forward players was not available and further research with these players included is warranted.

The analysis of high-intensity running activity (distances covered, mean recovery times, and lengths of actions) showed that performance did not vary for all players or across individual playing positions in the reference team when competing against the three opposition team formations. The efforts made at high intensities are often critical to the outcome of matches (Di Salvo et al., 2009), yet the present results suggest that opposition formation did not affect the overall demands placed on players in this aspect of play. In contrast, total distance covered in total high-intensity performance (movement ≥ 14.4 $km \cdot h^{-1}$) varied substantially according to team ball possession (Table I). Players in all positions combined covered more distance when their team had possession against a 4-4-2 compared with a 4-2-3-1 formation. In games against the latter and the 4-3-3/4-5-1 formations, players ran more when their team was out of possession than against the 4-4-2 formation. A related study in Premier League soccer players also showed that distance in high-intensity movement according to ball possession varied significantly across teams using different formations (Bradley et al., 2009a). The present results tend to support this observation and suggest a link with the attacking and defensive tactical demands imposed by opposition formations. Indeed, the significant variation in the percentage of time in ball possession in the reference team against three opposition formations is noteworthy, as the team had substantially less possession (-4.7%) in games against a 4-2-3-1 compared with a 4-4-2 formation. Players may therefore have had to cover greater distances in defensive play (e.g. to regain possession) in matches against a 4-2-3-1 formation. These results imply that the evaluation of performance in high-intensity running both in and out of possession should take into account opposition team formation and the time spent in ball possession.

Overall, the total distance covered by all players dropped significantly in the second half of matches when opposition formation was not taken into account ($P < 0.001$). This fall in overall performance between halves is commonly observed in elite-standard soccer (Reilly, Drust, & Clarke, 2008). In contrast, the physical efforts across match halves (total distance run and that covered at high and very high intensities, and recovery time between and length of actions in total high-intensity performance) were unaffected when opposition formation was considered. Similarly, no decrement in total high-intensity performance during the final 15-min period of matches was reported irrespective of opposition formation. In addition, opposition team formation did not influence any decline in physical performance across individual playing positions. Indeed, the aim of any team formation is to ensure optimal team organization to best utilize the physical capacities of players and reduce the efforts required to gain and use possession (Doucet, 2002). While the distance covered in low-/moderate-intensity movement declined significantly in the second half of games, this reduction was common to matches against all formations. These results as a whole generally imply that game-related decrements in physical performance in the present team were not influenced by opposition formation.

The choice of team formation is tactically important, as the designation of player positions and roles aims to give the team the best options for manoeuvring in both attacking and defensive play (Bangsbo & Peterson, 2000). In this study, the analysis of skill-related performance showed that the frequency of several game actions was heavily influenced by opposition team formation, although this was generally not the case for the individual playing positions. Once again, the moderate effect sizes observed for these differences may, to a certain extent, limit practical relevance. Nevertheless, when competing against a 4-4-2, defending and midfield players as a whole performed more passes and more ball touches per possession versus a 4-2-3-1 formation. These results again suggest a link with the time spent in ball possession, as the reference team dominated possession in games versus a 4-4-2 formation. In contrast, players performed considerably more duels (aerial and ground) and one-touch passes against a 4-2-3-1 compared with a 4-4-2 formation. In addition to time spent in ball possession, these findings may be linked to the specific tactical role of opposition players with respect to certain formations as well as the technical ability of individuals across teams (Carling et al., 2005). Nevertheless, the present findings are noteworthy and may have consequences for tactical preparation and team selection based on opposition formation. For example, the higher frequency of one-touch passes against teams using a 4-2-3-1 formation suggests that players in the reference team could have benefited from performing one-touch passing drills in preparation for matches against this particular formation.

The limitations of this study were the relatively low number of players within certain positional roles and the non-representation of all playing positions, especially centre forwards. Also, the process of determining team formations and ensuring that these were consistent throughout games relied solely on the subjective assessment of observers. Further study is warranted to attempt to determine an objective and reliable means for assessing the choice of team formation and when changes occur. Finally, comparative information on physical and skill-related performance in matches against other team formations (e.g. 3-5-2 or 4-4-1-1) used in professional soccer was not available.

Conclusions

The present study provides a comprehensive evaluation of physical and skill-related activity profiles in a professional soccer team when competing against three different team formations. These findings help broaden our understanding of one of the many factors that can impact on physical performance in professional soccer match-play. A major aim of motion analyses of physical performance is to aid coaches and practitioners in making objective decisions for structuring the conditioning elements of training and subsequent match preparation (Bradley et al., 2009b; Carling, 2010). However, the present results on the whole do not lend support to the implementation of specific physical conditioning regimes to prepare for matches against any of the three common formations adopted by the present opposition teams. In contrast, skill-related demands varied substantially for the reference team as a whole when competing against the three opposition formations, and these differences may have consequences for tactical and technical match preparation strategies and team selection policies.

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Appendix 3d: Copy of Paper 9, Carling, C, Le Gall, F., & Dupont, G. (2011). Are physical performance and injury risk in a professional soccer team in match-play affected over a prolonged period of fixture congestion? *International Journal of Sports Medicine, 32*, 1-7.

Are Physical Performance and Injury Risk in a Professional Soccer Team in Match-Play Affected Over a Prolonged Period of Fixture Congestion?

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Abstract

In this study, the effects of a prolonged period of fixture congestion (8 successive official matches in 26 days) on physical performance and injury risk and severity in a professional soccer team were investigated. Computerised motion-analysis was used to analyse the overall distance covered and that run at light- (0.0–11.0 $km\cdot h^{-1}$); low- (11.1–14.0 $km\cdot h^{-1}$); moderate- (14.1–19.7 $km\cdot h^{-1}$) and high-intensities (≥19.8 $km\cdot h^{-1}$) for the team as a whole. Distances were measured in metres per minute. Information on match injuries was recorded prospectively. The overall distance covered varied across successive matches ($p<0.001$) as more distance was run in games 4 and 7 compared to 2 and 3, respectively (126.6±12.3 $m\cdot min^{-1}$ and 125.0±13.2 $m\cdot min^{-1}$ vs. 116.0±8.0 $m\cdot min^{-1}$ and 115.5±11.0 $m\cdot min^{-1}$). Distance run in light-intensity exercise also varied ($p<0.001$) as more distance was covered in game 4 vs. 1, 2, 3, 5 and 6 (75.5±3.8 $m\cdot min^{-1}$ vs. 70.6±2.4 $m\cdot min^{-1}$, 71.8±3.4 $m\cdot min^{-1}$, 69.3±2.6 $m\cdot min^{-1}$, 71.5±3.1 $m\cdot min^{-1}$, and 70.3±2.8 $m\cdot min^{-1}$) and in game 8 vs. game 3 (73.1±3.8 vs. 69.3±2.6 $m\cdot min^{-1}$), respectively. When comparing match halves, there were no differences across games in overall or high-intensity distance covered and performance in these measures was similar for matches played before, during and after this period. Globally, no difference over the 8 games combined was observed between the reference team and opponents in any of the performance measures whereas the overall distance covered and that in low- (both $p<0.001$) and high-intensity running ($p=0.040$) differed in individual games. The incidence of match injury during the congested fixture period was similar to rates reported outside this period but the mean lay-off duration of injuries was substantially shorter during the former ($p<0.05$). In summary, while the overall distance run and that covered at lower intensities varied across games, high-intensity running performance and injury risk were generally unaffected during a prolonged period of fixture congestion. These results might be linked to squad rotation and post-match recovery strategies in place at the present club.

Introduction

In contemporary European professional soccer, teams can participate in over 60 competitive matches per season. Hence, there is potential for professional soccer players to experience residual fatigue over the playing season especially during dense competitive schedules [22]. Research has shown that participation in a soccer match results in muscle trauma and a reduction in the anaerobic performance of players with perturbations persisting up to 72 h [1,20]. Therefore, one would expect a drop in measures of physical performance in competition when there is an insufficient recovery time between matches.

Several investigations have examined the physical activity profiles of professional soccer players during intense periods of matches. Surprisingly perhaps, studies conducted in English [24], French [7], Scottish [11] and Spanish [27] players did not report any statistical differences in athletic performance across successive matches played in a short time. These findings suggest that professional players can cope physically even when the time-delay between matches is short. However, in these previous studies, physical performance was examined across only 2 or 3 consecutive games played over a 3–7 day timescale. Multiple longitudinal observations over an extended period of time are required to provide a more comprehensive estimation of the between-match variability in competitive performance indices [16]. Fixture congestion in contemporary professional soccer means it is common for teams to participate in multiple matches over more prolonged periods than those frequently used in previous studies to examine variations in physical performance. Yet no performance data are available on match-to-match variability and therefore the capacity of teams to 'physically' cope with intense competitive schedules over an extended period of time.

It has recently been suggested that professional soccer players regulate their physical efforts when participating in congested fixture periods [27]. While this self-imposition of efforts might partly explain the previously observed lack of a decline in physical performance during successive games with a short recovery period, no studies have verified this theory. Analysis of aggregated performance in multiple matches during periods of fixture congestion compared to that observed in matches played outside these periods would therefore be pertinent. In addition, none of the previous aforementioned studies that examined the effects of fixture congestion on athletic performance have investigated the potential confounding effects of opponent performance. Athletic performance has been shown to be directly related to the physical activity completed by opponent teams [4,25]. An investigation into the physical demands imposed by separate opposition teams in multiple games over a tight time-frame and the capacity of a reference team to directly respond to these demands is therefore warranted.

Fixture congestion is not only regarded as a threat to match performance but also to players' health [13]. However, only limited and contrasting information is available on the effects of calendar congestion and injury rates in professional soccer. Research in French players has shown that a very short interval between fixtures (≤3days) did not result in a higher injury risk or lay-off time per injury compared to a longer interval (≥4days) [9]. In contrast, injury incidence was approximately 6-times higher in Scottish players playing 2 games in a 4-day period compared to peers in the same team who had not played a match for 6 days or more [11]. Further research is thus necessary to explore the effects on injury rates of playing multiple games with a short delay between matches and especially over a prolonged period of fixture congestion. Finally, player rotation strategies have been suggested as a potential means to aid in reducing injury rates as well as maintaining match performance during dense competitive schedules and therefore warrant investigation [11,13].

In December 2009, the present French professional soccer team participated in 8 consecutive official matches (League and European competition) played over a 26-day period. Consequently, this competitive schedule provided a unique opportunity to analyse physical performance, injury rates, and squad rotation strategies during a prolonged period of fixture congestion. 4 hypotheses based on measures of physical performance and injury rates and severity were tested: i) physical performance would differ across games over the 26-day period, ii) physical performance during the congested fixture period would differ compared to in games before and after this period, iii) physical performance of opposition teams would be greater than the reference team over the prolonged period of fixture congestion; iv) match injury rates and severity would be greater during the prolonged period of fixture congestion compared to outside this period.

Methods

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Participants and match sample

Physical performance and injuries sustained in official competition were analysed in players from a professional soccer team that competed in the French League 1 (highest standard in French soccer). Performance data were collected from 6 French League 1 and 2 UEFA Europa League games played consecutively over a 26-day period. Matches were played on the 28/11/2009, 02/12/2009, 06/12/2009, 10/12/2009, 13/12/2009, 17/12/2009, 20/12/2009 and 23/12/2009). Competition commenced at either 5 p.m., 7 p.m. or 9 p.m. Data were also collected for matches before ($n = 9$) and after ($n = 13$) the prolonged period of fixture congestion.

This study generally meets the standards for research cited in the International Journal of Sports Medicine [18]. However, usual appropriate ethics committee clearance required by the International Journal of Sports Medicine was not sought as the present data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season [30]. Nevertheless, to ensure team and player confidentiality, all match performance and injury data were anonymised before analysis.

Match performance data collection procedures and measures

A semi-automatic computerised tracking system for soccer (AMISCO Pro®, Sport-Universal Process, Nice, France) was used to characterise match activity profiles in the reference team. This multiple-camera system passively tracks the movements of every player using a sampling rate of 10.0 Hz over the entire course of matches. The function, accuracy and reliability of the AMISCO Pro® system in measuring player movements in elite soccer competition have been described in detail elsewhere [6,26].

The measures of physical performance in match-play for the team as a whole included an analysis per minute in metres (m) of the overall distance covered and distances run in light-intensity (0.0–11.0 $km\cdot h^{-1}$); low-intensity (11.1–14.0 $km\cdot h^{-1}$); moderate-intensity (14.1–19.0 $km\cdot h^{-1}$) and high-intensity (>19.1 $km\cdot h^{-1}$) [3]. Data on the overall distance covered and that run in high-intensity activity, respectively, were collected for each half of games. Finally, the overall distance covered in individual ball possession was recorded. Only match performance in outfield players was included for analysis.

Injury collection procedures

First team match injuries were considered and inclusion criteria were those injuries leading to an outfield player being unable to fully participate in future training or matches (i.e., time-loss injury). Individual exposure time to match-play was collected to calculate injury incidence. Injuries are thereby presented as the number of injuries per 1 000 h exposure time. The type, location, and severity of the injury (lay-off time) were prospectively recorded by the team physician, the latter depending on the number of days the player was absent from and unable to take full part in collective training or competition. All injuries were followed until the final day of rehabilitation. Finally, the cause (contact or non-contact) of injuries was recorded. The methodologies and definitions of injury used in the present study closely follow those recommended by the International Soccer Injury Consensus Groups [15,17].

After and between match procedures

Recovery procedures employed post and between matches in the present club are based on those previously described in professional soccer [11] and elite academy players [2]. Contrast therapy (hot and cold water immersion) [2] was performed after match-play and lower-limb compression garments were worn by players [11]. In addition to these techniques, players generally had a Jacuzzi, a whole-body manual massage intervention and used lower-limb compression garments on the days between matches. When rest days were not imposed between competition, players performed short low-intensity training sessions (cycling and/or tactical/technical drills) and had video feedback sessions. Immediately after each match was completed, participating players consumed fluids and high-glycemic index carbohydrate foods and proteins and nutritional advice was provided to ensure that players had adequate nutrient and fluid intake over the 26-day period [11].

Statistical analyses

All statistical analyses were conducted using SigmaStat 3.5 (Systat Software, Point Richmond, California). Results are reported as means and standard deviations unless otherwise stated (mean ± SD). Before using parametric tests, the Kolmogorov-Smirnov test completed by Lilliefors' correction was used to evaluate normality of distribution of the data. A 1-way repeated measures ANOVA was used to compare outcome measures in each category of physical performance (overall distance covered per min and that in light-; low- moderate- and high-intensity running and in individual ball possession) across: 1) 8 games played over the 26-day period, and; 2) games played before (n = 9), during (n = 8) and after (n = 13) the congested fixture period. A 2-way repeated measures ANOVA was used to investigate changes in the overall distance covered and that run in high-intensity exercise across match halves over the 8 games played in a 26-day period. A 2-way repeated measures ANOVA was additionally employed to compare outcome measures in each category of physical performance between the reference team and opposition teams over the 8 games. Finally, a paired t-test was used to compare injury incidence and lay-off time for matches during and outside the congested fixture period. Follow-up post hoc univariate analyses using Tukey's Honestly Significant Difference test were used where appropriate. Statistical significance was set at $p < 0.05$. Coefficients of variation (CV) and their 95 % confidence intervals were calculated using the spreadsheet developed by Hopkins [19] to examine variability across matches for the measures of physical performance [16]. Cohen's d effect sizes for identified statistical differences were determined. When calculating effect sizes, pooled standard deviations were applied due to the absence of a control group. Effect sizes (ES) with values of 0.2, 0.5, and 0.8 were considered to represent small, medium, and large differences respectively [10].

Results

▼

Player participation

Over the 26-day period, the total exposure time to match-play for all players was 139.3 h. Altogether, 19 players from a squad of 26 professional players (73.1 %) participated in at least 1 or more matches and 2 players (1 goalkeeper and 1 central-defender) completed every game. In addition, 6 players participated in every game either as a starter or substitute, and 8 players participated in 75 % or more of the total number of minutes (8 357 min) played by the team. No sending offs occurred but 2 players incurred a 1-match suspension for accumulation of cautions. The maximum number of substitutes was used in every match and all substitutions were made in the second half.

Match performance

Across the 8 successive matches, a difference was reported for the overall distance covered ($p < 0.001$). More distance was run both in games 4 and 7 compared to 2 and 3, respectively (ES for these differences ranged from 0.8–1.0) (▸ **Table 1**). The distance covered at light-intensities also varied across games ($p < 0.001$) with more distance run in game 4 vs. 1, 2, 3, 5 and 6 and in game 8 vs. game 3 (ES for these differences ranged from 1.0–1.9). No differences were reported for distance covered in high-intensity, moderate or low-intensity running or that in individual possession of the ball although the latter approached significance ($p = 0.059$). The respective mean coefficient of variations across the 8 games for the overall distance run, distance run in high-intensity matches and in ball possession notably were: 5.7 % (CI 4.9–7.0 %), 33.5 % (CI 28.1–41.9 %) and 70.0 % (CI 57.6–90.3 %).

The comparison of physical performance in matches played before, during and after a prolonged period of fixture congestion showed no difference for the overall distance run ($p = 0.990$) or that covered in high-intensity ($p = 0.442$), moderate-intensity ($p = 0.424$), low-intensity ($p = 0.453$), light-intensity ($p = 0.059$) running or in individual possession of the ball ($p = 0.617$). The coefficients of variation for the accumulated means of performance for matches played before, during and after the prolonged period of fixture congestion were 2.0 % (CI 1.5–3.0) for the overall distance run and 10.4 % (CI 7.9–16.1 %) for the distance run in high-intensity, respectively ▸ **Table 2**.

The overall distance run was similar between the 1st and 2nd half over all 8 games combined ($119.6 \pm 8.0\ m \cdot min^{-1}$ vs. $120.0 \pm 12.0\ m \cdot min^{-1}$, $p = 0.728$) and no changes were observed for distance covered between halves in any of the successive matches ($p = 0.175$). Similarly, the distance covered in high-intensity activity did not differ between the 1st and 2nd half over all 8 games combined ($10.9 \pm 3.1\ m \cdot min^{-1}$ vs. $13.0 \pm 4.8\ m \cdot min^{-1}$, $p = 0.383$) and no differences were observed for this measure of performance between halves in any of the individual matches ($p = 0.189$).

No differences in means for the 8 games combined were observed between the reference team and opponents for any of the performance measures: overall distance ($120.7 \pm 8.4 \cdot min^{-1}$ vs. $118.1 \pm 7.1\ m \cdot min^{-1}$, $p = 0.122$) and distance in high-intensity (11.0 ± 2.9 vs. $10.4 \pm 2.3\ m \cdot min^{-1}$, $p = 0.141$), moderate-intensity (19.6 ± 4.4 vs. $18.6 \pm 3.1\ m \cdot min^{-1}$, $p = 0.268$), low intensity (18.3 ± 2.0 vs. $17.6 \pm 2.1\ m \cdot min^{-1}$, $p = 0.380$) and light-intensity (71.8 ± 1.8 vs. $71.5 \pm 2.41\ m \cdot min^{-1}$, $p = 0.150$) movement. In contrast, the overall distance covered varied across individual games ($p < 0.001$). More distance was covered in match 6 by the opposition ($131.5 \pm 13.2\ m \cdot min^{-1}$ vs. $119.8 \pm 7.8\ m \cdot min^{-1}$, $p < 0.01$, ES = 0.7) whereas this was the case for the reference team in match 5 ($122.0 \pm 13.9\ m \cdot min^{-1}$ vs. $115.2 \pm 9.6\ m \cdot min^{-1}$, $p < 0.05$, ES = 0.6). Similarly, the distance covered in high-intensity running varied across successive games ($p = 0.040$) with the distance run in match 6 being greater in the opposition ($13.6 \pm 5.6\ m \cdot min^{-1}$ vs. $10.9 \pm 3.9\ m \cdot min^{-1}$, $p < 0.05$, ES = 0.6). Low-intensity distance also varied across successive games ($p < 0.001$) as the overall distance run per min in match 6 was greater in the opposition ($22.9 \pm 6.1\ m \cdot min^{-1}$ vs. $17.7 \pm 2.0\ m \cdot min^{-1}$, $p < 0.001$, ES = 1.2)

Table 1 Changes in measures of physical performance in a reference team over a prolonged congested fixture period of 8 successive matches in 26 days.

Distances Covered	Match 1 28/11/09	Match 2 2/12/09	Match 3 6/12/09	Match 4 10/12/09	Match 5 13/12/09	Match 6 17/12/09	Match 7 20/12/09	Match 8 23/12/09	Statistical Difference	Post hoc Difference
overall distance	119.8 ± 8.3	116.0 ± 8.0	115.5 ± 11.0	126.6 ± 12.3	122.0 ± 13.9	119.8 ± 7.8	125.0 ± 13.2	120.9 ± 11.0	$p<0.001$	Match $4>2^b,3^b$; Match $7>2^c,3^c$
high-intensity	12.0 ± 3.3	9.5 ± 3.2	9.9 ± 5.6	12.2 ± 6.7	11.2 ± 4.6	10.9 ± 3.6	11.7 ± 3.9	11.0 ± 3.2	$p=0.413$	
moderate-intensity	20.2 ± 5.8	18.3 ± 5.0	18.9 ± 5.1	19.4 ± 5.5	19.5 ± 7.9	20.9 ± 4.3	21.2 ± 7.6	18.4 ± 5.3	$p=0.580$	
low-intensity	17.0 ± 3.2	16.4 ± 3.8	17.5 ± 3.1	19.5 ± 4.9	19.8 ± 5.1	17.7 ± 2.0	19.9 ± 3.8	18.4 ± 3.3	$p=0.076$	
light-intensity	70.6 ± 2.4	71.8 ± 3.4	69.3 ± 2.6	75.5 ± 3.8	71.5 ± 3.1	70.3 ± 2.8	72.2 ± 3.2	73.1 ± 3.8	$p<0.001$	Match $4>1^a,2^c,3^a,5^c,6^a$; Match $8>3^c$
running with ball	1.9 ± 1.9	2.1 ± 0.8	1.9 ± 1.0	2.2 ± 1.0	2.2 ± 1.4	1.8 ± 0.7	3.2 ± 1.7	2.8 ± 0.9	$p=0.053$	

Distances covered are presented as metres run per min

$^a = p<0.001$

$^b = p<0.01$

$^c = p<0.05$

while more distance was covered by the reference team in match 8 ($18.4 \pm 3.3\,m \cdot min^{-1}$ vs. $15.2 \pm 3.2\,m \cdot min^{-1}$, $p<0.05$, ES = 1.0). Distances covered in light- ($p=0.487$) and moderate-intensity exercise ($p=0.074$) did not differ between the reference team and opponents in any of the games.

In opponent teams, the mean coefficient of variation across the 8 games for the overall distance run and distance run in high-intensity matches, respectively, was: 7.6% (CI 6.5–9.3%) and 34.3% (CI 28.7–42.9%).

Match-play injuries

Of the 19 players who participated in 1 or more of the matches in the series, 26.3% sustained an injury. A total of 7 match injuries were reported over the 26-day period. The incidence of injury across the prolonged period of fixture congestion was similar to that reported in matches played outside the study period (50.3 vs. 49.8 per 1000 h exposure, $p=0.940$). The mean lay-off duration for injuries was shorter for matches during the congested period compared to those outside the study period (2.0 ± 1.5 days vs. 7.9 ± 14.6 days, $p=0.043$, ES = 0.6). The majority of injuries were classed as minor (6 out of 7, 85.7%) with only 1 injury requiring a longer lay-off period (5 days in total). Injuries included: 4 contusions affecting the quadriceps (1), knee (1) and foot (2) regions, 2 muscle strains affecting the groin (1) and hamstrings (1) regions and 1 sprain affecting the ankle region. All contusions were sustained after direct contact with an opponent whilst both strain and sprain injuries were incurred in non-contact situations.

Discussion

This study is unique as it is the first to investigate variations in physical performance and injury risk and severity in a professional soccer team over a prolonged period of fixture congestion: 8 successive matches over a 26-day period. The major findings were that the overall distance covered per min and that in light-intensities varied across games whereas the distance covered in high-intensity running was unchanged. The overall distance covered and distance run in high-intensity exercise across match halves were unaffected during the congested fixture period and performance in these 2 measures did not differ for matches played before, during and after the prolonged period of fixture congestion. Performance in all physical performance measures was globally consistent in relation to the performance of opponents but the overall distance covered and that in low- and high-intensity running did vary across individual games. While injury rates in competition during the congested period of fixtures were similar to that reported in matches outside this period, the mean lay-off duration of injuries was substantially shorter during the congested fixture period.

In the present study, the overall distance run per min and that covered at light-intensities varied across 8 consecutive games played over a 26-day period. This result suggests that overall physical performance was affected for the team as a whole during a prolonged period of fixture congestion. Indeed, substantial differences were observed between matches (mean coefficient of variation of 5.7% across 8 games) and the present team was statistically outperformed by its opponents in 1 match. However, the overall distance covered by the reference team was lowest in the 2nd and 3rd games, respectively, and was actually higher in the final vs. the first game in the series. Therefore,

Table 2 Comparison of the means for measures of physical performance in a reference team in matches played before, during and after a prolonged period of fixture congestion of 8 successive matches in 26 days.

Distances Covered	Before n = 9	% difference in means	During n = 8	% difference in means	After n = 13
total distance	120.8 ± 6.3	− 0.2 (− 2.1–1.7)	120.7 ± 8.4	+ 0.1 (− 1.3–1.5)	120.9 ± 9.1
tigh-intensity	10.4 ± 2.6	+ 5.9 (− 2.2–14.7)	11.0 ± 2.9	− 0.8 (− 9.3–8.4)	11.1 ± 3.8
moderate-intensity	19.2.2 ± 3.1	+ 1.2 (− 5.4–8.1)	19.6 ± 4.4	+ 2.7 (− 4.6–10.6)	20.1 ± 4.6
low-intensity	18.8 ± 2.0	− 2.6 (− 6.6–1.5)	18.3 ± 2.0	+ 1.2 (− 3.1–5.6)	18.6 ± 2.2
light-intensity	72.4 ± 1.4	− 0.9 (− 2.0–0.3)	71.8 ± 1.8	− 0.9 (− 2.7–0.8)	71.1 ± 1.0
running with the ball	2.4 ± 0.6	− 7.2 (− 24.7–14.3)	2.3 ± 0.6	− 0.5 (− 20.4–24.2)	2.3 ± 0.6

Distances covered are presented as metres run per min
% difference in means are presented with 95 % Confidence Intervals

these variations in overall running performance might be linked to other factors rather than residual fatigue accumulated over the sequence of games. Changes over the consecutive games in the reference team's choice of starting line-up and tactics and/or in the specific physical and skill demands, playing style and team formation imposed by 8 separate opponents [4, 16, 25] could explain these variations.

The overall distance run per player per half did not differ over the study period showing that the team was able to consistently maintain overall performance in the second-half of matches throughout the 8 successive matches. In addition, the overall distance run was similar when compared to that observed in games played both before and after the period of fixture congestion. Importantly, variability in this measure of physical performance across games was higher in opponent teams yet the reference team was generally able to respond to these changing physical demands as the team ran more distance overall in 6 out of 8 matches. Taken together, these results generally suggest that the present team was able to maintain overall physical performance even when subjected to a high number of games within a short time period.

The lack of a statistical difference in high-intensity running performance across the 8 successive matches for the team as a whole is generally in line with previous findings showing that high-intensity activity profiles are not affected by a short time-frame between successive professional soccer matches [7, 11, 24, 27]. However, these previous studies investigated sporadic congested fixture schedules and only analysed high-intensity performance across 2 or 3 consecutive matches within a short time-frame. The findings from the present report are therefore noteworthy as these are the first to show that professional soccer players are generally able to maintain high-intensity running performance over a prolonged period of fixture congestion. The relatively large variation in the distance run at high-intensity reported across the 8 games (mean coefficient of difference of 33.5 %) nevertheless merits attention. Indeed, the large natural variability inherent to high-intensity running exercise in professional soccer could have masked any real changes in physical performance across the 8 consecutive matches. A larger sample size than the one used in the present study combined with a more detailed breakdown of composite high-intensity activity into discrete components (e.g., high-speed running, sprinting) might be necessary to enable better detection of real systematic variations in high-intensity running performance during periods of fixture congestion [16].

In addition to the lack of change in high-intensity running distance across the 8 consecutive games, performance in this measure was also comparable to that in matches played both before and after the extended period of fixture congestion and was maintained in the second-half of the 8 successive games. Furthermore, the reference team outperformed the opposition in 6 out of 8 games in high-intensity running performance. Overall, the reference team performed approximately 5 % more distance in high-intensity exercise across the 8-games again, suggesting that performance in this measure was maintained. Further research is nevertheless recommendable to investigate whether inter-individual changes occur in physical performance for individual players participating in several consecutive matches over a short period. Similarly, analysis of the effects of individual playing position on variations in competitive running performance over a prolonged period of fixture congestion is warranted. Indeed, related research in professional soccer has reported substantial differences in match-to-match variability in high-intensity exercise across playing positions [16].

Several explanations for these findings can be forwarded including player rotation strategies either due to tactical choice and/or forced changes due to injury or suspension which might have kept the team 'fresh' as a whole and/or the post-match recovery techniques in place at the present club. It has been suggested that coaches, sports scientists, and medical teams should consider player rotation during fixture congestion to aid in maintaining health and performance [11, 13]. Over the present series of matches, 19 players were used in total, only 6 players participated in every game as a starter or substitute, and a single outfield player completed every game. These player rotation practices would therefore appear to have contributed to the maintaining of physical performance across the multiple games.

In addition, all players who participated in competition benefited from the implementation of systematic evidence-based post-match recovery procedures described earlier. When physical performance is likely to be impaired as a consequence of insufficient recovery time between matches, recovery interventions during the post-game period can provide a benefit to performance in the subsequent match [11]. Immediately after each match was completed, contrast bathing immersion was used as this can minimize player perception of leg soreness and general fatigue associated with playing successive matches [28]. 2 related studies conducted in highly-trained elite youth [2] and amateur junior soccer players [29] have shown that post-match recovery interventions using hydrotherapy and/or cryotherapy techniques (e.g., sauna, cold water immersion, jacuzzi) were effective in maintaining running performance in consecutive games played within a short time delay. However, while the present evidence tends to provide support for the use of the present post-match recovery techniques to maintain athletic performance during a prolonged period of fixture congestion, further experimental research using a control group in which no recovery interventions are performed is necessary.

Further explanations for the lack of a decline in high-intensity running performance across 8 successive matches might include the regulation of movement behaviour by players in the knowledge that they will be required to participate in successive games separated by a short interval [27]. However, running performance did not statistically differ to that observed in games played outside this period suggesting habitual performance was maintained despite fixture congestion. The physical efforts of substitutes might also have contributed to these findings as research has shown that replacement players can play a significant role in maintaining and/or increasing running performance at high-intensities [5,23]. Additional analyses on the present dataset show that this could have been the case as the distances run at high-intensities over the total time played by substitutes was substantially greater than those covered by the players they directly replaced (15.2 ± 5.8 vs. 11.3 ± 2.9 m per min, $p = 0.014$).

In a study of match injury in 23 professional European soccer clubs, an incidence of approximately 28 injuries per 1 000 h competition has been reported [12] compared to ~50 per 1 000 h in the present study suggesting that the present players were generally more at risk of sustaining injury in match-play. However, injury rates in competition during the congested fixture period were similar to those observed in matches outside this period. This finding is partly in contrast with the results from a related study in that sporadic fixture congestion was associated with a significantly higher incidence of injuries [11]. In addition, only a small percentage of the total number of working days was lost (2.9 %) and a single match missed due to injury. Furthermore, only 3 non-contact injuries were sustained and the mean layoff of injuries sustained in matches during the congested fixture period was significantly shorter than that observed in matches outside this period. These encouraging findings generally lend support to previous research conducted in the present club which showed that sporadic congested fixture schedules do not affect injury rates or severity [9]. Again, effective player rotation policies and recovery strategies as well as controlled functional injury prevention and rehabilitation protocols [8] currently in place at the present club might have contributed to these findings.

In summary, this study provided a valuable opportunity to study physical performance, injury risk and severity in match-play over a prolonged period of fixture congestion. Physical performance and injury rates were generally unaffected which shows that coaches, support staff and players in high-performance teams in a professional setting can cope with a congested playing calendar. As a whole, these results also lend support to findings observed in professional Spanish soccer in that players are capable of coping with a busy match schedule as the results of Spanish teams in official competition were not affected by fixture congestion [21]. Indeed, a total of 7 victories and 1 defeat were recorded by the present club over the 8 successive games (27 goals scored vs. 7 conceded) showing that the team coped well with a dense and prolonged match calendar. Additional research is nevertheless necessary using a larger sample of clubs and across different countries as the present cohort included players from 1 club. The patterns observed therefore, might only be a reflection of this particular team. Finally, an analysis of the potential variations in physiological responses to match-play across a similar prolonged period of fixture congestion is also merited. Data on objective markers of fatigue such as plasma creatine kinase concentration [14] combined with subjective measures of performance (e. g., rating of perceived exertion and sleep quality) could provide additional information on the individual and team responses to fixture congestion.

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The Effect of a Cold Environment on Physical Activity Profiles in Elite Soccer Match-Play

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Abstract

In this study, the effect of cold temperature on the physical activity profiles of professional soccer players in official match-play was investigated. Computerised motion-analysis was used to analyse performance in 9 players (4 defenders and 5 midfielders) in 4 temperature ranges: ≤5 °C (29 matches), 6–10 °C (62 matches), 11–20 °C (48 matches) and ≥21 °C (27 matches). Performance was analysed per minute for total distance covered and distance run in 3 categories: 0.0–14.3 km/h (walking/low/moderate); 14.4–19.7 km/h (running); ≥19.8 km/h (high-intensity). Results showed that while total distance run per minute was unaffected in colder conditions, midfielders ran significantly shorter distances in warmer temperatures: ≥21 °C = 118.7 ± 6.9 m vs. ≤5 °C = 124.2 ± 7.1 m, $p<0.01$; 6–10 °C = 123.6 ± 6.8 m, $p<0.01$; and, 11–20 °C = 123.4 ± 5.4, $p<0.05$). The total distance covered at 3 intensities and across halves was unaffected by temperature. Similarly, high-intensity efforts across match halves and in the first and final 5-min periods in each half of normal time were unaffected by temperature. In contrast, high-intensity efforts in midfielders across 15-min intervals were affected by temperature with greater distances covered per minute in the 30–45 min period in matches played in temperatures ≤5 °C vs. the corresponding period in those played in temperatures ≥21 °C (9.1 ± 3.8 m vs. 6.2 ± 3.0 m, $p<0.05$). The present findings generally suggest that physical performance in professional soccer does not decrease in cold temperatures.

Introduction

Soccer training and competition are often performed by players in unfavourable environments. Indeed, there are 3 major environmental conditions that raise concerns in relation to soccer performance: high altitude, heat and humidity, and cold [4]. For example, altitude negatively impacts physical performance by impairing aerobic power and delaying recovery of high-energy phosphates between high-intensity "interval" type efforts [14]. 2 recent studies [11, 13] have also attempted to address the issue of high ambient temperatures on physiological responses and physical activity profiles in soccer competition. A pronounced reduction in high-intensity running was observed toward the end of a friendly game (−54 % in the final compared to the first 15-min period) played by professional Spanish soccer players in a hot environment (~31 °C) [11]. Second-half high-intensity running performance in Turkish semi-professional players was also shown to be substantially affected in 2 games played in temperatures >30 °C (mean decrease of 19 %) [13]. Thermal stress and dehydration were factors linked to the drop in performance. However, these studies examined the effects of temperature on performance in 1 or 2 matches. The inherent variability in running performance in match-play means that research requires larger sample sizes in order to detect real systematic changes in characteristics of performance [6].

The issue of training and playing soccer in cold conditions has not been studied in a satisfactory manner [4]. A decrease in muscle temperature can affect the ability to produce dynamic explosive contractions [12] inducing significant decreases in sprinting ability [10]. Explanations for impaired muscle performance in the cold include a decreased mechanical efficiency of muscles and vasoconstriction leading to a reduced oxygen delivery [12]. Yet, it is unknown to what extent cold will influence physical activity patterns in intermittent endurance type sports such as soccer. In light of this, information on the impact of playing soccer in cold temperatures on key aspects of performance such as the total distance run and that covered in high-intensity running and on work-rate across different match periods could be useful to inform subsequent preparation strategies. Consequently, the aim of this study in French professional soccer players was to investigate the effect of cold temperatures on physical activity profiles during official competition.

Material and Methods

Participants and match sample

Physical performance in official competition was analysed for players from a professional soccer team that competed in the French Ligue 1 (top-flight division). While this study meets the ethical standards of the International Journal of Sports Medicine [7], these data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season [15]. Therefore, usual appropriate ethics committee clearance was not required. Nevertheless, to ensure team and player confidentiality, all performance data were anonymised before analysis.

Altogether, performance in 80 French League 1 games over 4 seasons (2007/2008: N=16, 2008/2009: N=26, 2009/2010: N=26, 2010/2011: N=12) was analysed. The sample included 50 home and 30 away matches in which players completed the entire match and played in their customary role. A total of 4 defenders and 5 midfield players were included for analysis leading to 173 and 166 instances of match performance, respectively. Forward players were not included due to insufficient numbers of games completed in different temperatures.

Data collection procedures and measures of competitive performance

Measures of ambient temperature within a 1-h period prior to kick-off in French Ligue 1 games are systematically taken by match-day officials belonging to the French Professional Football League [8]. The present measures were subsequently obtained from the League. The following temperature classification was employed: ≤5 °C = very cold, 6–10 °C = cold, 11–20 °C = moderate and ≥21 °C = warm. In defenders and midfielders respectively, 28 and 29 instances of performance were collected at temperatures ≤5 °C, 70 and 62 instances at 6–10 °C, 49 and 48 instances at 11–20 °C and 26 and 27 instances at ≥21 °C.

A semi-automatic computerised player tracking system (AMISCO Pro®, Sport-Universal Process, Nice, France) was used to analyse physical activity profiles in official match-play. This multiple-camera system passively tracks the movements of every player using a sampling rate of 10.0 Hz over the entire course of matches. The workings, accuracy and reliability of this system in measuring player movements in elite soccer competition have been described in detail elsewhere [2].

The measures of physical performance selected for the analyses included the total distance covered and the distance covered in 3 categories of movement intensity: 0.0–14.3 km/h (low/moderate); 14.4–19.7 km/h (running); ≥19.8 km/h (high-intensity) [3]. The overall duration of matches and halves frequently varied. Therefore, all distances covered are presented as the distance covered per minute (distance divided by duration of entire match or individual match period). A drop in high-intensity running performance is frequently observed at the end compared to the beginning of match halves (2). Therefore, distances covered at high-intensities were compared across selected intervals in normal match time: 0–5 mins, 40–45 mins, 45–50 mins and 85–90 mins, and; 0–15 mins, 15–30 mins, 30–45 mins, 45–60 mins, 60–75 mins and 75–90 mins.

Statistical analyses

All statistical analyses were conducted using SPSS for Windows Version 14.0 (SPSS Inc., Chicago, IL, USA). Results are reported as means and standard deviations (mean ± SD). 2-way ANOVAs were used separately for each playing position to compare overall performance across temperatures ranges and to identify the interactions between temperature and distance covered at various running intensities and across selected match periods. Follow-up univariate analyses using Bonferroni-corrected pair wise comparisons were used where appropriate. Statistical significance was set at $p < 0.05$.

Results

In defenders, the total distance run was similar across all 4 temperature ranges ($p = 0.135$) whereas a difference in performance was observed in midfielders ($p = 0.002$). A longer overall distance was covered by the latter in games played in all temperatures compared to those in temperatures ≥21 °C (see **Table 1**). Temperature did not influence the distances covered at 3 individual running intensities in defenders ($p = 0.943$) or midfielders ($p = 0.271$).

The comparison of match halves (**Table 1**) showed that the total distance run varied across halves in defenders and midfielders (both $p < 0.001$) as significantly more distance was run in the first- vs. the second-half in all temperatures ranges (statistical differences ranged from $p < 0.05$ to $p < 0.001$). However, performance in each respective half was not influenced by

Table 1 Comparison of the total distance run and distance covered at different intensities and between match halves in 4 temperature ranges.

Distance run	Defenders				Midfielders			
(metres/min)	≤5 °C	6–10 °C	11–20 °C	≥21 °C	≤5 °C	6–10 °C	11–20 °C	≥21 °C
total distance	114.0 ± 6.7	116.0 ± 6.9	114.7 ± 6.0	113.3 ± 6.7	124.2 ± 7.1	123.6 ± 6.8	123.4 ± 5.4	118.7 ± 6.9*
1st half	116.1 ± 7.0	118.4 ± 7.9	118.4 ± 7.1	116.9 ± 6.9	126.5 ± 7.4	125.3 ± 7.4	126.2 ± 7.1	121.0 ± 8
2nd half	112.1 ± 7.9	113.7 ± 7.4	111.2 ± 6.9	110.0 ± 7.9	122.0 ± 7.9	122.1 ± 8.2	120.7 ± 5.3	116.5 ± 6.6
0–14.3 km/h	91.2 ± 3.5	91.9 ± 3.5	91.3 ± 4.0	90.6 ± 3.6	94.3 ± 5.2	94.3 ± 4.2	93.8 ± 3.5	93.0 ± 4.9
14.4–19.7 km/h	15.6 ± 2.5	16.2 ± 3.2	15.7 ± 2.6	15.0 ± 2.9	21.8 ± 4.3	21.2 ± 3.7	21.3 ± 3.5	18.1 ± 4.0
≥19.8 km/h	7.2 ± 3.0	7.9 ± 3.0	7.6 ± 2.6	7.7 ± 2.5	8.1 ± 2.4	8.1 ± 2.2	8.2 ± 2.3	7.5 ± 2.4
1st half	7.2 ± 3.1	8.0 ± 3.3	8.1 ± 3.3	8.1 ± 2.5	8.0 ± 2.7	8.1 ± 2.8	8.1 ± 2.5	7.4 ± 2.7
2nd half	7.3 ± 3.5	7.8 ± 3.8	7.3 ± 2.5	7.4 ± 3.0	8.2 ± 2.9	8.1 ± 2.4	8.3 ± 2.8	7.6 ± 2.9

* Lower total distance covered in matches played by midfielders at temperatures ≥21 °C vs. ≤5 °C ($p < 0.01$), 6–10 °C ($p < 0.01$) and 11–20 °C ($p < 0.05$)

temperature in either defenders ($p=0.439$) or midfielders ($p=0.685$). In all temperatures, the distance run at high-intensities did not change between halves in either defenders ($p=0.269$) or midfielders ($p=0.625$) and performance in each respective half was not affected by temperature (defenders: $p=0.847$; midfielders: $p=0.994$).

The total distance covered varied across 15-min game intervals for matches played in all 4 temperatures ranges in defenders and midfielders (both $p<0.001$). However, no interaction was observed between temperature and performance across individual match intervals (defenders: $p=0.446$, midfielders: $p=0.125$) (▶ **Table 2**). While the distance covered by defenders in high-intensity running across 15-min intervals varied for all 4 temperature ranges ($p<0.001$) this was not influenced by temperature ($p=0.854$). In midfielders, the distance covered in high-intensity running across 15-min intervals did not vary ($p=0.413$) but was dependent upon temperature ($p=0.009$) as more distance was covered in the 30–45 min period in matches played at temperatures ≤5 °C compared to the corresponding period in matches played at temperatures ≥21 °C ($p<0.05$). In addition, more distance was covered at high-intensities in the 75–90 min period in matches played at temperatures from 11–20 °C compared to the corresponding period in matches played at 6–10 °C ($p<0.05$).

In both defenders ($p=0.038$) and midfielders ($p=0.016$), the total distance covered in high-intensity running varied across selected 5-min game intervals in normal time for matches played in different temperatures. In midfielders, a greater distance ($p<0.05$) was covered in games played at 11–20 °C for the first 5-min of play compared to the final 5-min of play in normal time of the first half (40–45 mins) (▶ **Table 2**). No significant post hoc differences were obtained in defenders. No interaction was observed between performance and temperature for any of the 5-min intervals in either defenders ($p=0.604$) or midfielders ($p=0.546$).

Discussion

In this study, an investigation into the effects on physical activity profiles of playing professional soccer in a cold environment was conducted. The main finding is that cold weather was not detrimental to overall physical performance (total distance and distances covered at 3 running intensities) in defenders and midfielders and that first and second-half running performance was unaffected in cold conditions. While the total distance covered across 15-min match intervals was unaffected in colder temperatures, a significant difference in performance in high-intensity running across intervals was observed in midfielders. In contrast, high-intensity running performance in the first and final 5-min periods in each half of normal time was unchanged in cold temperatures.

In many European countries, soccer is often played in near freezing conditions which are frequently associated with a reduction in core and muscle temperature in participants [14]. Subsequently, characteristics specific to soccer performance such as muscular strength and power output may be affected. Similarly, prolonged exercise in very cold conditions (<5 °C) may also lead to dehydration and reduced high-intensity endurance performance [1]. In this study, endurance performance characterised by the total distance run was significantly related to ambient temperature. However, performance was impaired in hot but not in cold conditions. In addition, the total distance covered at 3 different speed intensities was unaffected by temperature. These results suggest that overall work-rate activity profiles and the capacity to perform intermittent exercise in these elite players were not adversely affected in cold conditions. The average exercise intensity during soccer match-play is estimated to be 75% $VO_{2\,max}$ [14]. This intensity may be sufficient to offset the deleterious effects of a cold environment on body temperature as related research showed that performance in endurance exercise at an intensity of 70% $VO_{2\,max}$ in a cold environment (4 °C) was

Table 2 Comparison of distances covered across 15-min and selected 5-min match intervals in 4 temperature ranges.

Distance run (metres/min)	Defenders ≤5 °C	Defenders 6–10 °C	Defenders 11–20 °C	Defenders ≥21 °C	Midfielders <5 °C	Midfielders 6–10 °C	Midfielders 11–20 °C	Midfielders ≥21 °C
total distance								
0–15 mins	119.6 ± 9.0	123.9 ± 9.4	124.4 ± 8.8	125.7 ± 8.3	127.3 ± 10.3	128.8 ± 9.5	131.5 ± 8.7	128 ± 9.7
15–30 mins	116.3 ± 8.2	116.6 ± 11.3	115.4 ± 9.1	114.3 ± 11.2	126.5 ± 7.0	124.9 ± 11.0	123.7 ± 10.9	119.9 ± 10.4
30–45 mins	112.3 ± 9.1	114.1 ± 9.7	113.4 ± 9.2	110.0 ± 8.6	125.2 ± 9.1	121.0 ± 10.6	122.1 ± 10.8	115.2 ± 10.4
45–60 mins	114.7 ± 9.7	118.4 ± 9.8	116.3 ± 7.4	114.8 ± 13.0	125.0 ± 12.9	124.6 ± 17.0	122.6 ± 7.3	118.9 ± 11.3
60–75 mins	109.5 ± 8.6	111.6 ± 10.0	109.6 ± 8.5	107.3 ± 8.8	117.8 ± 7.1	119.9 ± 18.1	117.0 ± 9.1	114.7 ± 9.5
75–90 mins	110.9 ± 10.4	108.1 ± 11.2	107.5 ± 11.0	107.9 ± 12.0	122.7 ± 10.7	114.9 ± 17.1	120.5 ± 8.7	117.2 ± 8.7
≥19.8 km/h								
0–15 mins	8.1 ± 4.6	8.0 ± 4.7	8.8 ± 4.8	10.1 ± 4.0	7.4 ± 3.1	8.1 ± 3.9	9.2 ± 3.7	9.0 ± 3.0
15–30 mins	7.2 ± 4.4	8.2 ± 3.9	7.9 ± 3.7	7.2 ± 3.6	7.8 ± 3.8	8.6 ± 3.9	8.0 ± 3.7	7.0 ± 3.0
30–45 mins	6.5 ± 4.2	7.9 ± 4.1	7.2 ± 4.3	7.0 ± 2.7	9.1 ± 3.8*	7.6 ± 3.9	7.1 ± 3.3	6.2 ± 3.0
45–60 mins	7.8 ± 4.0	8.2 ± 4.8	7.8 ± 3.6	8.2 ± 4.0	8.7 ± 3.5	8.1 ± 3.7	7.9 ± 3.9	7.5 ± 2.8
60–75 mins	6.2 ± 4.0	7.0 ± 3.4	6.8 ± 2.3	7.5 ± 3.1	8.0 ± 3.8	8.9 ± 3.5	7.2 ± 3.8	7.7 ± 5.0
75–90 mins	7.1 ± 4.1	6.9 ± 4.6	7.4 ± 3.1	7.0 ± 4.7	7.4 ± 3.7	7.1 ± 3.8	9.2 ± 4.2#	7.4 ± 3.7
0–5 mins	10.1 ± 6.1	8.9 ± 7.1	9.0 ± 8.4	10.1 ± 5.4	9.8 ± 6.6	9.4 ± 6.8	11.1 ± 7.4§	9.5 ± 6.9
40–45 mins	6.2 ± 5.8	7.8 ± 6.5	6.5 ± 5.5	8.4 ± 4.4	8.0 ± 5.4	8.4 ± 7.5	7.5 ± 6.2	7.4 ± 5.0
45–50 mins	7.0 ± 5.7	8.2 ± 0.6	8.6 ± 7.2	6.4 ± 5.7	7.6 ± 4.2	8.9 ± 5.8	8.5 ± 6.1	7.3 ± 4.4
85–90 mins	7.7 ± 6.5	7.1 ± 6.3	6.7 ± 4.8	6.3 ± 4.8	7.5 ± 5.8	8.3 ± 6.1	10.8 ± 6.7	6.7 ± 5.8

* $p<0.05$: Greater distance covered by midfielders at intensities ≥19.8 km/h in the 30–45 min period of play in matches played at temperatures ≤5 °C vs. corresponding period in matches played at ≥21 °C

# $p<0.05$: Greater distance covered by midfielders at intensities ≥19.8 km/h in the 75–90 min period of play in matches played at temperatures between 11–20 °C vs. corresponding period in matches played at 6–10 °C

§ $p<0.05$: Greater distance covered by midfielders at intensities ≥19.8 km/h in the first 5-min of play compared to the final 5-min of play in normal time in the first half of games played at 11–20 °C similar to that performed in moderate temperatures (11 °C) [5]. Nevertheless, the total distance covered by midfield players was significantly lower in warmer temperatures (≥21 °C) partly confirming previous findings [11,13] that warmer environments can have a detrimental impact on work-rate performance in competitive soccer.

Research in elite soccer generally shows that players cover lower total distances in the second-half of competition and that physical performance can vary substantially across different periods of the game [2]. In the present players, a reduction in the total distance covered in the second compared to the first half and a significant variation in the total distance covered across 15-min intervals were common to matches played in all temperatures. However, the differences in total distance run in the second-half and that across 15-min intervals was not related to temperature suggesting that overall running performance in the second-half and in different periods of the game is unimpaired when performing in cold (and warm) temperatures. This result may be linked to nutritional and/or pacing strategies which enabled the present players to adequately respond to match-play demands throughout [3]. It may also be linked to the physical demands imposed by opponents who also adjusted their physical efforts according to the environmental conditions.

The analysis of high-intensity efforts showed that performance across halves and in the 5-min period at the start and end of normal time in each half was unaffected by temperature. In contrast, high-intensity performance across 15-min intervals in midfielders was dependent upon temperature. Players covered a significantly greater distance in the 30–45 min period in matches played at ≤5 °C compared to the corresponding period in those played at ≥21 °C. In addition, in games played at lower temperatures (≤5 °C and 6–10 °C), the distance covered by midfield players in high-intensity running progressively increased for each 15-min period reaching its maximum just before half-time (30–45 mins) whereas in moderate (11–20 °C) and warm (≥21 °C) temperatures, performance was at its maximum at the beginning of games (0–15 mins) and then progressively decreased until half-time. This result suggests that in cold temperatures, high-intensity running performance in midfielders is to some extent affected at the beginning of games and may only reach its optimum towards the end of the first-half. An investigation into the effectiveness of pre-match warm-up regimens in a range of temperatures is therefore merited as is a study examining the effects of duration and intensity of cold exposure prior to and during exercise as these can impact subsequent physical performance [9].

Limitations of this study included the lack of information on additional environmental factors such as relative humidity and wind-chill and changes in climatic conditions over the course of games. In addition, planning for performance in the cold requires an understanding of the mechanisms underpinning the physiological response [12]. Measures of dehydration, heart rate and thermal responses and the relationship between match activity and fitness test profiles are warranted to provide additional information on the physiological strain specific to competitive play in cold environments. Finally, controlled laboratory simulations of soccer match-play could be conducted in an attempt to determine the effects of individual anthropometric characteristics (e.g., body fat percentage and body surface area) and clothing status (thermal protective garments) when performing in a cold environment.

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3 *Carling C, Dupont G.* Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? J Sports Sci 2011; 29: 63–71
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Appendix 4: Collaborative letters of support for co-authored papers

Paper 1: Carling, C., Bloomfield, J., Nelsen, L., & Reilly, T. (2008). The role of motion analysis in elite soccer: Contemporary performance measurement techniques and work-rate data. *Sports Medicine, 38,* 839-862.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study,
- formulated the study rationale, experimental design and aims,
- compiled the data,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

…………………………

Jonny Bloomfield

…………………………

Lee Nelsen

…………………………

Tom Reilly
(deceased)

…………………………

Signature of Candidate

Signature of co-authors

Paper 3: Carling, C., Le Gall, F., & Dupont, G. (2012). Analysis of repeated high-intensity running performance in professional soccer. *Journal of Sports Sciences, 30,* 325-336.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study,
- formulated the study rationale, experimental design and aims,
- collected the fitness data in cooperation with Gregory Dupont,
- compiled the data and performed the statistical analysis,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

…………………………
Franck Le Gall

…………………………
Gregory Dupont

…………………………
Signature of Candidate

Signature of co-authors

Paper 4: Carling, C., & Dupont, G. (2011). Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play? *Journal of Sports Sciences*, *21,* 63-67.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study
- formulated the study rationale, experimental design and aims,
- compiled the data and performed the statistical analysis,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

…………………………
Gregory Dupont

…………………………
Signature of Candidate

Signature of co-author

Paper 5: Carling, C., Le Gall, F., & Reilly, T. (2010). Effects of physical efforts on injury in elite soccer. *International Journal of Sports Medicine, 31,* 181-185.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study
- formulated the study rationale, experimental design and aims,
- collected the injury data in cooperation with Franck Le Gall,
- compiled and performed the statistical analysis of data,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

…………………………
Franck Le Gall

…………………………
Tom Reilly (deceased)

…………………………
Signature of Candidate

Signature of co-authors

Paper 6: Carling, C., & Bloomfield, J. (2010). The effect of an early dismissal on player work-rate in a professional soccer match. *Journal of Science & Medicine in Sport, 13,* 126-128.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study,
- formulated the study rationale, experimental design and aims,
- compiled the data and performed the statistical analysis,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

………………………….
Jonny Bloomfield

………………………….
Signature of Candidate

Signature of co-author

Paper 7: Carling, C., Espié, V., Le Gall, F., Bloomfield, J., & Jullien, H. (2010). Work-rate of substitutes in elite soccer: A preliminary study. *Journal of Science & Medicine in Sport, 13,* 253-255.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study,
- formulated the study rationale, experimental design and aims,
- compiled the data and performed the statistical analysis,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

………………..……….
Vincent Espié

………………………….
Franck Le Gall

………………………….
Jonny Bloomfield

………………………….
Signature of Candidate

Signature of co-authors

Paper 9: Carling, C., Le Gall, F., & Dupont, G. Are physical performance and injury risk in a professional soccer team in match-play affected over a prolonged period of fixture congestion? *International Journal of Sports Medicine*, *32*, 1-7.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study,
- formulated the study rationale, experimental design and aims,
- collected the injury and exposure time data in cooperation with Franck Le Gall,
- compiled and performed the statistical analysis of data,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

………………………….
Franck Le Gall

………………………….
Gregory Dupont

………………………….
Signature of Candidate

Signature of co-authors

Paper 10: Carling, C., Dupont, G., & Le Gall, F. (2011). The effect of a cold environment on physical activity profiles in elite soccer match-play. *International Journal of Sports Medicine, 32,* 1-4.

This is to declare that, as first author of the above scientific paper, Christopher Carling:

- initiated the study,
- formulated the study rationale, experimental design and aims,
- compiled the data and performed the statistical analysis,
- wrote up the manuscript, taking into account comments and suggestions from the co-authors,
- took the lead with regards to the revision of the manuscript as per the reviewers' comments.

………………………….
Gregory Dupont

………………………….
Franck Le Gall

………………………….
Signature of Candidate

Signature of co-authors

Appendix 5: Personal research output

PEER REVIEWED JOURNAL ARTICLES

Bradley, P.S., **Carling, C.**, Archer, D., Roberts, J., Dodds, A., Di Mascio, M., Paul, D., Gomez Diaz, A., Peart, D., & Krustrup P. (2011). The effect of playing formation on high-intensity activity and technical profiles in English FA Premier League soccer matches. *Journal of Sports Sciences*, *29*, 821-829.

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Carling, C., Bloomfield, J., Nelsen, L., & Reilly, T. (2008). The role of motion analysis in elite soccer: Contemporary performance measurement techniques and work-rate data. *Sports Medicine*, *38*, 839-62.

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Carling, C., Dupont, G., & Le Gall, F. (2011). The effect of a cold environment on physical activity profiles in elite soccer match-play. *International Journal of Sports Medicine*, *32*, 1-4.

Carling, C., & Dupont, G. & Le Gall, F. (2012). Analysis of repeated high-intensity running performance in professional soccer. Journal of Sports Sciences, *Journal of Sports Sciences, 30,* 325-336.

Carling, C., Espié, V., Le Gall F., Bloomfield, J., & Jullien, H. (2010). Work-rate of substitutes in elite soccer: A preliminary study. *Journal of Science & Medicine in Sport*, *13*, 253-255.

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Carling, C. (2001). Sports science support at the French Football Federation. *Insight - The Football Association Coaches Journal, 4(4),* 34-35.

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