REVIEW ARTICLE

Sports Med 2007; 37 (9): 783-805
0112-1642/07/0009-0783/$44.95/0

Future Perspectives in the Evaluation of the Physiological Demands of Soccer

Barry Drust, *Greg Atkinson* and *Thomas Reilly*

Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Henry Cotton Campus, Liverpool, UK

Contents

Abstract

Soccer (association football) is a team sport that incorporates frequent fluctuations between high and low exercise intensities. These unpredictable changes may be accompanied by unorthodox patterns of movements and the performance of specific skills. The individual activity profiles are highly variable and include elements of self-pacing, since decision making about opportunities to become engaged in play dictates individual activities. Approaches utilised to investigate the demands placed on players during competitive performances include behavioural observations during games, physiological evaluations in matches and assessments of the physical capacity of players. Observations made during games to determine the work-rate patterns of individual players are highly variable and make generalisations based on individual activity patterns conditional, unless the sample sizes are large and data are collected on a number of occasions. The data may also be affected by the diverse methodological approaches to their collection and analysis and a failure to determine the reliability and objectivity of the relevant measuring tools. Techniques that can be used to collect data in matches are limited as the sports rules and regulations restrict some approaches. The validity of applying data from non-competitive matches to the competitive situation must, therefore, be subject to formal scrutiny. There is also a concern as to the degree to which principles of steady-state are applicable to dynamically changing exercise intensities. In the evaluation of the physical capacities of players, the variability in overall soccer performance is reduced to fitness statistics, whereas in reality, soccer performance is a construct based on many different performance components and their interaction at the level of both player and team. Despite these caveats, valuable insights have been acquired into the physiological requirements of the game that have subsequently informed both research projects and impacted upon practice. The challenge for future researchers is to overcome remaining research design hurdles and devise ways to understand more fully the complexities of invasive field games such as soccer. The interactions between individuals within a team require investigation and there is a need to refine and develop methods that employ sophisticated measurement techniques and yet possess both internal and external validity, such as laboratory-based simulations.

Sport and exercise scientists engaged in soccer research are interested in a multitude of factors that determine the performance of a player as well as the related underlying phenomena that explain how each factor influences that performance. Any attempt to answer such questions requires a systematic approach to knowledge generation by means of carefully designed research programmes. This research can, according to Atkinson and Nevill,[1] be placed on a continuum from 'basic' to 'applied' in nature. Basic and applied research can, therefore, be visualised as lying at opposite ends of a continuum[2] (see figure 1).

The distinction between basic and applied research is important, since it dictates the outcomes and conclusions that can be drawn from the results.[2] Nevertheless, this distinction has not really been discussed in relation to research in a soccer context. This omission is surprising given that the form of research (applied or basic) is important in determining not only the type of knowledge that is generated, but also how significant an impact the information has for soccer performance.

It is clear that the advancement of knowledge in any soccer scenario would require an equal commitment to both basic and applied research. Atkinson and Nevill[1] stated that the context of the research question, in relation to the basic–applied continuum, should be decided *a priori*, although it is not clear if such considerations are incorporated in the initial research design considerations in the field of soccer research. A failure to acknowledge the importance of such issues may lead to poorly designed research projects or even to conclusions and recommendations that are incorrect and misleading. These errors may ultimately prevent advances in the understanding of the sport and applied practice of coaches and players.

This article provides a systematic examination of the published research concerned with evaluations of the physiological demands of soccer. This article attempts to contextualise the available data on the basic–applied research continuum and to critically evaluate the current state of knowledge with respect to the demands of the game. It is hoped that this critical analysis will result in the development of a framework for evaluating soccer research and provide some guidance for future investigators. It is not the intention of this article to comprehensively summarise the available information on the physiological demands of match-play. Such information can be found in several excellent recent reviews.[3,4]

1. The Complexities of Performance in Soccer

Soccer (association football) is regarded primarily as an aerobic sport that includes frequent bouts of activity.[5,6] The activity periods vary in intensity and duration and are punctuated by recovery pauses when activity is light or the player is static. Superimposed on this erratic activity profile are actions directly related to involvement in play; these include

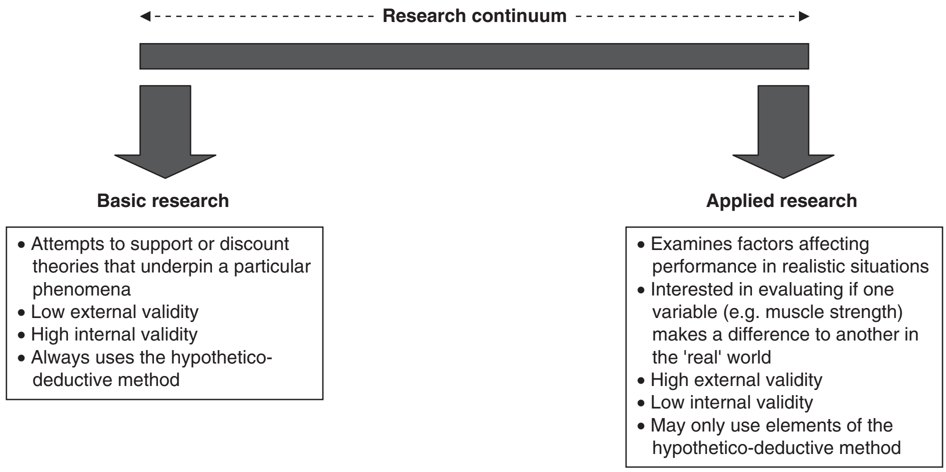

Fig. 1. Characteristics of basic and applied research.

the execution of tackles, physical challenges with opponents in contesting possession of the ball, jumping to head the ball, kicking and passing, throwing the ball into play and so on.[7]

Whilst exercise during match-play is non-continuous, its pattern defies precise modelling. The discrete events may be broken down and typically constitute well in excess of 1000 incidents in a game,[8,9] but they do not recur in sequences that are replicated or predictable. Therefore, this acyclical pattern is not amenable to time-series analysis and is incompatible with the traditional models of studying exercise in laboratory conditions. Attempts to apply stochastic processes to the chain of events when the ball is in a team's possession have resulted in only limited success.[7] The true fidelity of laboratory-based conditions to the reality of match-play in soccer remains questionable.

An added consideration for the locomotion characteristics of players is that movement is often unorthodox. Individuals move backwards or sideways during play, sometimes with a shuffling gait, they 'jockey' for position to match the movements of their markers or they 'spin away' from their markers into clear space to secure a tactical advantage. Runs may be diagonal or angled to outwit defensive lines, and players often accelerate or decelerate quickly and over short distances. All of these unorthodox movements increase the energy expenditure over normal locomotion.[10] Dribbling the ball, whilst running, also raises the energy expenditure, heart rate, blood lactate concentration and perceived exertion.[11]

The activity profiles can also vary from game to game depending on weather conditions, the strength of the opposition, the fitness of players, the consequences of previous games and a myriad of other factors. There are also differences between players according to their playing position and fitness levels. Reilly and Thomas[8] demonstrated that the greatest distances among outfield players were covered by those in the midfield, and the least distance was completed by the centre-backs. These findings have been replicated by others.[5,12] The result of these differences is that generalisation to all players does not account for individual differences due to tactical and positional responsibilities. For example, person-to-person marking induces higher blood lactate levels during play than does a space-allocation or zone-marking system.[13]

The overall work-rate is reduced when matches are played in hot conditions compared with a comfortable temperature, the major effect being evidenced by a decrease in high-intensity exercise.[14] Altitude is also likely to reduce work-rate because of the longer recovery periods that are necessary between the strenuous efforts.[15] The pattern of activity may also be influenced by the time of day, self-paced activity over 60 minutes tending to be relatively slower at the start in the morning than when performed at the time of day when body temperature is at its circadian peak value.[16] In the latter investigation on diurnal rhythms in exercise performance, the slower morning start was compensated by a relatively higher power output in the second half of the 60-minute continuous exercise compared with the power output over the first 30 minutes. As an illustration of the impact of the basic–applied research continuum, it should be borne in mind that the study by Reilly and Garrett[16] was internally valid in that physiological responses could be precisely measured during the continuous exercise protocol. Nevertheless, the results of this study have a lower external validity for soccer performance due to the intermittent nature of exercise during match-play (see figure 2).

Whilst the demands of the match-play on individual players are imposed by direct involvement in the game, the aggregate work-rate is largely spontaneously determined by individual decision-making about opportunities to become engaged in play, since <2% of the total distance travelled is in possession of the ball.[8] Such choices are made almost continuously and reflect the self-imposition of physiological stress by the players themselves. The activity profile that is observed is, therefore, a combination of direct involvement in play, responding to attacking and defensive movements of opposing players, tactical restrictions and willingness to support team-mates. These variations are likely to result in relatively large match-to-match variability in performance. Such variability has been described for performances in athletics and swimming,[17,18] where each athlete is required to perform simpler timed bouts of exercise maximally at all times. Nevertheless, the reduction of variability in soccer performance to an overall coefficient of variation (CV) would be difficult to interpret, given the myriad of factors that influence performance in the game. This soccer-specific caveat is unfortunate, since the description of performance variability can be important for predicting statistical power in research as well as how worthwhile a certain intervention is for performance.[19] Nevertheless, it is possible to describe the component of within-subject variability for tests or observations of specific aspects of soccer performance. The impact of this within-subject variability is discussed in section 2.2.

In this section, we have set the scene for the problems inherent in evaluating soccer as an activity compared with other more continuous-based sports. It helps towards an understanding of how people attempt to evaluate the demands of match-play – observations during games, physiological measures during games and training, and determining the physical capacity of players. In the sections that

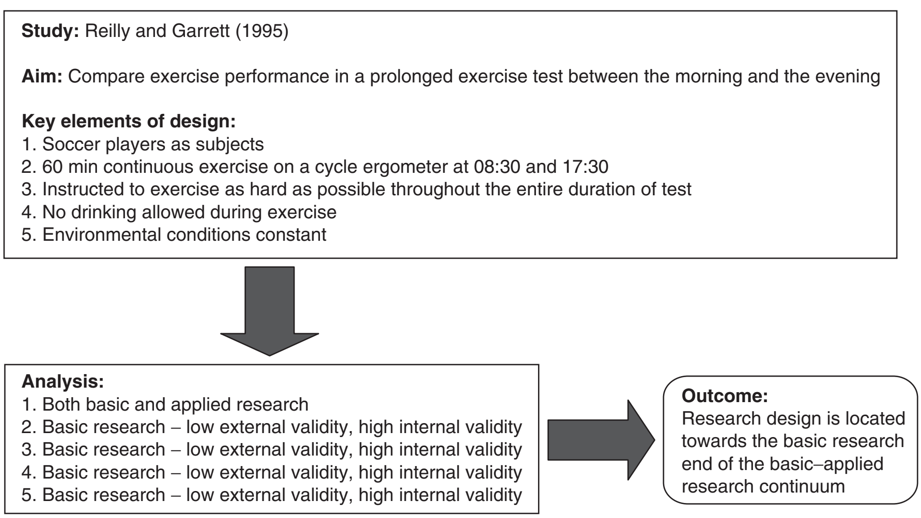

Fig. 2. Schematic representation of the evaluation of the research of Reilly and Garrett[16] in relation to the basic–applied research continuum.

follow the field observations (sections 2.1–2.3), appropriate analytical methods are considered before focusing on physiological evaluations in training and matches. The physical capacity of the individual player is considered prior to reviewing the laboratory simulations of the game that have been undertaken.

2. Field Observations (Motion Analysis)

The observation of athletes whilst they participate in specific sports may provide useful data on the physiological demands of an activity. Such approaches may be especially relevant to soccer as the application of other methodological techniques, such as the detailed recording of physiological data in competitive contexts, is limited by restricted access to elite players and the rules and regulations of the competitions in which they are involved.[20]

Work-rate or motion analysis has been used to investigate the physiological demands of soccer by a large number of authors.[8,12,21,22] The majority of these investigators have used observational techniques to evaluate the overall exercise intensity associated with match-play by recording and analysing the many different activities for the players observed.[23,24] In such approaches, the activities are frequently classified according to type, intensity (or quality), duration (or distance) and frequency.[25] These data can also then be set against a time base to provide an indication of exercise to rest ratios[26] or subjected to techniques that permit the calculation of the total distance covered or distance covered in any specific activity category to provide a measure of work-rate.[9]

The data provided by these investigators are of interest to both scientists and practitioners. The information collected should provide scientists with a detailed understanding of the physiological requirements of match-play. Such data could also have an impact upon the training regimen,[23] fitness assessment and selection of players[7] by providing an ergonomic framework for these activities.[4] The usefulness of the available data to the end user is, however, dependent on the application of correct measurement principles, the overall research design, experimental protocol and statistical analysis.[27] Appropriate application of these principles will lead to objective and quantifiable statistics that will permit principles and laws regarding the phenomena in question to be developed.

Section 2 evaluates various observational approaches that have been utilised to determine the physiological demands of soccer. This analysis should yield a methodological framework with which to evaluate the available data and provide directions for future research projects.

2.1 Evaluation of the Methodological Approaches to Motion Analysis

Standardisation of measurement methods is crucial for the development of principles and laws relating to specific phenomena.[27] An overview of the available research in this area shows that different methodological techniques have been employed to determine the demands of soccer.[25] The majority of these approaches incorporate some form of filming technique to provide a permanent record of the player's activity, although some authors[8] have completed real time analysis during match-play. The majority of work-rate profiles seem to be recorded without the specific prior knowledge of the individual in question,[28,29] although all subjects will have given their consent before being included in the sample. This seems to be a useful means of preventing the work-rate of players being artificially influenced by the observations of the research team.

The footage collected has traditionally been limited to a specific player whose activities have been recorded for the entire 90 minutes of the game;[21] however, some studies have used multiple cameras to focus on more than one individual player per game.[12] Other approaches have been to film specific players for limited periods of the match and attempt to extrapolate the work-rate from these periods to the activities expected for the entire match.[26,28,30] Incomplete recordings would seem to be limited in their ability to provide information on detailed individual work-rate profiles as the work-rate pattern is highly variable throughout a game and is, therefore, not easily predictable.[31] A thorough analysis of incomplete activity profiles may, however, be of interest in conjunction with investigations of the work-rate associated with replacement players. Mohr et al.[31] have demonstrated substantial differences in the work-rate profiles of replacement players compared with players in the starting 11 over the same period. This type of comparison provides insight into the tactical benefit of using substitutions.

Limiting the analysis of the activity profile to one player per game does not permit relationships between the concomitant work-rate profiles of teammates or opposing players to be evaluated. This information may be useful in the development of a full understanding of the tactical importance of work-rate. Attempts have been made to overcome this limitation by obtaining data on all the players involved in a given game using synchronised data from overhead views of the pitch and computer-linked analysis of movements.[32] More recently, commercial systems in use within the professional game have employed multiple cameras placed at strategically elevated positions in the stands to collect data on all the players. The images from these films are synchronized during computerised analysis to allow the collection of technical and tactical data as well as work-rate profiles, thereby providing a diverse range of information to the coach.

At the time of writing, no validated data are available in the scientific literature on the work-rate of players using this approach. This deficiency is a consequence of the data being primarily used to support the coaching processes within the professional environments. Such technology clearly has important implications for future data collection in the area, although the application of such techniques will require the methodologies employed to meet the necessary scientific criteria of quality control. This may include comparing the measurements obtained using these techniques with those already established in the literature and a detailed analysis of the errors associated with the analytical procedures used by the systems. These may include evaluations of the time taken to travel between different points on the pitch, the relative accuracy of the system when adding increasing numbers of players to the analysis area and the problems of using pre-established maximal running speeds to accurately determine intensity levels. It would, however, necessitate a wider network of stadia to be fitted with the required hardware for data capture to ensure that the information is representative of any specific level of play. Such analysis is associated with significant costs that may prohibit these techniques being employed by the research scientist. These factors may together combine to limit the application of such procedures in the scientific evaluation of the game. Irrespective of the methodological technique utilised, the importance of developing strategies that promote a better understanding of the interaction between team members and opposing players is clear. This development represents a major challenge to future researchers in this area.

Once the data are collected, the footage is replayed post-event and analysed. The classification of activities depends on the application of operational definitions to construct the instrumentation necessary for measuring the required variables.[33] The classifications used in the published literature have varied according to the aims of the investigation. The classification, therefore, tends to be quite arbitrary and based on the specific definitions adopted by the researchers in question. Some researchers have utilised more objective classification systems.[21,22,31,34] Such approaches may, however, misrepresent some activities as individuals within the sample may be unable to perform at the required running speeds needed to have their actions classified in specific categories. This may impact upon the work-rate profiles of players.

The characteristics of the classification system can determine both the time required for data analysis and the usefulness of the data.[35] If a limited number of categories is used, the data generated may not be detailed enough to provide a meaningful analysis of the work-rate pattern. If, in contrast, the analysis system is too detailed, there may be difficulty in distinguishing between movement activities and data may be impossible to interpret. Most investigations include a list of activities that span a range of exercise intensities from the sub-maximal to the maximal.[12,29] Static periods are also recorded and utility movements (backwards and sideways activities) and actions with the ball are frequently included.[8,21,28] These activities are associated with elevations in physiological demands compared with traditional locomotor activities.[10,11] Greater consensus in future investigations into the work-rate of players would be useful in ensuring consistency across observations and hence facilitating comparisons between studies.

The calculation of the total distance covered or the distance in specific activities has been determined using different methodological approaches.[8,21-23,31,34,36,37] It should, however, be stated that the data on the total distance covered by individual players are within a similar range irrespective of the data collection and analysis method. This may not be the case for the distances covered in specific activity categories.[21] This would suggest that all the techniques are accurate enough to provide raw data for gross estimations of the energy expenditure of players, although they may be limited in their ability to differentiate between small differences in specific activity patterns. No method has currently been accepted as the 'gold' standard approach to work-rate analysis and few, if any, investigators have attempted to compare different methods to validate different approaches. Attempts to address these issues would seem to be valuable areas of future research. It is also possible that new data collection techniques such as global positioning systems may make current methodologies obsolete. These techniques are already being utilised in specific research projects in the area;[38] however, the sensitivity of these methods needs to be improved beyond their current capabilities.

Stolen et al.[3] have suggested that current methods of reporting the work-rate profiles of players may result in a substantial loss of specific information that would aid the preparation of players. This may especially be the case for the specific movement categories incorporated in the overall work-rate profile. Mohr et al.[31] showed the importance of analysing and reporting data with sufficient magnification to enable small segments of matches (e.g. 5-minute periods) to be compared. This approach should become increasingly common in future studies to enable the intricacies of the work-rate pattern and the factors that affect it to be thoroughly understood.

2.2 Match Analysis Measurement Checks: Is There Something Missing?

Sports science support personnel observe players' competitive activities in order to provide feedback to specific players following a match. Soccer researchers, on the other hand, desire to obtain a sample of player performance measurements in order to examine whether the 'true' population performance level differs significantly between categorical variables (e.g. player position) or change significantly over time (e.g. as a result of seasonal variation in performance). It is important that such observations are reliable in these contexts of sports science support and empirical research. 'Reliability' refers to the agreement between repeated observations (by the same observer) of the same behaviour or physical phenomenon. 'Objectivity' refers to the agreement between different observers on the same behaviour or measurement (figure 3). A simple example of a reliability check would be a player who has his/her body mass measured by the same observer using the same equipment but in two separate test sessions separated by 1 week. Reliability would be assessed by examining the variability between these two measurements. This includes variability instrument error, within-observer error and within-subject (player) error, which all combine to cloud the general 'true value' of body mass.[19]

In a typical match-analysis measurement check, Krustrup and Bangsbo[39] assessed reliability or 'reproducibility' by allowing one observer to analyse the same five matches on two occasions. These two observation sessions were 6 months apart, but importantly involved the same sample of matches. CVs were reported to be small (≤4%). A similar study was undertaken by Duthie et al.[40] Repeated observations, separated by 1 month, were made on the same player performances. Data from these studies are relevant to the reliability of match analysis systems for sports science support work. Nevertheless, it is important to note that the design of these 'reliability' studies is different to that outlined in the simple body mass example cited above. In the body mass example, within-subject variability (e.g. due to day-to-day biological variation in body mass) is inherent in the analysis of overall test-retest error. This component of error is absent from the match analysis reliability checks of Krustrup and Bangsbo[39] and Duthie et al.,[40] since players were not analysed twice in *different* matches. This type of reliability check may be appropriate for sports science support work when specific performance information is needed to be fed back to a particular player after a specific match. This check might not be as relevant to research involving a sample of players,

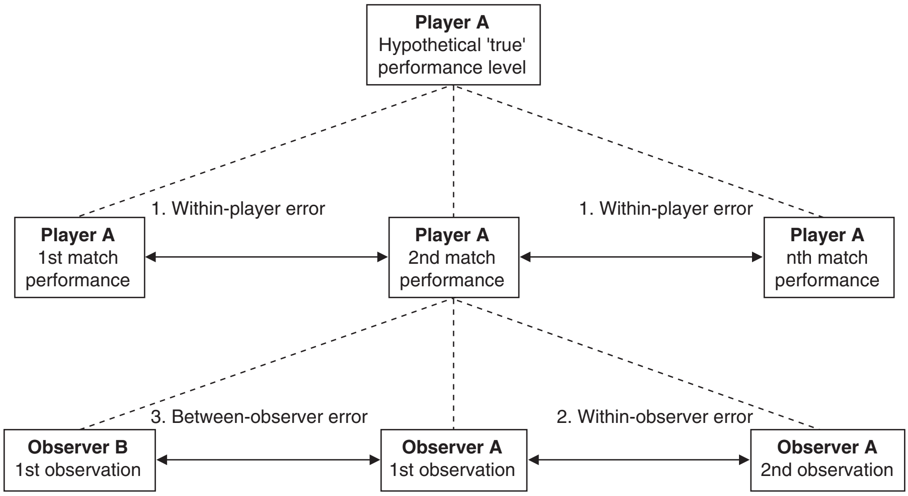

Fig. 3. Schematic showing the various components of variability in match analysis observations relative to a hypothetical 'true' performance level for a given player, i.e. the general level of performance obtained from the average of many games. Between-observer error is also known as 'objectivity'. This measurement check has been performed in some studies even though all data have been obtained by just one observer. Researchers have typically concentrated on within-observer variability in studies of reliability, whereas the component of within-player error has tended to be overlooked. This component of error would be present in any study of player performances measured over different matches, e.g. an intervention study involving pre- and post-intervention measurements of actual performance.

possibly examined over entirely different matches. For example, Krustrup and Bangsbo[39] employed their match analysis system to measure performance characteristics of 27 referees, obviously observed in different matches.

It can be seen from figure 3 that the conventional assessment of 'reliability' in a match analysis context[39] includes the component of within-observer error, but not necessarily the component of within-subject (player) error. This oversight is interesting, given that within-subject error would be present in any measurement of player performance that is used for research. For example, a researcher who wishes to examine the effects of a training intervention on player performance in real matches does not analyse the performances of players in just one match. Performances in different matches, pre- and post-intervention would be compared in such a study. An example from the literature on field hockey is the study by Spencer et al.[35] These researchers made observations on repeated match performance during a hockey tournament and attempted to attribute changes in performance to fatigue. Even if a research design is cross-sectional (e.g. a comparison of different player positions), researchers usually need to sample players across a number of different matches in order to obtain an adequate sample size. Therefore, it is possible that the measurement checks that are conventionally employed in match analysis are not completely relevant to the research situations in which the match analysis methods are used. Moreover, given the impact of match-to-match variability in tactics on real player performances, one would expect the component of within-subject (player) variability to be relatively large, which would lead to a decreased sensitivity for the match analysis system to detect differences or changes in research. Therefore, it would be important that in future assessments of match analysis reliability, researchers should quantify the variability in player performance between different matches.

Since variability between matches may be inherent to the game, it might be that a number of matches is needed to check when the average values stabilise in order for a true work-rate profile to be established.

It is clearly important to include all relevant components of error in the measurement check of a match analysis system. Atkinson and Nevill[41] also described the various important statistical considerations in an appraisal of reliability. Although objectivity is a different concept to reliability (figure 3), the issues surrounding analysis of data agreement are essentially the same. First, it should be noted that the above traditional view of reliability covers *only* the description of error, and there are many (>10) statistical methods for this description.[42] Moreover, there is also imprecision inherent in this description process itself, the degree of which depends on the sample size of the reliability study. Secondly, Atkinson and Nevill[41] maintained that the (ideally *a priori*) rationalisation for deeming a certain amount of error as acceptable is often overlooked by researchers in a reliability study. Thirdly, the amount of error that is deemed acceptable may depend on whether the proposed method of observation is to be employed for sports science support work on individual players or empirical research on samples of players. This differentiation of measurement purpose may also have an impact on the choice of error statistic made at the outset of the study.[19]

With respect to the first point above, soccer researchers have employed several different statistical methods for describing test-retest observation error, all of which have different underlying assumptions. This broad range of methods is not surprising given that several different measurement scales are relevant to soccer match analysis. There are continuous variables such as distance covered as well as nominal data such as the number of fouls committed. Nevertheless, even when working with the same type of data, several different statistical methods have still been employed by researchers. For example, and as mentioned above, Krustrup and Bangsbo[39] calculated the CV statistic for the continuous variables of total distance covered, walking, low-intensity running, high-intensity running and backward running, respectively. Withers et al.[28] employed correlation analysis to quantify the objectivity of distance covered in one game. A correlation coefficient of 0.998 was found. The distance covered during individual behaviour categories, such as high-intensity activity, showed poorer agreement, consistent with the findings of Krustrup and Bangsbo.[39] Despite this descriptive information on reliability and objectivity, the question remains in soccer-related research as to what is an *acceptable* level of agreement between repeated observations?

The correlation coefficient obtained by Withers et al.[28] may seem high enough for acceptable objectivity to be claimed, but it should be noted that the magnitude of the correlation coefficient is influenced by the range of measured values.[41] A large range of total distance covered, for example, is extremely likely, especially if one includes players from all outfield positions in the analysis, resulting in a heterogeneous sample. It would be likely even for poor observation tools to show a high observation-to-observation correlation in this situation. The CV statistic employed by Krustrup and Bangsbo[39] is not influenced by the range of measured values in this way, but it should be emphasised that, when using the CV, it is assumed that the players who cover the most distance show the greatest variability in measurements; this assumption is rarely challenged.[41] Moreover, there is still the question of how small does a CV need to be for agreement to be deemed adequate?

Establishing what is an acceptable amount of disagreement should be determined by the intended purpose of the measurements. In sports science support work, it would be useful to know whether an apparent change in player performance can be attributed merely to observer error. A useful statistic in this respect is the 95% limits of agreement, which describes the ‘worst scenario’ disagreement that could be found, with reasonable certainty, for any individual player. Rienzi et al.[12] employed this statistic to describe the variability of measurements of distance covered. Researchers might be sometimes concerned about the relatively large width of these limits. In this respect, it should be remembered that variability will always be more marked for individuals compared with any ‘average’ variability calculated for a sample of individuals. One other factor that influences the width of the limits of agreement, and is open to debate, is the researcher’s delimitation of the above ‘reasonably certain’ tag. For the limits of agreement, like many other statistics, the coverage probability is conventionally 0.95 (95%). This level of confidence is common in clinical measurements when error could have significant impact on clinical diagnosis and judgement, especially in falsely diagnosing the presence of a disease (a false-positive result). The patient might undergo unnecessary and potentially harmful treatment in such circumstances. If one assumes that most soccer interventions are relatively harmless, one might be satisfied with a lower probability of a given change in match performance being attributable to observer error. In this respect, it may be informative to calculate an exact probability of a change being attributable to error, which is possible.[43]

In a research context, observation variability could inevitably lead to an underpowered study. Observation error contributes to the standard error term in calculations of statistical tests and confidence intervals. The other contribution to this term is the sample size. Therefore, it is possible, not just to describe the observation error in a soccer-specific reliability study, but to estimate, through statistical power calculations, whether there is so much observation error that the detection of a change or difference in the measured variable would be unlikely with a feasible sample size.[44] This link between error and statistical power has not been explored by soccer researchers, but closes a very important loop in the process of deeming agreement as being acceptable or not.

A complication in match analysis measurement checks is that data can be of the categorical type (e.g. the player's actions of walking, sprinting). Moreover, it may be important to describe the variability between matches or observers in the measured frequency of such actions, but also the variability in the time during the match that the actions occur. A statistic designed for describing agreement between categorical observations is the Kappa correlation coefficient. Thatcher and Batterham[45] used this statistic in order to assess intra- and inter-observer agreement on the categorisation of player actions (e.g. sprinting and jogging). Rienzi et al.[12] organised all their data on a time-base and also used Kappa correlation to assess observer agreement on category judgements. It should be noted that the caveat outlined above with quantitative correlation analysis can also be relevant with the Kappa correlation.[41] If the range of observations on categories is wide, then the Kappa correlation will always tend to be high. Such a scenario would arise, for example, whilst measuring the number of sprints in a sample of players that includes the whole range of outfield player positions. Nevill et al.[46] proposed a method of describing category agreements based on proportions. Such a method has the advantage that it is not sensitive to the range of category observations (e.g. the number of tackles made ranging widely between defenders and attackers), but has seldom been employed by soccer researchers.

2.3 Inherent Problems in Motion Analysis Data

The methodological approach taken to data collection is not the only consideration that is important in evaluating the usefulness of observational techniques in the determination of the work-rate profile of soccer players. Tenebaum and Driscoll[33] suggested that data should be 'lawful', that is to say that there is some degree of certainty regarding the observations that enable them to be understood and used ultimately for prediction purposes. This characteristic is essential if the activity pattern of players that is produced is to be useful in either a scientific or practical context.

The number of research groups that have investigated the demands of soccer using observational techniques is not large. The majority of the available research seems to be related to the European professional game,[3] although some data are also available on Australian,[28] Canadian,[26] Japanese[37] and South American international players.[12] This would suggest that there is a limited amount of available data in the area and a specific lack of studies that have attempted to address either cultural or geographical differences in the work-rate pattern.[3] Other important playing populations such as female players[22] and young players[29] are also limited in their representation with proportionally more data available on other individuals involved in the game, such as match officials,[34,36,47-49] than these special groups.

This lack of important data may impact upon our ability to understand the work-rate requirements of different styles of soccer and different types of players and hence our ability to develop laws that may help predict the performance potential of individuals in a wide range of situations. The available data also span three decades, from the mid-1970s to the current date. This time span has been associated with both developments in the conditioning of players and numerous rules changes that may impact upon the relevance of the data to the current demands placed on players. Strudwick and Reilly[50] have shown that the current work-rate of English Premier League players is in excess of that associated with previous information collected on similar players in the 1970s. The relative 'shelf life' of data is not known as no one has completed longitudinal studies across relevant time spans. This type of research would be difficult to complete because of the highly mobile nature of the playing staff at all elite clubs. Continuous updating of the work-rate profile does, therefore, seem to be important if the currency of the data is to be maintained.

It is also possible that variables that may confound the activity pattern are inadequately reported in the available data. For example, few reports include the ambient conditions under which the relevant games are played despite the existence of data suggesting that the ambient temperature can affect the performance of players.[14] Ambient temperature is just one of the few factors that are known to affect the work-rate profile of players.[4] Other factors include playing position and the level and style of play.[7] A large variability is observed in the work-rate profiles of players even when these known confounding factors are controlled by careful sampling.[3] This between-subject variability may be expected and may relate to differences in the physical capacity or tactical role of an individual player.[9] The large within-subject variation that is observed when an individual player's activity patterns are analysed on more than one occasion[15,25] may be a greater threat to the scientific validity of the approach.

Limited data are available with respect to the inherent variation in the work-rate profile of players as the majority of studies are designed to determine the activity pattern of players on only one occasion as has already been discussed (section 2.1). Bangsbo et al.,[21] Krustrup et al.[22] and Mohr et al.[31] have all clearly illustrated large intra-individual variation in the region of 5–25% of the distance covered in a range of activity classifications by players during match-play. Similar data are also available for both assistant referees[34] and referees.[36,39,48] 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.[31]

It is unlikely, however, that changes in physical fitness explain the entire variation, as variability is still noted when observations are completed in short time spans, within which fitness is unlikely to change. It is suggested that, on certain occasions, players do not fully utilise their physical capacity.[21] Therefore, it is likely that factors such as the tactical changes within the team's playing system or the specific roles of individual players are also involved in the inherent variation. This view would be supported by the influence of playing position and level and style of play on the work-rate profile.[7] The impact of such factors is, however, difficult to evaluate, as the researcher is seldom privy to the tactical instructions provided by the coach for any performance. Model games may be useful in addressing such questions as they may provide an opportunity to recreate specific tactical situations. Irrespective of the cause of the variability, it is clear that data should ideally be collected on more than one occasion to ensure that the work-rate profile of any player is truly representative of his/her ability to perform in a competitive situation. More thorough analysis of the individual components of the work-rate profile may also be useful as certain parameters may be less prone to any inherent variation than others.[21]

Work-rates in soccer reflect the sum total of contributions from individual players. The self-chosen nature of the activity pattern is an important determining factor in an individual's activity profile. Reilly[4] suggested that the self-imposed demands chosen by players reflect their commitment to the team's efforts and their own abilities to pace themselves throughout the game. Such ideas are supported by D'Ottavio and Castagna[36] who have illustrated reductions in low- and medium-intensity activity, but similar high-intensity work-rates, in both the first and second halves of matches in elite referees. This is thought to demonstrate the application of a pacing strategy that spares useless low-level activity in an attempt to enable high-intensity efforts to be maintained at crucial periods of the game. Similar pacing strategies do not seem to be observed in players, as numerous studies provide evidence of reductions in the both the overall work-rate of players as the game progresses[8,12,21] and in specific relation to high-intensity efforts.[31]

These reductions seem to be related to physiological fatigue mechanisms,[31] although these mechanisms cannot completely explain the change in work-rate as it would be expected that such reductions would also be observed in the activity profile of referees. As this is not the case (as discussed earlier in this section), alternative explanations must be sought. D'Ottavio and Castagna[36] suggested that as referees play a more active role in the game, they have less opportunity to self-select their activities as a consequence. Therefore, it is possible that the reductions noted in the work-rate of players reflect factors inherent in the game that combine to influence the player's active involvement in the contest as well as any individual pacing strategy that may exist. One possible example of such a factor would be the increasing certainty of the result. A better understanding of the factors that influence the self-chosen work-rate of players would seem to be a valuable area of study.

3. Obtaining Physiological Measurements During Games

Assessment of the physiological demands of match-play requires observations on responses of players, which then should be related to measures of individual players' capacities and capabilities. In this way, an inference is drawn on the relative loading that is imposed. There are two major difficulties with this approach. The first is that the methods employed for monitoring physiological responses during play must be socially acceptable, not interfere with performance and in most cases be non-invasive. Nevertheless, various research groups have been successful in getting participants to comply with the requirements. The second problem is the validity of applying principles of steady-state to the dynamically changing exercise intensities that comprise match-play. For the most part, this limitation has been circumvented by adopting averaging-out approaches over the competitive period or judiciously sampling responses within the period or immediately post-exercise. The former strategy has been an accepted means of operation in measuring energy expenditure and heart rate, whereas the latter is represented in sampling of body fluids and tissues.

3.1 Energy Expenditure

The distance covered during the course of a game has been used as a global surrogate of energy expenditure. Whilst the energy expended in travelling a fixed distance during continuous exercise is determined by the actual distance and is independent of the velocity of movement, this relationship does not hold under the conditions of locomotion that apply during a soccer game. The average distance covered would grossly underestimate the energy cost of playing soccer since it would not account for the frequent changes in velocity and direction of motion as well as the skills of the game.[8]

Methods of measuring energy expenditure in field conditions have been reviewed by Ainslie et al.[51] The most common method is respiratory gas analysis, energy expended being calculated from the oxygen uptake and the respiratory exchange ratio. Durnin and Passmore[52] cited a range of 21–50 kJ/min (5–12 kcal/min) for the energy requirements of the game. These figures are likely to be underestimates since the subjects were university students kicking a ball about a pitch and wearing respirometers. Covell et al.[53] reported a range of 22–44 kJ/min (5.2–10.6 kcal/min), their subjects also being undergraduate students. Seliger[54] got subjects to wear Douglas bags whilst playing model games for 10 minutes, reporting mean energy expenditure values of 0.75 kJ/kg/min (0.18 kcal/kg/min), amounting to 56.5 kJ/min (13.5 kcal/min) for a 75kg individual. Yamaoka[55] also used Douglas bags to record the oxygen uptake of Japanese players of undefined skill level and reported energy expenditure values of 32.4 kJ/min (7.7 kcal/min). The relative metabolic loading relative to rest was a factor of 2 for the goalkeeper and 7–9 for outfield players. These studies would now be regarded as primitive attempts to establish the physiological strain during a game, although the data are likely to be representative only of casual recreational play and the activity of players was probably hampered by wearing the apparatus. This limitation applies to such portable equipment, since wearing cumbersome apparatus for experimental purposes is incongruous with competitive matches.

The availability of lightweight telemetric devices for recording oxygen consumption ($\dot{V}O_2$) has increased the possibilities for obtaining metabolic responses of football players. Invariably, observations have been made in training conditions, model games or during performance of game-related drills. Kawakami et al.[56] measured $\dot{V}O_2$ using a telemetric system (Cosmed K2®, Rome, Italy)[1] that players wore as a back-pack while carrying out different football manoeuvres. The emphasis seems to have been more on highlighting the utility of the recording system than on gaining insights into the game. Hoff et al.[57] used a similar lightweight device (Cortex Metamax®, Leipzig, Germany) to record responses of players executing an all-out run with the ball on a ball-dribbling track, comparing the highest $\dot{V}O_2$ achieved with the maximum oxygen consumption ($\dot{V}O_{2max}$) determined in laboratory conditions. They concluded that the players operated sufficiently close to $\dot{V}O_{2max}$ for this form of task to be used as a test of relevance to footballers and as a means of aerobic interval training. The protocol has subsequently been used by McMillan et al.[58] for training professional youth players. Nevertheless, it does not yield insights into the physiological strain of playing the game itself.

The doubly labelled water method of measuring energy expenditure would avoid the use of cumbersome apparatus during activity. The method provides information on the total energy expended by a free-living subject for a period of 4–20 days and has been used to establish daily energy expenditure in Japanese professional players.[59] The subject takes an oral dose of water containing a known amount of stable non-radioactive isotopes of both hydrogen and oxygen, which mix with the normal hydrogen and oxygen in the body within a few hours; the procedures for calculating the energy expended have been outlined elsewhere.[60] The durations of a training session and of a game are too short for the method to be sensitive to locating energy expenditure to these exact time periods, but the method has value when the monitoring of individual activity over a typical week is of interest.

The more commonly adopted method for estimating energy expenditure in training and in a game is to record heart rate responses and relate the mean values to the heart rate-$\dot{V}O_2$ (HR-$\dot{V}O_2$) regression line determined in laboratory conditions during incremental exercise to voluntary exhaustion. This 'averaging out' approach may be criticised on the basis that the regression line is based on steady-rate responses, conditions that are not found in the game. Furthermore, the heart rate can be influenced by factors other than metabolism that include thermal load, emotion and the type of exercise. Nevertheless, Bot and Hollander[61] have shown that the HR-$\dot{V}O_2$ regression was a good predictor of aggregate responses to an irregular exercise protocol that included vigorous anaerobic activity such as vertical jumps. Bangsbo[5] confirmed that the error in estimating overall energy expended in an intermittent exercise protocol using the HR-$\dot{V}O_2$ relationship was sufficiently small for it to be applied to soccer contexts. The ultimate test of validity would require measurements in real competition, which is not yet practical.

3.2 Heart Rate

The heart rate itself can be a useful indicator of circulatory strain, quite apart from being a surrogate for energy expenditure. As short-range radio-telemetric devices became more sophisticated, so too has the interpretation of heart rate responses to exercise become more refined. Contemporary systems may be used by all players in competitive friendly matches, the inference being that the intensity is similar to normal contests.

The monitoring of heart-rate data by means of radio telemetry has been reported for referees in important soccer matches,[47,49] but this method is not acceptable to players engaged in real competitive games. Some observations have been made during friendly games,[32,62] and inferences drawn for competitive match-play. This extrapolation is valid only if the work-rate profiles correspond in the two conditions.[63] Some researcher groups[5,62] have related their heart rate observations to the fitness levels of the players concerned. Such calibrations have led Bangsbo[5] to conclude that the demands of match-play correspond to an average heart rate of about 170 beats/min and a 75% proportionate utilisation of maximal aerobic power.

1 The use of trade names is for identification purposes only and does not imply endorsement.

Heart rate responses have been used to grade the exercise intensity in a range of sports, and also for evaluating training activities in soccer.[63] More recently, heart rate has been used to discriminate between different training drills.[64] For example, a higher physiological stimulus was presented when playing small-sided games without a goalkeeper and when pressing the player in possession than was the case with other drills. Heart rate responses may be used to regulate the training intensity during a systematic training programme for improving $\dot{V}O_{2max}$,[20] and for maintaining light-intensity exercise on recovery days.[65]

Whilst monitoring of heart rate has been accepted as valuable for sports science practitioners, its relevance does not apply to all training circumstances, It is, for example, dissociated from metabolic responses during weight-training exercises that employ light-muscle groups, overhead exercises or isometric work. The heart rate kinetics do not match the activities performed, with a lag at the start and a post-exercise elevation so that heart rate is increased over resting values during static pauses between exercises in training.

The interpretation of heart rate data is likely to be facilitated by contemporary developments in the technology of radio telemetry. So-called 'team systems' now commercially available permit the recording of heart rate data for all members of the playing squad at one time and are currently being used by many European professional teams in training contexts. The application of such systems in conjunction with individual work-rate profiles determined by use of synchronized multi-camera systems should advance the understanding of both specific and overall demands on participants.

3.3 Thermoregulatory Responses

As a result of the relatively low mechanical efficiency of human locomotion, heat is stored in the body as the skeletal muscles are active during exercise. During soccer play the temperature in the body's core rises and heat loss mechanisms are brought into play to prevent overheating. Even so, Ekblom[14] reported rectal temperatures of 39.5°C in Swedish top-league players, average values being 39.1°C in a lower division. Data on the core temperature responses of players to actual match-play are very limited as a consequence of the difficulties in obtaining the required data. Therefore, it is possible that some players may reach even higher levels than those currently reported, which may be limiting to performance. This may be the case when matches are played in hot environments.

Intermittent exercise causes a greater rise in core temperature than does continuous exercise at the same overall work-rate.[66] Nevertheless, casualties from heat strain seem to be fewer in soccer than in events such as distance running.[67] Players have more opportunities to reduce their work-rate spontaneously to decrease heat production and are typically substituted when alarm signs appear. Core temperatures are measured to indicate hyperthermia and rectal temperature is a convenient measurement site. Soccer players are normally reluctant to volunteer for measurements where these might have value, for example at half-time. Gut temperature, recorded from a temperature-sensitive pill by radio telemetry, provides a reasonable alternative for monitoring during training.[68] Edwards and Clark[62] used an intestinal pill to record core temperature in eight university players and seven professional players in matches held in ambient temperatures of 16°C and 19°C, respectively. Mean values of gut temperature reached 39.3°C for the recreational players, but were <39°C in the professional players, a difference attributed to the higher $\dot{V}O_{2max}$ and better heat acclimatisation of the professionals. A major limitation of both rectal and intestinal sites is that they do not respond immediately when there is a sudden rise in internal heat storage. In these instances, oesophageal or tympanic temperature are preferred, but are not readily monitored in practical conditions.

The rise in core temperature invokes heat loss mechanisms, evaporative sweat loss being the main route for exchange of heat with the environment during exercise. The result is a disturbance of hydration status and a loss of electrolytes in sweat. The need to restore body water homeostasis is now well recognised, most professional players being familiar with fluid rehydration strategies. Various means are available for monitoring hydration status,[69] but under standard conditions rather than concomitant with exercise.

Whilst sweat losses may reach 2 L/hour in some players, the sweat rate varies between individuals.

Professional players training in the evening when ambient temperature was 32°C experienced a net loss of body mass of 1.6% (SD = 0.6), despite having free access to a sports drink for the 90-minute duration of training.[70] With heat acclimatisation there is a reduction in electrolyte losses so that the sweat is more dilute and there are increased losses of body water due to adaptations to the sweat glands. Even so, some individuals may be more vulnerable than others to electrolyte losses and the use of sweat patches distributed around the body to obtain samples for analysis after training allows for a hydration strategy (with supplementation if needed) to be targeted to individual needs.

3.4 Muscle Biopsies and Blood Samples

Professional players are understandably reluctant to engage in studies that entail invasive methods, although real insights have been gained into physiological responses to play where such studies have been conducted. Saltin[30] obtained muscle biopsies from the vastus lateralis of nine top Swedish players before a game, at half-time and immediately afterwards. One of the groups (n = 4) had trained hard the previous day and had reduced glycogen stores in their thigh muscles at the start of the game. This group had a decreased work-rate in the second half, markedly below that of the five players who had rested beforehand. The study may be criticised for its use of incomplete match recordings and the short sampling periods for each player. Nevertheless, the data were sufficiently robust to highlight the importance of nutritional preparation and tapering before a game and the important role of carbohydrate as a fuel for exercise in the soccer context.

Blood sampling is more commonly accepted by players, whether from a fingertip, earlobe or vein. Portable analysers have rendered field sampling routine, although health and safety and human ethics procedures are now mandatory in most countries. Blood lactate data may be obtained by taking samples at half-time and post-game, but measurements in training conditions are more likely. This approach can entail intervening during practices to target preselected individuals. Blood lactate values imply anaerobic activity, but reflect the balance between its production in muscle and its elimination from the blood. Values are also dependent on the activity engaged in during the minutes prior to sampling.[5]

The roles of other energy systems have been partly clarified from measurements of blood samples. Bangsbo[5] showed that the preferential use of fuel source altered during the course of a game, becoming more reliant on fat and sparing the depleting stocks of carbohydrate. Responses were broadly similar to the trends in endurance running and cycling over the same duration. The roles of the inosine monophosphate system and the rise in ammonia (NH_3) were also addressed in this series of studies.

The inferences made from experimental interventions in friendly or model matches are reliant on the fidelity of activity to the real competitive condition. Whilst the locomotor patterns may match,[63] the intensity of discrete actions and the mental engagement with events of competition may not be reached in the practice situation. Therefore, activation of the CNS, and the specifics of endocrine responses may only be approximated in training and simulated matches. Nevertheless, this limitation applies throughout the sports and is not unique to soccer. It reflects the attempts of researchers to satisfy ecological validity, even if the criteria to follow are not precise.

4. Determining the Physical Capacities of Players

Physiological tests can provide useful information on the physical capacities of players and on the training status of the athlete.[71] Such assessments provide a logical framework for the use of performance tests to gain insight into the physiological demands of soccer. The assumption is that ‘high’ levels of performance, in any specific aspect of fitness, indicate that the particular attribute under consideration (e.g. aerobic fitness) has been systematically stressed during exercise and has, therefore, led to physiological adaptations that improve the ability of the individual to tolerate similar stresses. This adaptation is manifest in performance improvements compared with populations that are not associated with such systematic exposures. This rationale is somewhat simplistic as performance on such tests is not only a function of training status, but also determined by the genetic endowment and the health status of the athlete.[72]

Despite the potential limitations to this approach, the assessment of the physical capacities of players is widely utilised in both research and applied contexts in an attempt to gain an understanding of the player's performance capabilities.[73] Fitness assessment is also utilised for evaluating the effects of a training intervention on the physiological functions concerned. Such assessments usually incorporate a battery of different tests to evaluate the various components of fitness important for soccer. These assessments range from simple field tests that can be carried out in field conditions by coaches with even the most limited of resources to laboratory-based assessments that require expensive and sensitive analytical equipment and procedures. It is beyond the scope of this article to present detailed information on the range of tests used and the data that they provide. Interested readers are referred to Svensson and Drust[73] for a thorough discussion of this subject. This section instead is focused on an analytical evaluation of the usefulness of such approaches in determining the physiological demands of soccer and to make recommendations for the use of such techniques in future investigations.

4.1 Philosophical Issues

Soccer performance is a construct, in that a multitude of different performance components or 'indicators' interact together at both the level of the player and the level of the team.[74] Whilst the reduction of the variability in overall soccer performance into a single statistic might be difficult and lacking in usefulness, there have been attempts to describe the variability in separate indicators of high-performance soccer play. Such attempts are prone to pitfalls in the logic associated with measurement of validity and reliability. For example, what criterion should test performances be compared with for exploration of validity? If test performances (e.g. 10m sprint times) are compared with real soccer play characteristics, then agreement might be poor, not because the test is inherently invalid, but merely because real soccer play is inherently variable due to within-player error across repeated matches (see section 2.2). It does not make sense to control test conditions carefully and then compare the results of these tests with other measurements obtained in the variable environment of real soccer play. The philosophy of measurement validity may also be influenced by the researcher's desire to explain the physiological mechanisms involved or avoid such considerations. If the researcher's interest is simply performance measurement, it does not seem logical to select a field test that predicts $\dot{V}O_{2max}$, which in turn might predict soccer performance.[75] Such a 'round the houses' philosophy may merely be adding extra predictive error to the test development process (i.e. the additional component of error resulting from within-subject variability in the physiological response, e.g. $\dot{V}O_2$, to a performance test). Rather, the field-test could be soccer-specific in the first place without any reference to a physiological measurement. Such an *a priori* made decision about emphasising the performance or physiological response fits in, again, with the philosophies underpinning applied and basic research (see the introductory section).

The above problem in relating a test performance to real soccer match-play may be exacerbated by the general difficulty of obtaining large samples of elite soccer players for research. Given the inherent variability of soccer performances, relatively low correlation coefficients ($r = 0.4–0.5$) between two aspects of soccer performance (e.g. sprint test performance and match analysis data) might be important. For acceptable width of confidence interval and/or attainment of statistical significance for such correlation coefficients, the required sample size can be estimated to be 20–25 participants,[44] which is larger than that selected by most researchers in the past. This sample size may need to be even larger if the researcher maintains that some aspect of an individuals' soccer performance can be *predicted* by a soccer-specific test. Standard errors of prediction for individual players can still be relatively large, even with the highest correlation coefficients ($r = 0.8–0.9$) that have been reported in the literature, and especially if these statistics have been calculated from data obtained in a heterogenous sample. The sample size requirements may be even greater if the researcher wishes to distinguish between two or more indicators of soccer performance (e.g. sprint performance and endurance 'capacity') in terms of their *relative* importance. Logistic binary regression may be used in this situation to examine the relative influence of these variables on some measurement of soccer 'success' (e.g. an Academy player being selected for the first team or not), but such an analysis may require at least 50 cases per predictor variable that is considered.[76] These relatively high sample sizes may necessitate data collection over a number of matches, which raises the issue, again, of the increase in research error variance that this tactic would cause (see section 2.2).

Given the above problems in applying the conventional requirements for validity to soccer-specific research, the concept of logical validity should be emphasised. If the goal is to develop a test that measures an indicator of soccer performance, then the test should mimic the work-rate requirements of the particular action. Large samples in research should be aimed for and multivariate statistical procedures should be adopted. A revealing characteristic of a test may be its 'sensitivity', which involves confirming whether the test can 'detect' changes (e.g. over the competitive season or between competitive standards of players) in soccer-specific performance indicators. Reassuringly, such explorations exist in the literature and offer encouragement that several measurements of soccer match components are sensitive to positional differences and can track changes in real soccer performances over time.

5. Simulations

It is clear that the most realistic way of evaluating the physiological demands of soccer-specific intermittent activity is to monitor the actual physiological responses to match-play. This review has highlighted a range of difficulties with such approaches including the constraints to carrying out detailed physiological assessment and ensuring appropriate experimental control of the environment.[77] These limitations have resulted in a number of research groups developing simulations of soccer match-play. These simulations attempt to re-create the exercise pattern observed in games with the additional benefit of more comprehensive control of key experimental variables. This approach may allow more detailed physiological responses to soccer-specific intermittent exercise to be determined, thereby providing a better understanding of the demands of this activity. It may also provide a model that would allow potential ergogenic aids to be evaluated.

Attempts at developing soccer simulations can be split broadly into two categories, those that have attempted to recreate the relevant activity patterns on a treadmill[66] and those that have utilised repetitive intermittent shuttle running.[78] The principle behind both attempts is to develop a simulation that includes similar activities in similar proportions to those observed in match-play and induces similar relative physiological loading.

5.1 Treadmill Protocols

The first soccer-specific intermittent exercise protocol on a motorised treadmill was developed by Drust et al.[66] and based on the motion-analysis data of Reilly and Thomas.[8] Since its development, adaptations of the protocol have been used to investigate the effects of pre-warming,[79] the heat loss properties of soccer equipment,[77] the salivary IgA response to soccer-specific intermittent exercise,[80] strategies for hydration and energy provision[81] and muscular fatigue associated with prolonged intermittent exercise.[82]

This protocol was originally designed to last for a total duration of 46 minutes, although it has since been adapted to simulate a full 90-minute game including a 15-minute half-time recovery period.[79] Activities incorporated in the protocol include static pauses, walking, jogging, cruising and sprinting in proportions similar to those observed in match-play. Utility movements (backing and sideways movements) are not included as a result of the technical limitations of the ergometer and the health and safety risks of changing orientation on the treadmill. Treadmill speeds assigned to each activity category are based on the data of Van Gool et al.[32] to increase the ecological validity of the simulation. These speeds range from 6 km/hour for walking to 21 km/hour for sprinting.

The original protocol was arranged using two identical 22.5-minute periods (see figure 4). These are separated by a static recovery period of 71 seconds. Each cycle is made up of 23 bouts of activity: 6 × walking (35.3 seconds), 6 × jogging (50.3 seconds), 3 × cruises (51.4 seconds) and 8 × sprints (10.5 seconds). These bouts are arranged to

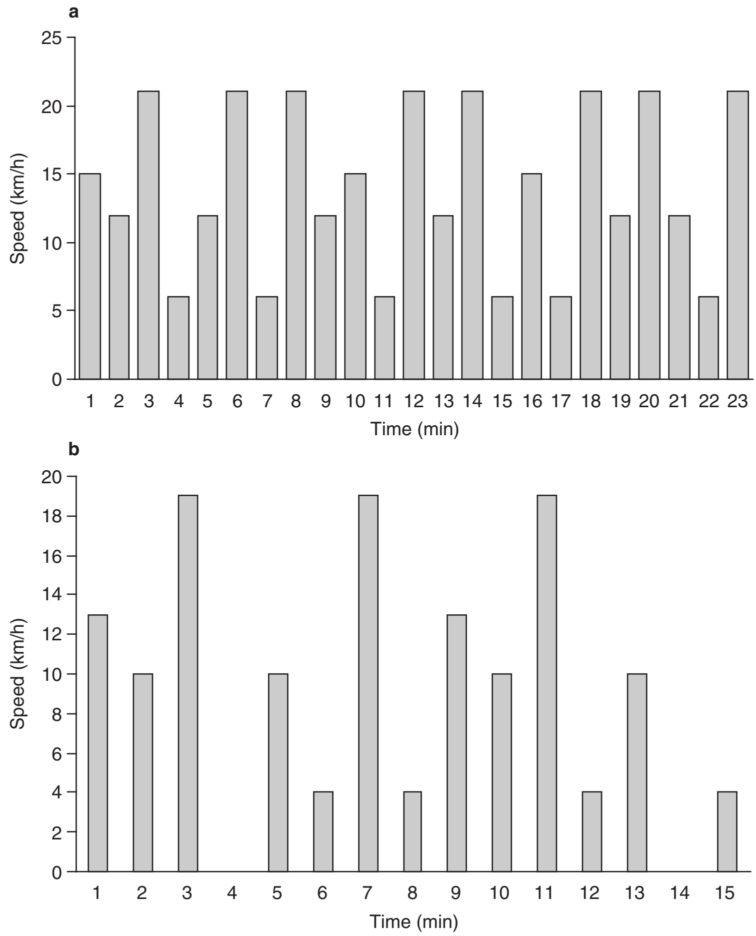

Fig. 4. Cycles of soccer-specific intermittent exercise protocols. (**a**) Soccer-specific intermittent exercise protocol developed by Drust et al.[66] and (**b**) adapted by Clarke et al.[81]

replicate the non-cyclical exercise pattern observed in soccer with low-intensity recovery periods separating high-intensity efforts. The remainder of the time in the 22.5-minute cycle in this specific protocol is associated with fluctuations in the treadmill speeds required to enable the subject to perform at the different exercise intensities. More recent versions of this protocol have benefited from the use of modern treadmills that demonstrate significantly faster acceleration and deceleration periods[81-83] (see figure 4). This modification provides the advantage of greater periods of time at each specific exercise intensity and, therefore, reduces the uncertainty of interpreting the physiological responses associated with non-uniform exercise intensities.

Similar approaches to the development of soccer-specific intermittent protocols have also been used with non-motorised treadmills.[45,84] Non-motorised treadmills allow instantaneous accelerations and decelerations and so provide a better approximation of the activity profile observed in match-play. They can also allow individuals to reach maximal sprinting speeds, enabling evaluations of the power associated with maximal sprint efforts to be recorded.[85] This measure provides a useful indication of high-intensity exercise performance in well motivated subjects. Careful consideration, however, needs to be given to the assignment of the intensity of exercise for each specific activity category, apart from sprinting, as the treadmill speeds assigned should be corrected for the intrinsic resistance of the treadmill belt. This resistance has been shown to reduce the maximal velocity by about 20% compared with normal running[85] and may be used to provide a useful correction factor. It is also important to incorporate some form of feedback mechanism on the treadmill speed during each sub-maximal exercise bout as the subjects will be required to self-propel the treadmill at the correct speed. This can be easily achieved by a real time tachometer attached to the forward rolling drum of the treadmill that is interfaced with a microcomputer displaying the speed produced.[45]

5.2 Intermittent Shuttle-Running Simulations

Intermittent shuttle running has been used to simulate the activity pattern of soccer by a number of authors.[86-89] The most widely used simulation of this kind is the Loughborough Intermittent Shuttle Run Test (LIST) described by Nicholas et al.[78] The LIST can be performed in a sports hall and includes the completion of various exercise bouts between two lines, 20m apart, performed at various speeds related to the estimated individual $\dot{V}O_{2max}$. The specific speeds for each activity pattern are dictated by audio beeps emitted from a micro-computer.

The test is comprised of two parts that attempt to simulate the activity pattern of soccer (part A) and evaluate the capacity of the subjects in high-intensity intermittent running (part B). Part A lasts for a total duration of 75 minutes. This total time is separated into 5 × 15-minute exercise blocks separated by 3-minute recovery periods. Each exercise block consists of a pre-determined pattern of intermittent activity that is based on motion analysis data.[8,28] The pattern of activity includes walking, sprinting and low- (55% of individual $\dot{V}O_{2max}$) and high-speed (95% of individual $\dot{V}O_{2max}$) running. Short (4-second) static recovery periods are also included. This activity varies between low and high intensities as would be observed in match-play.

Part B was specifically designed to act as a performance test that would exhaust the subjects within approximately 10 minutes. The test is continued until the individual is unable to maintain the required running speed. The component of the test includes alternate bouts of low-intensity running at 55% of individual $\dot{V}O_{2max}$ with high-intensity bouts at 95% of individual $\dot{V}O_{2max}$. The intensity of exercise alternates every 20m. This performance test has enabled a variety of nutritional interventions to be evaluated, such as carbohydrate electrolyte solutions[90] for enhancing intermittent exercise performance. It has also been used to examine the impact of environmental temperature[91] on intermittent exercise capacity and to assess the recovery from intermittent endurance running.[92] Careful consideration must be given to the application of these data to actual match-play situations as a consequence of possible limitations to the validity of these procedures to outdoor soccer performance. This may be especially the case when examining the thermoregulatory responses to exercise as these are heavily influenced by environmental factors such as air velocity.

Bishop et al.[89] adopted similar approaches to simulating soccer-specific intermittent exercise by developing a 90-minute shuttle-running protocol. This protocol was based on the activity profile described by Bangsbo et al.[21] and used the percentage of total time and the mean speeds for each category to calculate the approximate distance that needed to be covered in each activity category. Seven 2-minute circuits of activity were separated by rest periods to simulate the relevant intermittent activity pattern. These were repeated six times to create 90 minutes of activity (divided into 2 × 45-minute periods separated by 15 minutes of recovery). Specific match actions (dribbling with the ball) and utility movements (backwards running) were both included in addition to the usual forms of locomotion (walking, jogging and sprinting).

Other research groups have attempted to adapt the LIST for their own specific research objectives. Edwards et al.[88] attempted to generalise the running speeds incorporated in the simulation to enable more than one person to be studied at any one time. The average running speeds at 95%, 55% and 35% were calculated for incorporation in the protocol by using as a reference the running speed at 100% of $\dot{V}O_{2max}$ attained by 23 male subjects in a progressive shuttle-run test. This may be a useful development of the test if the experimental protocol allows large numbers of subjects to be assessed at any one time. Other researchers[93] have altered the total exercise time and the shuttle-running distance in an attempt to make the tests more suitable for female adolescent soccer players. These adaptations have currently not been subjected to the detailed comparisons with physiological data from soccer match-play that are necessary to demonstrate their appropriateness as simulations of soccer-specific intermittent activity.

5.3 Validity of Simulations of Match-Play

The effectiveness of any of these simulations as analogues of soccer-specific intermittent exercise observed in match-play can be evaluated by comparing both the activity pattern and the physiological responses to the exercise stress. The vast majority of the simulations seem to have activity patterns that are similar to those associated with soccer in that they provide a good representation of the locomotor pattern (static periods, walking, jogging, cruising and sprinting) for durations that are similar to competitive games. This results in the total distance covered during the simulation being more than or broadly similar to that observed in match-play.[89,94] The major limitations in this area are related to the failure to include a similar number of activity changes as would be observed in match-play (around 14 000),[12] and incorporate a range of soccer-specific actions (e.g. ball contacts, physical contacts, utility movements). Such activities have been shown to be an important determinant of the physiological requirements of soccer-specific intermittent exercise.[5] This may mean that the protocols lead to reductions in the energy requirements compared with actual match-play and hence lower levels of physiological strain. This margin allows for the difficulty in getting volunteers to replicate the activities in a competitive situation in a laboratory simulation.

The majority of the studies that have attempted to develop intermittent exercise protocols representative of soccer have included measurements of physiological indices,[66,78,89,94] thereby permitting an evaluation of physiological strain. The majority of these studies[45,78,94] demonstrate similar physiological loads, as indicated by heart rate, blood lactate concentrations and $\dot{V}O_2$, to those associated with soccer match-play. The metabolic response has also demonstrated remarkable similarities.[84] This correspondence would seem to suggest that these protocols represent reasonable approximations of soccer match-play despite the omission of a number of important activities.

The comparisons may, however, be criticised on methodological grounds. The physiological responses to match-play are known to exhibit large variability.[5] Approximating the mean ± standard deviation physiological response to match-play may not, therefore, be evidence that the physiological demands of the two exercise stresses are similar. This may be especially true when the research design has focused on comparisons of the physiological responses to the simulation with those published in the literature. This approach is frequently used and is probably a consequence of the difficulties in obtaining suitable physiological measures in this type of work.[78,84,89,94] To be valid, such comparisons would require the same subject populations to be examined under both conditions – match-play and the simulation. This approach has been taken by Thatcher and Batterham[45] who completed the only study to attempt a direct validation of their protocol. Heart rate responses showed a standard error of measurement of 2.6 beats/min for the first half and 2.8 beats/min for second half. This result demonstrates the comparability of the physiological responses between the two conditions and suggests that the soccer-specific protocol they devised provided a good approximation of the stresses of match-play.

It would seem, therefore, that the development of laboratory-based simulations can be a suitable means for investigating soccer-specific intermittent exercise patterns. These protocols are probably best suited to investigations that require high levels of experimental control and include detailed or invasive physiological assessments. The number of protocols currently reported in the literature is small and future research programmes would benefit by refining the available protocols. This refinement may focus on increasing the ecological validity of such protocols by further enhancing their soccer specificity. The inclusion of more specific activities and the development of a more individual basis for the work-rate on which the protocol is based are advocated.

6. Conclusions

This article has attempted to contextualise the available research that has attempted to evaluate the physiological demands of soccer on the basic–applied research continuum. This approach has been pursued with a view to evaluate the current state of knowledge on the demands of the sport and to provide some guidance for future investigators in the area. It is acknowledged that researchers in the practical setting must operate in challenging circumstances and under various constraints. The analysis within this article in no way undermines the available data on the physiological demands of soccer. This work has been important in providing a critical mass of material in relation to the sport that has informed both a research and an applied agenda. The present content should inform both the direction and methodology of future studies to ensure that the knowledge base that is created will lead to conclusions and recommendations that are of importance to both the scientific and applied community.

Acknowledgements

The authors received no funding for the preparation of this article and have no conflicts of interest relevant to its contents.

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Correspondence: Dr *Barry Drust*, Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Henry Cotton Campus, 15-21 Webster Street, Liverpool, L3 2ET, UK.
E-mail: B.Drust@ljmu.ac.uk

