Sports Med (2016) 46:657–670
DOI 10.1007/s40279-015-0449-x

REVIEW ARTICLE

Gold Standard or Fool's Gold? The Efficacy of Displacement Variables as Indicators of Energy Expenditure in Team Sports

Ted Polglaze[1] · **Brian Dawson**[1] · **Peter Peeling**[1]

Abstract Over recent decades, the use of player tracking technology to monitor physical work output has become established practice in many team sports. Early tracking systems were manual in nature, relying on subjective assessments and arbitrary classifications of movement intensity. Poor spatial and temporal resolution meant that only gross displacement measures could be used to infer energy demands. However, the advent and evolution of automated systems, with higher sampling rates and improved accuracy, have enabled data collection to occur on a mass scale, and served as a catalyst for extensive research into the demands of team sport activity, including comparisons between different groups of athletes, and the effects of various interventions on performance. The inherent assumption with this research is that, based on steady-state models where energy cost is independent of speed, total distance and average speed are indicative of the amount and rate of work done, respectively. This assumption could be justified if the activity was performed at a constant speed in a straight line. However, team sport movement involves continual changes in both speed and direction, both of which increase energy cost. Accordingly, new models have emerged that incorporate both speed and acceleration to determine metabolic power. This provides a more complete measure of energy expenditure in intermittent activity, and is potentially more suitable than displacement variables for research into the demands of team sports.

Key Points

Player tracking technology is used extensively in team sports to quantify physical demands and energy expenditure.

The underlying assumption that displacement variables reflect energy cost is applicable only when activity is performed in a constant speed, straight-line manner.

Changes in speed and direction increase energy cost and should be considered when assessing movement demands in team sport.

1 Introduction

Since as far back as 1931 [1], investigators have tracked players in competition to quantify movement patterns and infer the energy demands of team sport activity. Since then, and particularly in recent times, it has become established practice to use total distance and average speed as indicators of the amount and rate of work done, respectively. Moreover, these displacement variables are used as a basis for making various comparisons of match demands (e.g. between positions or competition levels) and to assess the impact of various interventions on *performance*. It could be argued that, by default, distance and speed have become the criterion measures when assessing team sport energy demands. However, based on metabolic analysis of intermittent activity, it is apparent that the energy demands of team sport competition (and training) are under-estimated when it is assumed that movement is executed at a constant

---

✉ Ted Polglaze
ted.polglaze@research.uwa.edu.au

[1] School of Sport Science, Exercise and Health, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

pace, rather than the perpetually changing series of accelerations and decelerations typically seen in team sports. Accordingly, the energy cost of constantly changing speed must be considered in order to more comprehensively understand the energy demands of team sport activity.

The purpose of this review is to describe how displacement variables have been used to infer energy expenditure in team sports, and to determine whether energy cost principles based on steady-state, constant speed exercise are appropriate for intermittent, variable-speed activity. Whilst it is acknowledged that non-locomotor actions, such as jumping and tackling, contribute substantially to the energy and physical demands in many team sports, this review focuses on how locomotor activity has been used to estimate energy demands in team sport competition. Studies utilising player tracking techniques to assess the physical demands of team sport competition were retrieved from numerous sources, including electronic databases and manual searches. Throughout this manuscript, *displacement variables* is used as a collective term to describe measures of distance, speed and acceleration, in accordance with previous research in this area [2, 3].

2 Evolution of Player Tracking Technology

An initial impetus for indirectly determining energy demands via displacement variables was that direct physiological assessment was neither possible nor practicable, particularly for official competition. Without the capability to measure variables such as oxygen consumption, heart rate or changes in core temperature, alternative methods to assess physical workload were required. Distance covered was considered to be a measure of mechanical work output, and was therefore proposed as a surrogate measure of energy expenditure, given the direct relationship between these two variables [4].

2.1 Manual Tracking and Classification Methods

In the absence of the purpose-built player tracking technology widely available today, early investigations relied on more primitive methods of assessment, although some ingenious techniques were devised to track player position. In the 1930s, for example, investigators etched a basketball court to scale onto a small tin sheet, and then traced the movement of players with a brass wheel encoder [1], with each half inch rotation of the wheel corresponding to 2 feet of movement on the court, which “seemed to measure very accurately” (p. 57). Somewhat less sophisticated was the use of graph paper, drawn to scale to depict a water polo pool, with player movements traced using different coloured pens, each signifying a different speed band [5]. Even cartographers have been called upon to accurately reproduce scale diagrams of an Australian Football oval [6]. For the most part, however, early team sport time–motion analyses relied on manual, subjective and often paper-based techniques to record and classify movement in a range of sports, including soccer [4, 7–9], Australian Football [6, 10], water polo [5, 11], rugby [12, 13], hockey [14, 15], lacrosse [16], volleyball [17] and basketball [18].

Although detailed methodologies were not reported in some early papers [19, 20], a common approach was to use reference points such as field/court markings to estimate, rather than directly measure, distance covered in each discrete movement [4, 5, 17]. Even advertising hoardings and mowing patterns in the grass [4] were used to assist in making more precise estimates. Grid patterns have also been super-imposed over an image of the playing area to more accurately pinpoint the position of players and track their movements [11, 21]. More contemporary manual tracking methods include voice-recognition software [22] and movement tracing onto a scaled computer tablet [23].

Rather than estimate distances, investigators simply reported the *time spent* in various locomotor categories (e.g. walking, jogging, running, sprinting) [12–15, 18], although others extended this and determined the mean speed for each particular movement, and then multiplied it by time spent in that movement to approximate distance covered [9, 10]. Additionally, investigators have measured the average stride length for a player in each locomotor category, counted the number of strides taken in those categories, and then multiplied these two values to determine distance [4, 7, 16]. A similar approach was adopted using stroke length in water polo [24].

Whilst these analyses generally reported acceptable reliability [4, 10, 14, 24], the manner in which the data were collected (i.e. categorical rather than numerical) meant they had poor spatial and temporal resolution [25], and were therefore insensitive to anything other than gross displacement measures such as total distance and average speed. An ability to detect and measure the continual changes in speed (including fluctuations within nominated locomotor categories) was not possible, and speed was assessed according to subjective classifications of running mode, rather than by direct measurement. Other limitations with these methods included only being able to analyse one player at a time—and only after a match—rather than analysing all players or positions within a team, the need for significant training of the observer and, in some cases, only analysing part of, rather than the entire, match [26]. Consequently, manual player tracking systems were used mostly for university-based research projects [27], rather than in applied sport settings.

2.2 Automated Player Tracking Systems

In recent times, purpose-built automated team sport player tracking systems (i.e. incorporating hardware and software) have become commercially available, and are widely used in elite international competition [28, 29] and professional sports leagues [27, 30]. They are available in a variety of technologies across three broad categories [31]: (1) camera-based visual recognition systems; (2) local position measurement (LPM); and (3) satellite signal reception [global positioning system (GPS)]. Multi-camera systems are non-intrusive [32], whereas the latter two categories require the player to wear a device that either transmits their location to an array of base-stations [33] or scans for signals from satellites orbiting overhead [2]. Visual systems have the advantage of being able to track all players, including the opposition team and referee, and in some cases can also follow the ball [32]. Signal-based systems are limited to those players actually wearing a device, although contemporary studies usually include the whole team, including bench players [34]. Visual and LPM systems require permanent or temporary installation of equipment around the playing area. Conversely, satellite systems require no additional equipment, and can therefore be used wherever competition or training occurs, but are limited to outdoor locations. LPM systems utilise various signals, including radio frequency [33, 35, 36] and electro-magnetic wavelength [37] identification.

In addition to the aforementioned factors, the type of tracking system utilised is partly dependent on the rules of the sport. Because wearable technology has hitherto been prohibited in soccer during official competition [38], camera-based systems, such as Amisco® [39] and ProZone® [40], are typically employed [41]. In sports where no restrictions exist (e.g. hockey [28, 42], Australian Football [30, 43]), GPS technology, in particular, has become an established player-tracking method. For indoor sports where GPS signals cannot be accessed, LPM is an emerging alternative [33]. Other factors, such as the size of the playing area (and therefore the distance over which signals must be transmitted), robustness of devices and player safety, must also be considered when deciding on a particular tracking method [44].

Visual tracking systems have been shown to be reliable across a wide range of speeds incorporating both straight-line and change of direction movements [40], and to be accurate for both averaged [45] and instantaneous [46] speed and game-specific movements in real time [47]. LPM has been shown to be highly accurate in measuring distance and speed over short agility courses [35] and soccer-specific circuits [36]. Whilst not reliable for assessing dynamic movements or instantaneous speeds [29], they were accurate for measuring mean, but not peak, acceleration and deceleration [48].

For GPS tracking systems, initial validation studies demonstrated some suitability for quantifying total distance and average speed [49, 50], but reliability was reduced when measuring distance covered at high speed [51], rapid changes in speed over a short distance [52] and speed on a non-linear path [53]. Furthermore, devices with a low sampling rate (1 Hz) were reliable when reporting total movements over extended periods, but not accurate in measuring brief, discrete efforts, especially at high speed [52] or in a confined space [54]. It must be noted, however, that some validation methods used in early studies, such as timing gates or trundle wheels, are questionable [2]. Newer devices with a higher sampling rate (10 Hz) demonstrated improved reliability for measuring speed [50, 55]—particularly at high speed [56]—and acceleration [57], although instantaneous speed measures became less reliable when acceleration rose above 4 m/s^2 [58]. Measurement of high-speed activity over short distances and/or brief periods has also improved [59], but is compromised in the event of rapid directional changes [60]. The accuracy and reliability of 10 Hz GPS devices to detect instantaneous displacement measures have been established against criterion measures of 32 Hz radar [56] and 2000 Hz laser [58].

Although the reliability and accuracy of GPS tracking systems have improved, limitations remain, particularly with respect to identifying and measuring rapid changes in speed [61]. Furthermore, many validation studies utilise pre-planned movement patterns, which do not necessarily replicate the reactive changes in motion typical of team sports. In addition, whilst validation studies are often conducted in open environments, many sports are played in large stadia, which may interfere with signal reception and compromise accuracy.

Some investigators have explored the comparability and interchangeability of various automated player tracking methods and brands. An early comparison found large differences between systems for total distance and also across various speed bands, but good agreement with respect to detecting relative changes over the course of a soccer match [62]. Similar results were found in a direct comparison between visual and GPS systems, in which the camera-based system reported lower total distance but greater high-intensity distance in a competitive (reserve grade) soccer match [63]. More recently, trivial to small differences for total distance between a visual, LPM and two separate GPS systems were incorporated into a regression equation to allow integration of data obtained from the various systems [64].

Irrespective of the actual measurement technique, automated player tracking systems directly measure player location with comparatively high resolution and at a high sampling rate. In contrast to manual systems, they can provide instantaneous displacement measures (i.e. distance, speed, acceleration), and are therefore more sensitive to the continually changing movement patterns typical of team sport activity. Unlike manual systems, they are also able to process multiple players simultaneously, usually in real time.

3 Extent of Player Tracking Technology Use in Team Sport Research

The ability to quantify and classify team sport movement patterns on a mass scale and within a short timeframe has seen a concomitant rise in the amount of published match analysis research [65]. The expression of ‘work rate’ via distance covered, based on the notion that total distance determines energy expenditure irrespective of movement speed [66], has enabled researchers to assess competition demands and evaluate the impact of a range of variables on physical performance [67]. By extension, in situations where playing time is not equal, the expression of distance covered per minute of playing time (i.e. speed) is an appropriate alternative [27] which provides a “more accurate reflection of match intensity than total distance covered” (p. 1031) [68]. In recent team sport research, displacement variables have been used as the criterion measure to (1) describe the physical demands of competition; (2) compare physical demands between certain groups or conditions; and (3) determine the effect of various interventions or circumstances on physical demands. Displacement variables have also been used as independent variables, where their association with other performance-related variables was assessed, and also in the design or validation of various physical fitness tests or simulation circuits.

3.1 Descriptive Studies—Typical Demands of Competition

The total distance covered in a match has been used extensively to indicate the overall physical demands of competition in numerous sports. Unsurprisingly, given its global reach, a large proportion of this research has been in soccer [25, 69, 70], but analyses in hockey [42], rugby [71], Australian Football [43] and basketball [72], for example, have also been conducted. Many of these investigations have focussed on a single team, although some studies have described typical activity profiles across an entire league in soccer [25, 73] and Australian Football [30]. In sports with frequent player interchange (e.g. hockey, Australian Football, basketball, lacrosse), distance covered has also been reported per minute of playing time to allow for differences in on-field duration between individual players [42, 43, 72, 74]. In addition to total distance and/or average speed, most researchers usually report the distribution of movement across various locomotor categories or intensity bands (Barros et al. [25], Lythe and Kilding [42], and Coutts et al. [43]), and also how that distribution changes over the course of a match (e.g. between the first and second half). The amount of high-speed running has been proposed as a key marker of competition demands [75], although the definition of high speed is not standardised, and often uses arbitrary, generic values rather than individualised thresholds based on physiological criteria [76].

Importantly, some studies have also reported the frequency of a change in motion (i.e. mode and/or intensity), which demonstrates the intermittent (or non-steady-state) nature of team sport activity. For example, changes in motion occur every 4.0 s in soccer [77], 5.5 s in hockey [14], 2.0 s in basketball [18] and 6.2 s in water polo [24]. Given the capability of automated tracking systems to measure instantaneous speed, more recent investigations have also been able to assess acceleration characteristics in competition, including their frequency, magnitude and distribution [78, 79], as well as changes in them over the course of a match [74, 80].

3.2 Comparative Studies—Differences between Playing Groups or Conditions

In addition to describing the physical demands of competition, displacement variables have been used as the basis for comparing those demands between and amongst groups for a multitude of factors. The most common comparison has been across player positions [74, 81–84]. Although there are obviously differences in positional groups between sports, and positional classifications within sports are not standardised [67], a consistent finding seems to be that midfield or roaming players tend to cover more distance than players with a more condensed playing area [30, 34, 81], whilst attacking players tend to cover a higher proportion of their distance at high intensities [73, 85]. Besides positional comparisons, studies have also investigated differences in displacement variables between substitutes and starters [86], and according to age [87], sex [88], playing experience [89] and player calibre [29, 84].

The level and type of competition has been another common theme for comparison. This has included different level leagues within the same country [90], similar-level leagues in different countries [91] and the same players playing in different levels of competition [84]. Likewise, comparisons have been made between domestic and international matches [92], including evaluation of the same player(s) competing in each of those competition levels [93]. Differences between league and tournament play in basketball have also been evaluated [94].

Studies have also compared the accumulated distance and average speed over the course of a match [74, 95, 96], across a tournament [28], at different stages within a season [97], across multiple seasons [30, 98], and between regular season and finals matches [99]. Numerous other comparisons have been made, including when a team [100] or individual [101] has possession of the ball (compared to not having possession), zone versus man-on-man defence [102], playing at home versus away [89, 103], winning versus losing teams [104] and higher- versus lower-ranked teams [105]. Total distance and average speed have also been used as a way of comparing physical demands amongst multiple sports [106, 107]. With all of the comparisons outlined in this section, the underlying assertion or inference is that higher distance and speed represent higher match volumes and intensities, respectively. The efficacy of this approach is discussed below.

3.3 Displacement as the Dependent Variable—the Effect of 'X' on Physical Performance

It has been proposed that "Motion analysis may be employed to determine the effects of a training intervention on competition work rate" (p. 858) [27]. In other words, competition displacement variables can be used as the basis for assessing the effect of a particular treatment, or scenario, on physical performance. Consequently, the impact of a vast array of factors has been investigated in recent times [41], with displacement variables used as the dependent variable. In addition to total distance and average speed, the amount and proportion of high-intensity running is often used to indicate match workloads, in particular to demonstrate a reduction in work rate over the duration of a match [43, 108].

Direct game-related variables that have been evaluated include the quality [45] and work rate [97] of the opposition team, prevailing score margin [109] and match status (i.e. winning, drawing or losing) [110], playing formation of the observed [111] and opposition [112] team, dismissal of a player [113] and substitution frequency [114, 115]. Researchers have also examined the interaction between various *situational* or *contextual* factors [103, 116]. Circumstantial variables such as ambient temperature [117, 118], altitude [119], prior air travel [120], time of day [89] and a congested fixture period [121, 122] have also been investigated. The influence of physical fitness on the competition work rate has been established in soccer [123], Australian Football [124] and basketball [125]. Variations in distance or speed have been used as evidence of fatigue and/or pacing [95, 108].

From an experimental perspective, several treatments or interventions have been evaluated, with changes in total distance and/or average speed during matches used to demonstrate their efficacy. These include specific aerobic conditioning [126], pre-cooling [127], half-time re-warm-up [128] and recovery protocols [129, 130]. Nutritional factors that have been assessed include hydration status [131], carbohydrate intake [132], caffeine consumption [133, 134] and multi-nutrient supplementation [135].

3.4 Displacement as an Independent Variable, and Miscellaneous Uses

As well as determining the effect of various factors on competition work rate, investigators have reversed the situation and assessed the influence of displacement variables on other performance-related parameters or outcomes. These include individual technical performance [96], team positioning and tactical approach [136], team selection [137] and final ladder position [138]. Displacement variables have also been used to identify the risk of soft-tissue injury [139, 140] and muscle damage [141]. Finally, competition displacement information has been used to validate a range of field tests [142, 143], create match-specific repeated sprint test protocols [144, 145] and design laboratory-based simulation circuits [146, 147], where the demands of intermittent activity appropriate to the sport can be imposed in a controlled and consistent manner.

3.5 Summary

Whilst it has been stated that "no current method has been accepted as the 'gold' standard approach to work rate analysis" (p. 860) [27], it would seem that, in the supposed absence of any alternative for measuring energy expenditure in team sport activity, total distance and average speed have assumed the role by convention—or default—and continue to be used in this way in team sport research. Whilst alternative approaches are continually evolving, the sheer volume and scope of research demonstrates that displacement variables are entrenched as indicators of workload in team sports.

4 Issues and Limitations of Established Player Tracking Analysis Techniques

The inherent assumption that distance and speed represent the amount and rate of work, respectively, could be justified if the activity being assessed was performed at constant speed in a straight-line, steady-state manner, where the energy cost is known [148]. However, team sport movement rarely occurs at constant speed, and instead typically involves a chaotic, unpredictable and perpetually changing series of accelerations and decelerations, of varying magnitude, duration and starting speed. This is compounded by the fact that movement often entails changes in direction and/or orientation, as well as numerous static, vertical and skill-based actions. In any case, according to the definition for work (mass × acceleration × distance), the determination of energy expenditure requires consideration not only of time and distance, but also the absolute speed and the rate of change of speed [149]. Therefore, the assumption that displacement variables are indicative of energy demands in team sport activity is both dubious and erroneous, and it is time to reconsider their use for this purpose.

Whilst automated tracking systems have made data *collection* a relatively simple and expedient process, as well as offering improved accuracy and reliability, methods of data *analysis* have not evolved to the same extent. Manual systems were restricted to gross measures of displacement across *chunks* of time where, in effect, data collected over a certain period were smoothed. This approach persists despite the possibilities offered by current technology, where a higher sampling rate provides the ability to measure speed and acceleration instantaneously, and subsequently analyse the variability of movement speed observed in team sport activity. In fact, the more sensitive measurement techniques available today have not been fully exploited. Whereas manual tracking systems were not able to detect continual changes in speed, modern analysis techniques mostly ignore these variations. However, evidence of the energy cost of intermittent, non-steady-state exercise suggests this variability must be considered when determining energy expenditure in team sport activity. Accounting for the energy cost of acceleration could potentially provide valid estimates of energy expenditure during team sport activity [150].

5 Energy Cost of Locomotion

The energy cost of human locomotion has been thoroughly investigated [148, 151]. Unlike walking, where the energy cost increases with speed, the energy cost of running is independent of speed [152, 153]. In other words—and in line with the assumptions outlined earlier—the amount of energy required to run a given distance is the same, irrespective of the speed at which it is undertaken. Importantly, however, the fixed relationship between energy cost and running speed was established using (mostly) steady-state responses to a series of constant speed efforts. Numerous factors determine the actual energetic demands of locomotion, and the manner in which those factors contribute and interact is most likely altered when speed is variable and metabolic response unsettled.

5.1 Energy Cost of Constant Speed Locomotion

At low movement speeds on flat terrain, the energy cost of walking is less than running, but that cost rises with increasing speed so that at approximately 8 km/h it becomes more economical to switch to a running action [154], although the transition speed is lower when decelerating than when accelerating [155]. Given the propensity of humans to seek the most efficient method of propulsion [156], it makes sense that there are numerous transitions between walking and running in team sport activity—and consequent variations in energy demand per unit of distance covered.

Whilst researchers have found both increasing [157] and decreasing [158] energy cost with higher running speed, it is generally accepted—and demonstrated by research—that “the metabolic cost to run a given distance is not influenced by running speed” (p. 28) [153] when running at a constant speed on flat terrain. However, even at a constant speed, it has been shown that the energy cost of running increases with the distance covered, and that this increase cannot be fully attributed to fatigue [159].

Although the energy cost per metre for high-speed running is the same as for lower speeds, the attainment of steady state is not possible, and consequently the duration for which it can be maintained decreases rapidly as speed approaches an individual’s maximum [160]. Whereas the *metabolic* cost of running does not increase with speed, the *mechanical* cost decreases [153]. This suggests a reduction in metabolic efficiency (i.e. less mechanical work done per unit of metabolic energy consumed) as speed increases, particularly given the increased contribution of elastic energy (with no metabolic outlay) at higher speeds [161]. With respect to the rate of energy expenditure, *metabolic power* output can be determined as the product of energy cost and speed [148].

5.2 Energy Cost of Variable Speed Locomotion

Because humans rarely travel at a constant speed in normal activity—let alone whilst playing team sports—the energy cost of walking and running at an oscillating speed has been investigated [162]. Whereas the energy cost of walking increased with the degree of oscillation, there was no increase in energy cost for running at a mean speed of 11 km/h, with continual oscillations ranging from 0 to ±4 km/h over a 6 s period (i.e. 3 s excursion above mean, 3 s below). Whilst this was unexpected, the investigators postulated that the elastic energy stored during each stride at that speed was sufficient to meet the additional energy demands of the accelerations without impacting on metabolic output. Although these findings suggest that fluctuating speed does not increase energy cost, this was a comparatively narrow oscillation range, with brief fluctuations evenly and consistently distributed either side of the average speed. Furthermore, only steady-state responses to sub-maximal workloads were assessed. Hence, it is unclear whether these findings would apply to the stochastic and wide-ranging speed traces typically seen in team sport activity.

5.3 Energy Cost of Acceleration and Deceleration

Compared with constant speed running, acceleration has greater neural activation and a higher metabolic cost, which is partly explained by a larger contribution of Type II muscle fibres and a smaller contribution from elastic energy [163]. It is difficult to directly measure the energy cost of acceleration, which by its very nature is not steady state and occurs over a brief period. Therefore, investigators have had to devise ways to estimate the energy cost of acceleration and other brief, intense actions [164]. Mathematical models have been devised to determine the energy cost of elite 100 m sprinting performance [165, 166]. Typically, these models include two components of energy supply (aerobic and anaerobic) and three components of energy demand (that required to move forward, overcome air resistance and change kinetic energy). However, models that use average speed over a given distance will under- and over-estimate different components of energy demand, and therefore instantaneous speed measures should be used [167].

A novel approach to determining the energy cost of acceleration has been proposed [168], whereby increasing (or decreasing) speed on level ground was equated with running uphill (or downhill) at constant speed. Theoretically, the angle of driving force of the runner whilst accelerating on flat terrain corresponds to the gradient of the slope whilst maintaining speed uphill, such that the vectorial sum of propulsive and gravitational accelerations are equal. Given that the energy cost of running uphill at a constant speed is known [152], by converting acceleration on flat terrain to constant speed on the *equivalent slope*, the energy cost and metabolic power output of acceleration could be determined. Testing of this model on well-trained sprinters completing a maximal effort 30 m sprint from a stationary start revealed excellent agreement between measured and modelled speed ($r^2 = 0.99$). Importantly, the highest energy costs occurred immediately after the start of the effort (i.e. during maximal acceleration with minimal speed) and progressively decreased until reaching a plateau that matched the energy cost of running at a constant speed on a level gradient. Furthermore, the energy cost of accelerating maximally over the 30 m distance was three times greater than covering that same distance in the same time at constant speed [168]. Unlike steady-state models, this model considers both speed and acceleration on an instantaneous basis, and is therefore a potentially more suitable method for assessing the energy cost of the perpetually and erratically changing speed typical of team sport movement [150].

Whilst there is scant research into the energy cost of deceleration [169], it can be determined using the same method outlined above [168]. According to this model, the energy cost of deceleration—or downhill running—is much less than for acceleration at the same rate. This can be explained by the increasing contribution of negative work, which has a lower energy cost than positive work [170], and the removal of the requirement to raise (or propel) the centre of mass [152]. Furthermore, eccentric muscle contractions are more efficient [171] and induce less fatigue [172] than concentric contractions.

If the energy costs of acceleration and deceleration were equal and opposite, it would seem reasonable to propose that they cancel each other out over a given time period, and therefore the application of constant speed models for team sport energy expenditure would be acceptable. However, because the effect of deceleration on energy cost is much less than that of acceleration [168], it is clear that change in speed must be accounted for when assessing the demands of intermittent activity.

5.4 Energy Cost of Changing Direction

Changing the direction of movement during locomotion involves a deceleration followed by an acceleration, as well as additional force application to re-direct the initial momentum of the body [173]. The energy cost of shuttle running with 180° changes of direction is higher than constant speed running at the same average speed, and this difference increases with speed [174, 175] and turning frequency [176] and with decreasing shuttle distance [174]. The additional cost of changing direction is dependent on both the magnitude and duration of acceleration [177].

Compared to discontinuous in-line running (i.e. stop–start but no change of direction) with the same distance, speed and acceleration characteristics, shuttle running with 180° changes of direction elicited a higher heart rate, blood lactate concentration and rating of perceived exertion [178], indicating that the change of direction itself invokes an additional energy cost beyond that attributable to changes in speed. This additional energy cost is partly due to the requirement for greater postural stability of the upper body [177]. Interestingly, the angle of direction change does not influence energy cost [179], suggesting that it is the mere act of changing direction, rather than the degree of change, which increases energy demands. Effectively, then, a change in direction invokes two additional and separate demands on energy supply—that required to change speed, and that required to re-direct the trajectory of the body.

Just as team sport activity is rarely performed at a constant speed, it is also not performed purely in a straight-line, forward-facing manner. Direction changes occur frequently in team sports [180, 181], and are therefore likely to contribute significantly to the energy demands of team sport activity.

5.5 Energy Cost of Unconventional Locomotion

Numerous variations on the conventional locomotor actions of walking and running are not only utilised throughout team sport activity, they in fact make up a considerable proportion of overall movement patterns [180]. These include different gait patterns such as shuffling and skipping [180]; different movement orientation, including backward, lateral, diagonal and arcing [180]; and unorthodox postures or stances, particularly whilst in possession of the ball (i.e. dribbling). Some, but not all, of these actions have been assessed with respect to energy cost. For humans, skipping is approximately 150 % more metabolically demanding than running at the same speed [182]. Backwards and lateral running (in either direction) have similar energy costs to each other at any given speed, but are significantly higher than forward running at the same speed [183, 184], and this difference increases with speed—to the point where it becomes necessary to switch to a forward running motion. The energy cost of dribbling is significantly higher than running at the same speed for both soccer [185] and hockey [186]. Current team sport research does not incorporate the additional energy cost of these unconventional movement patterns.

5.6 Summary

Changes in gait, speed, direction and orientation all lead to a different—and in most cases, higher—energy cost than constant-speed, straight-line, forward running. Given that these actions represent typical team sport movement characteristics, it is clear that applying steady-state models of energy expenditure will lead to a substantial under-estimation of the demands of team sport activity. Although player tracking technology may not be able to detect and classify all of these movement characteristics, the integration of both speed and change in speed on an instantaneous basis will, at the very least, provide a more complete and appropriate measure of energy expenditure for team sport activity [149].

6 Alternative Models for Assessing Energy Expenditure in Team Sports

As previously discussed, modern player tracking methods allow for the determination of instantaneous speed and acceleration. Given that the cost of changing speed is different to the cost of maintaining speed, and that the additional cost of changing speed varies according to the magnitude of change and the actual speed at that point [150], a model incorporating both speed and acceleration will provide a more valid measure of energy cost when speed is continually changing. Such a model has been developed and was used to calculate instantaneous metabolic power and accumulated energy demands in elite soccer players [150]. Unsurprisingly, high power outputs (and therefore energy demands) occurred not only when speed was high, but also when acceleration was elevated. In fact, a wide array of speed and acceleration combinations yielded high power outputs, including at velocities that would have been considered moderate or even low intensity.

This model has also been used to report energy demands in Australian Football [187] and rugby league [188]. In both sports, distance covered under-estimated the overall demands of competition, as demonstrated by the equivalent distance index (EDI), which is the ratio of distance covered if total energy is expended at a constant speed to the actual distance covered. The higher this figure, the more intermittent the activity. Interestingly, the degree of under-estimation was low for Australian Football (EDI 1.10), reflective of its sustained running nature, but considerably higher for rugby league (EDI 1.28), which involves more stop–start running. In conjunction with this, speed-based classification of intensity under-estimated the energy demands of rugby league, but not Australian Football. This bias is supported by analysis of soccer training, which showed that as the proportion of high-speed running decreased, differences in classification of high-intensity activity via displacement and energetic criteria magnified [189]. Therefore, it would appear that power, as opposed to distance and speed, may be a more suitable variable for assessing the energy demands of team sport activity.

The above model assumes that stride frequency and metabolic efficiency do not vary for either acceleration or constant-speed running, and ignores the (likely negligible) effect of air resistance [190]. It incorporates the metabolic cost of speed and acceleration, but does not consider the mechanical work of locomotion [191]. If speed is known, total mechanical work can be determined, and can also be apportioned between that done to propel (horizontal) and raise (vertical) the centre of mass, to swing the limbs and to overcome air resistance [191]. Speed-dependent efficiency factors can then be assigned to calculate metabolic power. This model has been used to determine the energy cost of Australian Football [169] and demonstrated that energy expenditure is sensitive to variations in running speed.

As with interpretation of displacement variables, these models assume that all motion is in a forward orientation, and that loads do not vary (which would not be the case with respect to physical contact/tackling, etc.). Although metabolic power models do not consider all of the factors that influence the energy cost of locomotion outlined previously, they nevertheless provide a more complete estimate of energy expenditure in situations where speed is continually changing. Whilst further research is necessary, metabolic power is potentially a more appropriate indicator of workload for team sports, and may be suitable for investigating the exercise dose–response relationship [192] and identifying the occurrence of fatigue during competition [193]. Future research should validate metabolic power against direct measures of energy expenditure and internal load, and determine its relationship with measures of physical fitness and performance.

7 Conclusion

Early player tracking systems were not sensitive to the continual changes in speed evident in team sport. Consequently, gross measures of total distance and average speed were used as indicators of work done and energy expended. This would be acceptable if the activity was performed at a constant speed in a straight line. However, because the activity entails continual changes in speed and direction, the energy cost is under-estimated. Modern player tracking technology is more accurate and sensitive than previous methods, and can determine instantaneous speed and acceleration with high resolution. Integration of these two variables satisfies the definition for work and provides a more complete estimate of the energy cost of intermittent team sport activity, and should therefore be the standard for future team sport movement analysis.

Acknowledgments This manuscript is a component of Ted Polglaze's Ph.D. qualification.

Compliance with ethical standards

Funding No sources of funding were used to assist in the preparation of this article.

Conflict of interest Ted Polglaze, Brian Dawson and Peter Peeling declare that they have no conflicts of interest relevant to the content of this review.

References

1. Messersmith LL, Corey SM. The distance traversed by a basketball player. Res Q Am Phys Educ Assoc. 1931;2(2):57–60.
2. Aughey RJ. Applications of GPS technologies to field sports. Int J Sports Physiol Perform. 2011;6(3):295–310.
3. Lacome M, Piscione J, Hager J-P, et al. A new approach to quantifying physical demand in rugby union. J Sports Sci. 2014;32(3):290–300.
4. Reilly T, Thomas V. A motion analysis of work-rate in different positional roles in professional football match-play. J Hum Mov Stud. 1976;2(2):87–97.
5. Lilley G. A basis for the conditioning of state level water polo players. PELOPS: Stud Phys Educ Leis Organ Play Sport. 1982;3:25–9.
6. Jaques T, Pavia G. An analysis of the movement patterns of players in an Australian rules league football match. Aust J Sport Med. 1974;5(10):23–4.
7. Withers R, Maricic Z, Wasilewski S, et al. Match analysis of Australian professional soccer players. J Hum Mov Stud. 1982;8:159–76.
8. Mayhew S, Wenger H. Time-motion analysis of professional soccer. J Hum Mov Stud. 1985;11(1):49–52.
9. Bangsbo J, Nørregaard L, Thorsoe F. Activity profile of competition soccer. Can J Sport Sci. 1991;16(2):110–6.
10. Dawson B, Hopkinson R, Appleby B, et al. Player movement patterns and game activities in the Australian Football League. J Sci Med Sport. 2004;7(3):278–91.
11. Hohmann A, Frase R. Analysis of swimming speed and energy metabolism in competition water polo games. In: MacLaren D, Reilly T, Lees A, editors. Swimming science VI: biomechanics and medicine in swimming. London: E & FN Spon; 1992. p. 313–9.
12. Docherty D, Wenger H, Neary P. Time-motion analysis related to the physiological demands of rugby. J Hum Mov Stud. 1988;14(6):269–77.
13. Duthie G, Pyne D, Hooper S. Time motion analysis of 2001 and 2002 super 12 rugby. J Sports Sci. 2005;23(5):523–30.
14. Spencer M, Lawrence S, Rechichi C, et al. Time–motion analysis of elite field hockey, with special reference to repeated-sprint activity. J Sports Sci. 2004;22(9):843–50.
15. MacLeod H, Bussell C, Sunderland C. Time-motion analysis of elite women's field hockey, with particular reference to maximum intensity movement patterns. Int J Perform Anal Sport. 2007;7(2):1–12.
16. Romas I, Isles R. A game analysis of the physiological requirements of attack and midfield state league lacrosse players. Sports Coach. 1986;10(1):42–5.
17. Polglaze T, Dawson B. The physiological requirements of the positions in state league volleyball. Sports Coach. 1992;15(1):32–7.
18. McInnes S, Carlson J, Jones C, et al. The physiological load imposed on basketball players during competition. J Sports Sci. 1995;13(5):387–97.
19. Wade A. The training of young players. Med Sport. 1962;3:1245–51.
20. Zelenka V, Seliger V, Ondrej O. Specific function testing of young football players. J Sports Med Phys Fitness. 1967;7:143–7.
21. Rechichi C, Lyttle A, Doyle M, et al. Swimming velocity patterns in elite women's water polo: a case study. Int J Perform Anal Sport. 2005;5(3):139–48.
22. Schokman P, Le Rossignol P, Sparrow W. Validity and reliability of a voice-recognition game analysis system for field sports. J Sci Med Sport. 2002;5(4):362–71.

23. Burgess D, Naughton G, Norton KI. Profile of movement demands of national football players in Australia. J Sci Med Sport. 2006;9(4):334–41.
24. Tan F, Polglaze T, Dawson B. Activity profiles and physical demands of elite women's water polo match play. J Sports Sci. 2009;27(10):1095–104.
25. Barros RM, Misuta MS, Menezes RP, et al. Analysis of the distances covered by first division Brazilian soccer players obtained with an automatic tracking method. J Sport Sci Med. 2007;6(2):233.
26. Drust B, Atkinson G, Reilly T. Future perspectives in the evaluation of the physiological demands of soccer. Sports Med. 2007;37(9):783–805.
27. Carling C, Bloomfield J, Nelsen L, et al. The role of motion analysis in elite soccer: contemporary performance measurement techniques and work rate data. Sports Med. 2008;38(10):839–62.
28. Jennings D, Cormack SJ, Coutts AJ, et al. GPS analysis of an international field hockey tournament. Int J Sports Physiol Perform. 2012;7(3):224–31.
29. Bradley PS, Di Mascio M, Peart D, et al. High-intensity activity profiles of elite soccer players at different performance levels. J Strength Cond Res. 2010;24(9):2343–51.
30. Wisbey B, Montgomery PG, Pyne DB, et al. Quantifying movement demands of AFL football using GPS tracking. J Sci Med Sport. 2010;13(5):531–6.
31. Ogris G, Leser R, Horsak B, et al. Accuracy of the LPM tracking system considering dynamic position changes. J Sports Sci. 2012;30(14):1503–11.
32. Santiago CB, Sousa A, Estriga ML, et al. Survey on team tracking techniques applied to sports. In: 2010 international conference on autonomous and intelligent systems (AIS), Povoa de Varzim. IEEE; 2010. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=5547021. Accessed 23 Nov 2015.
33. Hedley M, Mackintosh C, Shuttleworth R, et al. Wireless tracking system for sports training indoors and outdoors. Proc Eng. 2010;2(2):2999–3004.
34. Polglaze T, Dawson B, Hiscock D, et al. A comparative analysis of accelerometer and time-motion data in elite men's hockey training and competition. Int J Sports Physiol Perform. 2015;10(4):446–51.
35. Sathyan T, Shuttleworth R, Hedley M, et al. Validity and reliability of a radio positioning system for tracking athletes in indoor and outdoor team sports. Behav Res Methods. 2012;44(4):1108–14.
36. Frencken WG, Lemmink KA, Delleman NJ. Soccer-specific accuracy and validity of the local position measurement (LPM) system. J Sci Med Sport. 2010;13(6):641–5.
37. Silva JPdRC. Development of a tracking system using invisible markers for association football. Lisbon: Universidade Técnica De Lisboa; 2012.
38. Carling C. Interpreting physical performance in professional soccer match-play: should we be more pragmatic in our approach? Sports Med. 2013;43(8):655–63.
39. Brulé P, Carling C, David A, et al. AMISCO: the development of a computerised match analysis system to automatically track the movements of soccer players. In: Hughes M, Tavares F, editors. IV world congress of notational analysis of sport, Porto; 1998.
40. Di Salvo V, Collins A, McNeill B, et al. Validation of ProZone®: a new video-based performance analysis system. Int J Perform Anal Sport. 2006;6(1):108–19.
41. Castellano J, Alvarez-Pastor D, Bradley PS. Evaluation of research using computerised tracking systems (Amisco® and Prozone®) to analyse physical performance in elite soccer: a systematic review. Sports Med. 2014;44(5):701–12.
42. Lythe J, Kilding A. Physical demands and physiological responses during elite field hockey. Int J Sports Med. 2011;32(7):523–8.
43. Coutts AJ, Quinn J, Hocking J, et al. Match running performance in elite Australian rules football. J Sci Med Sport. 2010;13(5):543–8.
44. Edgecomb S, Norton KI. Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian football. J Sci Med Sport. 2006;9(1):25–32.
45. Di Salvo V, Gregson W, Atkinson G, et al. Analysis of high intensity activity in Premier League soccer. Int J Sports Med. 2009;30(3):205.
46. Impellizzeri F, Sassi A, Rampinini E. Accuracy and reliability of a commercial video-computerised, semiautomatic soccer-match analysis system: preliminary results. In: Hoppeler H, Reilly T, Tsolakidis E, Gfeller L, Klossner S, editors. Proceedings of the eleventh annual conference of the European College of Sport Science, Lausanne; 2006.
47. Redwood-Brown A, Cranton W, Sunderland C. Validation of a real-time video analysis system for soccer. Int J Sports Med. 2012;33(08):635–40.
48. Stevens TG, de Ruiter CJ, van Niel C, et al. Measuring acceleration and deceleration in soccer-specific movements using a local position measurement (LPM) system. Int J Sports Physiol Perform. 2014;9(3):446–56.
49. MacLeod H, Morris J, Nevill A, et al. The validity of a non-differential global positioning system for assessing player movement patterns in field hockey. J Sports Sci. 2009;27(2):121–8.
50. Portas MD, Harley JA, Barnes CA, et al. The validity and reliability of 1-Hz and 5-Hz global positioning systems for linear, multidirectional, and soccer-specific activities. Int J Sports Physiol Perform. 2010;5(4):448–58.
51. Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. J Sci Med Sport. 2010;13(1):133–5.
52. Jennings D, Cormack S, Coutts AJ, et al. The validity and reliability of GPS units for measuring distance in team sport specific running patterns. Int J Sports Physiol Perform. 2010;5(3):328–41.
53. Gray AJ, Jenkins D, Andrews MH, et al. Validity and reliability of GPS for measuring distance travelled in field-based team sports. J Sports Sci. 2010;28(12):1319–25.
54. Duffield R, Reid M, Baker J, et al. Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. J Sci Med Sport. 2010;13(5):523–5.
55. Johnston RJ, Watsford ML, Kelly SJ, et al. Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. J Strength Cond Res. 2014;28(6):1649–55.
56. Rampinini E, Alberti G, Fiorenza M, et al. Accuracy of GPS devices for measuring high-intensity running in field-based team sports. Int J Sports Med. 2015;36(1):49–53.
57. Varley MC, Fairweather IH, Aughey RJ. Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. J Sports Sci. 2012;30(2):121–7.
58. Akenhead R, French D, Thompson KG, et al. The acceleration dependent validity and reliability of 10 Hz GPS. J Sci Med Sport. 2014;17(5):562–6.
59. Castellano J, Casamichana D, Calleja-González J, et al. Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. J Sport Sci Med. 2011;10(1):233.
60. Rawstorn JC, Maddison R, Ali A, et al. Rapid directional change degrades GPS distance measurement validity during intermittent intensity running. PLoS One. 2014;9(4):e93693.

61. Buchheit M, Al Haddad H, Simpson BM, et al. Monitoring accelerations with GPS in football: time to slow down? Int J Sports Physiol Perform. 2014;9(3):442–5.
62. Randers MB, Mujika I, Hewitt A, et al. Application of four different football match analysis systems: a comparative study. J Sports Sci. 2010;28(2):171–82.
63. Harley JA, Lovell RJ, Barnes CA, et al. The interchangeability of global positioning system and semiautomated video-based performance data during elite soccer match play. J Strength Cond Res. 2011;25(8):2334–6.
64. Buchheit M, Allen A, Poon TK, et al. Integrating different tracking systems in football: multiple camera semi-automatic system, local position measurement and GPS technologies. J Sports Sci. 2014;32(20):1844–57.
65. Coutts AJ. Evolution of football match analysis research. J Sports Sci. 2014;32(20):1829–30.
66. Reilly T. The science of training: soccer. London: Routledge; 2007.
67. Sarmento H, Marcelino R, Anguera MT, et al. Match analysis in football: a systematic review. J Sports Sci. 2014;32(20):1831–43.
68. Cummins C, Orr R, O'Connor H, et al. Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. Sports Med. 2013;43(10):1025–42.
69. Vigne G, Gaudino C, Rogowski I, et al. Activity profile in elite Italian soccer team. Int J Sports Med. 2010;31(05):304–10.
70. Vescovi JD, Favero TG. Motion characteristics of women's college soccer matches: Female Athletes in Motion (FAiM) study. Int J Sports Physiol Perform. 2014;9(3):405–14.
71. Coughlan GF, Green BS, Pook PT, et al. Physical game demands in elite rugby union: a global positioning system analysis and possible implications for rehabilitation. J Orthop Sports Phys Ther. 2011;41(8):600–5.
72. Erčulj F, Dežman B, Vučković G, et al. An analysis of basketball players' movements in the Slovenian basketball league play-offs using the Sagit Tracking System. FU Phys Ed Sport. 2008;6(1):75–84.
73. Dellal A, Wong DP, Moalla W, et al. Physical and technical activity of soccer players in the French First League-with special reference to their playing position. Int SportMed J. 2010;11(2):278–90.
74. Polley CS, Cormack SJ, Gabbett TJ, et al. Activity profile of high level Australian lacrosse players. J Strength Cond Res. 2015;29(1):126–36.
75. Mohr M, Krustrup P, Bangsbo J. Fatigue in soccer: a brief review. J Sports Sci. 2005;23(6):593–9.
76. Abt G, Lovell R. The use of individualized speed and intensity thresholds for determining the distance run at high-intensity in professional soccer. J Sports Sci. 2009;27(9):893–8.
77. Rienzi E, Drust B, Reilly T, et al. Investigation of anthropometric and work-rate profiles of elite South American international soccer players. J Sports Med Phys Fitness. 2000;40(2):162–9.
78. Ingebrigtsen J, Dalen T, Hjelde GH, et al. Acceleration and sprint profiles of a professional elite football team in match play. Eur J Sport Sci. 2015;15(2):101–10.
79. Varley MC, Aughey RJ. Acceleration profiles in elite Australian soccer. Int J Sports Med. 2013;34(1):34–9.
80. Akenhead R, Hayes PR, Thompson KG, et al. Diminutions of acceleration and deceleration output during professional football match play. J Sci Med Sport. 2013;16(6):556–61.
81. Di Salvo V, Baron R, Tschan H, et al. Performance characteristics according to playing position in elite soccer. Int J Sports Med. 2007;28(3):222–7.
82. Abdelkrim NB, Chaouachi A, Chamari K, et al. Positional role and competitive-level differences in elite-level men's basketball players. J Strength Cond Res. 2010;24(5):1346–55.
83. Suárez-Arrones LJ, Portillo LJ, González-Ravé JM, et al. Match running performance in Spanish elite male rugby union using global positioning system. Isokinet Exerc Sci. 2012;20(2):77–83.
84. Brewer C, Dawson B, Heasman J, et al. Movement pattern comparisons in elite (AFL) and sub-elite (WAFL) Australian football games using GPS. J Sci Med Sport. 2010;13(6):618–23.
85. Macutkiewicz D, Sunderland C. The use of GPS to evaluate activity profiles of elite women hockey players during match-play. J Sports Sci. 2011;29(9):967–73.
86. Carling C, Espié V, Le Gall F, et al. Work-rate of substitutes in elite soccer: a preliminary study. J Sci Med Sport. 2010;13(2):253–5.
87. Mendez-Villanueva A, Buchheit M, Simpson B, et al. Match play intensity distribution in youth soccer. Int J Sports Med. 2013;34(2):101–10.
88. Bradley PS, Dellal A, Mohr M, et al. Gender differences in match performance characteristics of soccer players competing in the UEFA champions league. Hum Mov Sci. 2014;33:159–71.
89. Hiscock D, Dawson B, Heasman J, et al. Game movements and player performance in the Australian Football League. Int J Perform Anal Sport. 2012;12(3):531–45.
90. O'Donoghue P, Boyd M, Lawlor J, et al. Time-motion analysis of elite, semi-professional and amateur soccer competition. J Hum Mov Stud. 2001;41(1):1–12.
91. Dellal A, Chamari K, Wong DP, et al. Comparison of physical and technical performance in European soccer match-play: FA Premier League and La Liga. Eur J Sport Sci. 2011;11(1):51–9.
92. Jennings DH, Cormack SJ, Coutts AJ, et al. International field hockey players perform more high-speed running than national-level counterparts. J Strength Cond Res. 2012;26(4):947–52.
93. Andersson HÅ, Randers MB, Heiner-Møller A, et al. Elite female soccer players perform more high-intensity running when playing in international games compared with domestic league games. J Strength Cond Res. 2010;24(4):912–9.
94. Klusemann MJ, Pyne DB, Hopkins WG, et al. Activity profiles and demands of seasonal and tournament basketball competition. Int J Sports Physiol Perform. 2013;8(6):623–9.
95. Aughey RJ. Australian football player work rate: evidence of fatigue and pacing? Int J Sports Physiol Perform. 2010;5(3):394–405.
96. Rampinini E, Impellizzeri FM, Castagna C, et al. Technical performance during soccer matches of the Italian Serie A league: effect of fatigue and competitive level. J Sci Med Sport. 2009;12(1):227–33.
97. Rampinini E, Coutts A, Castagna C, et al. Variation in top level soccer match performance. Int J Sports Med. 2007;28(12):1018–24.
98. Barnes C, Archer D, Hogg B, et al. The evolution of physical and technical performance parameters in the English Premier League. Int J Sports Med. 2014;35(13):1095–100.
99. Aughey RJ. Increased high-intensity activity in elite Australian football finals matches. Int J Sports Physiol Perform. 2011;6(3):367–79.
100. Gronow D, Dawson B, Heasman J, et al. Team movement patterns with and without ball possession in Australian Football League players. Int J Perform Anal Sport. 2014;14(3):635–51.
101. Carling C. Analysis of physical activity profiles when running with the ball in a professional soccer team. J Sports Sci. 2010;28(3):319–26.
102. Abdelkrim NB, Castagna C, El Fazaa S, et al. The effect of players' standard and tactical strategy on game demands in men's basketball. J Strength Cond Res. 2010;24(10):2652–62.
103. Castellano J, Blanco Villaseñor A, Álvarez D. Contextual variables and time-motion analysis in soccer. Int J Sports Med. 2011;32(6):415–21.

104. Black GM, Gabbett TJ. Match intensity and pacing strategies in rugby league: an examination of whole-game and interchanged players, and winning and losing teams. J Strength Cond Res. 2014;28(6):1507–16.
105. Gabbett TJ. Activity and recovery cycles of National Rugby League matches involving higher and lower ranked teams. J Strength Cond Res. 2013;27(6):1623–8.
106. Tanisho K, Ito K, Maeda M, Hirakawa K. Comparisons of movement characteristics and intermittent exercise pattern in ball games. Japan J Phys Educ Health Sport Sci. 2009;54:99–106.
107. Varley MC, Gabbett T, Aughey RJ. Activity profiles of professional soccer, rugby league and Australian football match play. J Sports Sci. 2014;32(20):1858–66.
108. Bradley PS, Noakes TD. Match running performance fluctuations in elite soccer: indicative of fatigue, pacing or situational influences? J Sports Sci. 2013;31(15):1627–38.
109. Sullivan C, Bilsborough JC, Cianciosi M, et al. Match score affects activity profile and skill performance in professional Australian football players. J Sci Med Sport. 2014;17(3):326–31.
110. Redwood-Brown A, O'Donoghue P, Robinson G, et al. The effect of score-line on work-rate in English FA Premier League soccer. Int J Perform Anal Sport. 2012;12(2):258–71.
111. Bradley PS, Carling C, Archer D, et al. The effect of playing formation on high-intensity running and technical profiles in English FA Premier League soccer matches. J Sports Sci. 2011;29(8):821–30.
112. Carling C. Influence of opposition team formation on physical and skill-related performance in a professional soccer team. Eur J Sport Sci. 2011;11(3):155–64.
113. Carling C, Bloomfield J. The effect of an early dismissal on player work-rate in a professional soccer match. J Sci Med Sport. 2010;13(1):126–8.
114. Lythe J, Kilding A. The effect of substitution frequency on the physical and technical outputs of strikers during field hockey match play. Int J Perform Anal Sport. 2013;13(3):848–59.
115. Mooney M, Cormack S, O'Brien B, et al. Do physical capacity and interchange rest periods influence match exercise-intensity profile in Australian football. Int J Sports Physiol Perform. 2013;8(2):165–72.
116. Lago C, Casais L, Dominguez E, et al. The effects of situational variables on distance covered at various speeds in elite soccer. Eur J Sport Sci. 2010;10(2):103–9.
117. Duffield R, Coutts AJ, Quinn J. Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. J Strength Cond Res. 2009;23(4):1238–44.
118. Özgünen K, Kurdak S, Maughan R, et al. Effect of hot environmental conditions on physical activity patterns and temperature response of football players. Scand J Med Sci Sports. 2010;20(s3):140–7.
119. Garvican LA, Hammond K, Varley MC, et al. Lower running performance and exacerbated fatigue in soccer played at 1600 m. Int J Sports Physiol Perform. 2014;9(3):397–404.
120. Fowler P, Duffield R, Vaile J. Effects of domestic air travel on technical and tactical performance and recovery in soccer. Int J Sports Physiol Perform. 2014;9(3):378–86.
121. Lago Peñas C, Rey E, Lago Ballesteros J, et al. The influence of a congested calendar on physical performance in elite soccer. J Strength Cond Res. 2011;25(8):2111–7.
122. Dellal A, Lago-Peñas C, Rey E, et al. The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. Br J Sports Med. 2015;49(6):390–4.
123. Krustrup P, Mohr M, Ellingsgaard H, et al. Physical demands during an elite female soccer game: importance of training status. Med Sci Sports Exerc. 2005;37(7):1242–8.
124. Mooney M, O'Brien B, Cormack S, et al. The relationship between physical capacity and match performance in elite Australian football: a mediation approach. J Sci Med Sport. 2011;14(5):447–52.
125. Abdelkrim NB, Castagna C, Jabri I, et al. Activity profile and physiological requirements of junior elite basketball players in relation to aerobic-anaerobic fitness. J Strength Cond Res. 2010;24(9):2330–42.
126. Helgerud J, Engen LC, Wisloff U, et al. Aerobic endurance training improves soccer performance. Med Sci Sports Exerc. 2001;33(11):1925–31.
127. Duffield R, Steinbacher G, Fairchild TJ. The use of mixed-method, part-body pre-cooling procedures for team-sport athletes training in the heat. J Strength Cond Res. 2009;23(9):2524–32.
128. Edholm P, Krustrup P, Randers M. Half-time re-warm up increases performance capacity in male elite soccer players. Scand J Med Sci Sports. 2015;25(1):e40–9.
129. Rowsell GJ, Coutts AJ, Reaburn P, et al. Effect of post-match cold-water immersion on subsequent match running performance in junior soccer players during tournament play. J Sports Sci. 2011;29(1):1–6.
130. Buchheit M, Horobeanu C, Mendez-Villanueva A, et al. Effects of age and spa treatment on match running performance over two consecutive games in highly trained young soccer players. J Sports Sci. 2011;29(6):591–8.
131. Mohr M, Mujika I, Santisteban J, et al. Examination of fatigue development in elite soccer in a hot environment: a multi-experimental approach. Scand J Med Sci Sports. 2010;20(s3):125–32.
132. Souglis AG, Chryssanthopoulos CI, Travlos AK, et al. The effect of high vs. low carbohydrate diets on distances covered in soccer. J Strength Cond Res. 2013;27(8):2235–47.
133. Del Coso J, Portillo J, Muñoz G, et al. Caffeine-containing energy drink improves sprint performance during an international rugby sevens competition. Amino Acids. 2013;44(6):1511–9.
134. Pettersen SA, Krustrup P, Bendiksen M, et al. Caffeine supplementation does not affect match activities and fatigue resistance during match play in young football players. J Sports Sci. 2014;32(20):1958–65.
135. Minett G, Duffield R, Bird SP. Effects of acute multinutrient supplementation on rugby union game performance and recovery. Int J Sports Physiol Perform. 2010;5(1):27–41.
136. Sampaio J, Gonçalves B, Rentero L, et al. Exploring how basketball players' tactical performances can be affected by activity workload. Sci Sports. 2014;29(4):e23–30.
137. Gabbett TJ, Seibold AJ. Relationship between tests of physical qualities, team selection, and physical match performance in semiprofessional rugby league players. J Strength Cond Res. 2013;27(12):3259–65.
138. Gabbett TJ. Effects of physical, technical, and tactical factors on final ladder position in semiprofessional rugby league. Int J Sports Physiol Perform. 2014;9(4):680–8.
139. Carling C, Gall F, Reilly T. Effects of physical efforts on injury in elite soccer. Int J Sports Med. 2010;31(3):181–5.
140. Colby M, Dawson B, Heasman J, et al. Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. J Strength Cond Res. 2014;28(8):2244–52.
141. McLellan CP, Lovell DI, Gass GC. Creatine kinase and endocrine responses of elite players pre, during, and post rugby league match play. J Strength Cond Res. 2010;24(11):2908–19.

142. Rampinini E, Bishop D, Marcora S, et al. Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. Int J Sports Med. 2007;28(03):228–35.
143. Castagna C, Manzi V, Impellizzeri F, et al. Relationship between endurance field tests and match performance in young soccer players. J Strength Cond Res. 2010;24(12):3227–33.
144. Spencer M, Fitzsimons M, Dawson B, et al. Reliability of a repeated-sprint test for field-hockey. J Sci Med Sport. 2006;9(1):181–4.
145. Tan F, Polglaze T, Dawson B. Reliability of an in-water repeated-sprint test for water polo. Int J Sports Physiol Perform. 2010;5(1):117–20.
146. Sirotic AC, Coutts AJ. The reliability of physiological and performance measures during simulated team-sport running on a non-motorised treadmill. J Sci Med Sport. 2008;11(5):500–9.
147. Tan F, Polglaze T, Cox G, et al. Effects of induced alkalosis on simulated match performance in elite female water polo players. Int J Sport Nutr. 2010;20(3):198.
148. Di Prampero P. The energy cost of human locomotion on land and in water. Int J Sports Med. 1986;7(2):55–72.
149. Furlan N, Osgnach C, Andrews M, et al. Match-analysis techniques: a critique of current methodology. J Aust Strength Cond. 2014;22(5):95–8.
150. Osgnach C, Poser S, Bernardini R, et al. Energy cost and metabolic power in elite soccer: a new match analysis approach. Med Sci Sports Exerc. 2010;42(1):170–8.
151. Margaria R, Cerretelli P, Aghemo P, et al. Energy cost of running. J Appl Physiol. 1963;18(2):367–70.
152. Minetti AE, Moia C, Roi GS, et al. Energy cost of walking and running at extreme uphill and downhill slopes. J Appl Physiol. 2002;93(3):1039–46.
153. Harris C, Debeliso M, Adams KJ. The effects of running speed on the metabolic and mechanical energy costs of running. J Exerc Physiol. 2003;6(3):28–37.
154. Menier D, Pugh L. The relation of oxygen intake and velocity of walking and running, in competition walkers. J Physiol. 1968;197(3):717–21.
155. Thorstensson A, Roberthson H. Adaptations to changing speed in human locomotion: speed of transition between walking and running. Acta Physiol Scand. 1987;131(2):211–4.
156. Alexander RM. Models and the scaling of energy costs for locomotion. J Exp Biol. 2005;208(9):1645–52.
157. Dill D. Oxygen used in horizontal and grade walking and running on the treadmill. J Appl Physiol. 1965;20(1):19–22.
158. Van der Walt W, Wyndham C. An equation for prediction of energy expenditure of walking and running. J Appl Physiol. 1973;34(5):559–63.
159. Brueckner J, Atchou G, Capelli C, et al. The energy cost of running increases with the distance covered. Eur J Appl Physiol. 1991;62(6):385–9.
160. Bundle MW, Hoyt RW, Weyand PG. High-speed running performance: a new approach to assessment and prediction. J Appl Physiol. 2003;95(5):1955–62.
161. Cavagna G, Kaneko M. Mechanical work and efficiency in level walking and running. J Physiol. 1977;268(2):467–81.
162. Minetti AE, Gaudino P, Seminati E, et al. The cost of transport of human running is not affected, as in walking, by wide acceleration/deceleration cycles. J Appl Physiol. 2013;114(4):498–503.
163. Mero A, Komi PV. Electromyographic activity in sprinting at speeds ranging from sub-maximal to supra-maximal. Med Sci Sports Exerc. 1987;19(3):266–74.
164. Weyand PG, Bundle MW. Energetics of high-speed running: integrating classical theory and contemporary observations. Am J Physiol Regul Integr Comp Physiol. 2005;288(4):R956–65.
165. Péronnet F, Thibault G. Mathematical analysis of running performance and world running records. J Appl Physiol. 1989;67(1):453–65.
166. Ward-Smith A, Radford P. Investigation of the kinetics of anaerobic metabolism by analysis of the performance of elite sprinters. J Biomech. 2000;33(8):997–1004.
167. Arsac LM, Locatelli E. Modeling the energetics of 100-m running by using speed curves of world champions. J Appl Physiol. 2002;92(5):1781–8.
168. Di Prampero P, Fusi S, Sepulcri L, et al. Sprint running: a new energetic approach. J Exp Biol. 2005;208(14):2809–16.
169. Gray A. Energetic analysis of running demands in Australian football using global positioning systems technology, PhD thesis. Brisbane: School of Human Movement Studies, The University of Queensland; 2011.
170. Abbott B, Bigland B, Ritchie J. The physiological cost of negative work. J Physiol. 1952;117(3):380–90.
171. Ryschon T, Fowler M, Wysong R, et al. Efficiency of human skeletal muscle in vivo: comparison of isometric, concentric, and eccentric muscle action. J Appl Physiol. 1997;83(3):867–74.
172. Pasquet B, Carpentier A, Duchateau J, et al. Muscle fatigue during concentric and eccentric contractions. Muscle Nerve. 2000;23(11):1727–35.
173. Sheppard J, Young W. Agility literature review: classifications, training and testing. J Sports Sci. 2006;24(9):919–32.
174. Buglione A, di Prampero PE. The energy cost of shuttle running. Eur J Appl Physiol. 2013;113(6):1535–43.
175. Stevens T, de Ruiter CJ, van Maurik D, et al. Measured and estimated energy cost of constant and shuttle running in soccer players. Med Sci Sports Exerc. 2015;47(6):1219–24.
176. Hatamoto Y, Yamada Y, Sagayama H, et al. The relationship between running velocity and the energy cost of turning during running. PLoS One. 2014;9(1):e81850.
177. Akenhead R, French D, Thompson K, et al. The physiological consequences of acceleration during shuttle running. Int J Sports Med. 2015;36(4):302–7.
178. Dellal A, Keller D, Carling C, et al. Physiologic effects of directional changes in intermittent exercise in soccer players. J Strength Cond Res. 2010;24(12):3219–26.
179. Zamparo P, Zadro I, Lazzer S, et al. Energetics of shuttle runs: the effects of distance and change of direction. Int J Sports Physiol Perform. 2014;9(6):1033–9.
180. Bloomfield J, Polman R, O'Donoghue P. Physical demands of different positions in FA Premier League soccer. J Sport Sci Med. 2007;6(1):63–70.
181. Abdelkrim NB, El Fazaa S, El Ati J. Time–motion analysis and physiological data of elite under-19-year-old basketball players during competition. Br J Sports Med. 2007;41(2):69–75.
182. Minetti AE. The biomechanics of skipping gaits: a third locomotion paradigm? Proc R Soc Lond B Biol Sci. 1998;265(1402):1227–33.
183. Reilly T, Bowen T. Exertional costs of changes in directional modes of running. Percept Motor Skills. 1984;58(1):149–50.
184. Williford HN, Olson MS, Gauger S, et al. Cardiovascular and metabolic costs of forward, backward, and lateral motion. Med Sci Sports Exerc. 1998;30(9):1419–23.
185. Reilly T, Ball D. The net physiological cost of dribbling a soccer ball. Res Q Exerc Sport. 1984;55(3):267–71.
186. Reilly T, Seaton A. Physiological strain unique to field hockey. J Sports Med Phys Fitness. 1990;30(2):142–6.
187. Coutts AJ, Kempton T, Sullivan C, et al. Metabolic power and energetic costs of professional Australian football match-play. J Sci Med Sport. 2015;18(2):219–24.
188. Kempton T, Sirotic A, Rampinini E, et al. Metabolic power demands of rugby league match-play. Int J Sports Physiol Perform. 2015;10(1):23–8.

189. Gaudino P, Iaia F, Alberti G, et al. Monitoring training in elite soccer players: systematic bias between running speed and metabolic power data. Int J Sports Med. 2013;34(11):963–8.
190. Di Prampero PE, Botter A, Osgnach C. The energy cost of sprint running and the role of metabolic power in setting top performances. Eur J Appl Physiol. 2015;115(3):451–69.
191. Gray A, Jenkins D, Andrews M. Monitoring running workloads in field based team sports: a new energetic approach using GPS technology. J Sci Med Sport. 2010;13:e36–7.
192. Akubat I, Patel E, Barrett S, et al. Methods of monitoring the training and match load and their relationship to changes in fitness in professional youth soccer players. J Sports Sci. 2012;30(14):1473–80.
193. Waldron M, Highton J. Fatigue and pacing in high-intensity intermittent team sport: an update. Sports Med. 2014;44(12):1645–58.