The Current Use of GPS, Its Potential, and Limitations in Soccer

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ABSTRACT

IN SOCCER, GLOBAL POSITIONING SYSTEM (GPS) MONITORING OF PLAYER WORKLOADS IS NOW EXTENSIVELY USED ACROSS ALL LEVELS OF THE SPORT. TO MAKE BETTER USE OF THIS TECHNOLOGY IT IS IMPORTANT TO APPRECIATE HOW IT WORKS. FURTHER, WHEN THE LIMITATIONS OF GPS USE ARE APPRECIATED AND THE RATIONALE OF USE IS AGREED AND ARTICULATED, THEN THE POTENTIAL OF GPS MONITORING CAN BE EFFECTIVELY REALISED TO BETTER MANAGE PLAYERS PERFORMANCE, WORKLOAD AND WELFARE. (SEE VIDEO, SUPPLEMENTARY DIGITAL CONTENT, NUMBER 1, WHICH SUMMARIZES GPS USE, LIMITATIONS, AND POTENTIAL IN SOCCER, HTTP://LINKS.LWW.COM/SCJ/A238).

INTRODUCTION

With over 265 million participants, soccer is the most popular sport in the world across both sexes and all age groups (25). The sport provides one of the greatest challenges to the strength and conditioning coach with the multitude of fitness components needed to perform at a high level. Added to this are the logistical challenges of developing these capacities in conjunction with the extensive technical and tactical training a player will need to undertake, on a daily basis. This challenge is further exacerbated by the increasing length of playing seasons and an increasing density of fixtures within these seasons (42).

Partly in response to these developments, there has been an increased focus on the overall monitoring of player workloads in an attempt to understand the stress placed on the player during training and match play, with the goal of maximizing performance and minimizing the risk of injury (30,70). To facilitate this, there has been a great increase in the use of global positioning system (GPS) technology (31). However, although this technology is now used by many clubs at both amateur and professional levels, it is important to appreciate the limitations of this technology. Furthermore, it is important to understand how the technology works and how related metrics are derived. Finally, it is equally important to appreciate the potential of GPS and related technology in supporting the goals to improve player performance and ultimately, to ensure better player welfare.

GLOBAL POSITIONING SYSTEM DEFINED

GPS is a satellite-based navigation system and is made up of over 30 orbiting satellites. The system was originally put into orbit by the U.S. Department of Defense for military use in the early 1970s. Later, in the 1980s, it was made available for civilian use. The orbiting satellites transmit unique signals that allow GPS devices to locate the satellites precise location. Essentially, the GPS receiver calculates the distance to each satellite by the amount of time it takes to receive a transmitted signal with the result that the user's location can then be precisely determined. Once the receiver links with a number of orbiting satellites, a GPS receiver can provide a reasonably exact position and speed of the receiver device. There are 2 main communication systems associated with GPS technology. The direct satellite to receiver device system of communication described above is known as nondifferential, whereas the use of ground-based correction techniques to enhance the quality of location data gathered using GPS receivers is known as a differential system (44,45). The important point to

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note is that although the nondifferential system can provide useful data, there will always be a degree of error which the practitioner needs to be aware of (44). Some of this can come for the sampling frequency of the device and others from factors that affect the signal, as the signal from the satellites can be influenced by the atmosphere and obstructions such as tall buildings (45). Differential GPS can help to reduce this error. Differential GPS uses stationary receivers placed at known locations on the ground. These fixed-position receivers are then used to facilitate better communication with orbiting satellites (45).

EVOLUTION OF GLOBAL POSITIONING SYSTEM TECHNOLOGY

One of the first studies using GPS technology was published by Ishii et al. (38). This group used mobile GPS units to track referees during match play in both rugby union and soccer. The study compared video tracking, manual recording, and GPS tracking of the referee and found that there was little difference among all 3 methods for total distance covered in the match. Since the original study of Ishii et al. (38), GPS technology has become more sophisticated in the metrics it can provide and has been integrated with other microelectromechanical sensors (MEMS) such as accelerometers and gyroscopes. This has been facilitated by team sport governing bodies that now allow players to use GPS tracking devices during match play (24,57). Recently, the world governing body for soccer (FIFA) amended their rules to allow the use of GPS technology in competitive match play (26). This has created the opportunity for the quantification of several physical workload metrics associated with elite competitive soccer match play (Table 1).

The integration of MEMS technology now allows for the quantification of metrics related to body impact, adding to the concept of workload monitoring (1,7,14,15,20,29,64,71). Metrics such as dynamic stress load and step balance are examples of impact-related metrics currently derived from integrated GPS and MEMS technology (Table 1). There is no doubt that GPS technology has facilitated a greater understanding of the physical activity demands of different team formations and positional profiling during match play, as well as training, and when integrated with internal responses such as heart rate (HR) monitoring, a more holistic workload evaluation may be attained (1,14,53,61,63,68).

EARLY WORKLOAD MONITORING IN SPORT

Foster et al. (26,27) established the validity of using "rating of perceived exertion" or RPE as a tool to monitor physical workload. Both team and individual sports have since used this method to establish exercise workload (34). Studies also reported the use of session RPE and duration as a valid instrument for tracking workload within anaerobic sports and within a resistance training exercise environment (49,62,66). In parallel with this growth and interest in sport-related workload monitoring, methods were investigated that could provide objective data on workload. An important factor that assisted in this development was when GPS selective availability was removed in 1999, making it available for use within a sporting environment (45). Subsequently, RPE and session duration workload quantification were supplemented with GPS-derived workload metrics and these measures became increasingly popular (3,34,35,39).

With a view to establish a broader definition of what workload means in a sporting environment, Quarrie et al. (57) defined "load" within a team sport perspective as "the total stressors and demands applied to the players." This included sport-related and non–sport-related stress inputs. Furthermore, the authors noted that the relevance of load to athlete performance, well-being, and injury risk should be considered from an acute and cumulative perspective. Thus, taken together, workload should be considered from the totality of all stressors, as an acute and chronic or cumulative concept, be they physical or otherwise. The quantification and use of these workload data within a broader concept of workload is a desirable goal for all involved in sport but it is also a challenge for the support staff of a team of players.

RELIABILITY AND VALIDITY

As with all measuring devices in sport, it is important to assess both reliability and validity of GPS and related devices. GPS devices are classified by the rate at which they sample per second. In the early years of GPS use in sports, the devices used a sampling rate of 1 Hz or 1 sample per second (3,43). When such devices were assessed for reliability and validity, studies reported that these devices were somewhat unreliable and not valid especially for short high-intensity sprint runs (18,39,41,43,46). Jennings et al. (39), for example, used GPS devices sampling at 1 and 5 Hz and concluded that GPS systems may be limited for the assessment of short high-speed straight-line running and efforts involving change of direction. The authors did note that an increased sample rate improved validity and reliability of GPS devices. Other authors supported this finding when assessing 1- and 5-Hz GPS devices (18,41).

Johnston et al. (41) reported that GPS error was found to increase along with the velocity of movement and noted that more caution should be exercised when analyzing movement demands >20 $km \cdot h^{-1}$. Coutts and Duffield (18) reported an acceptable level of accuracy and reliability for total distance during high-intensity, intermittent exercise but not for higher intensity activities. Subsequently, the use of 10-Hz devices became more common in team sport and Varley et al. (69) reported that devices using such higher sampling rates were 2–3 times more accurate than the 5-Hz devices. The same authors then concluded that newer GPS devices may provide an acceptable tool for the measurement of constant velocity, acceleration, and deceleration during straight-line running and have sufficient sensitivity for detecting changes in movement velocity in

Table 1
Metrics listed and definitions used are derived and informed from a number of sources (19,64,73,74)

Metrics commonly determined using GPS technology	Definition
Total distance	This is a measurement of the total distance traveled during the playing period by a player. This is commonly measured in kilometers.
Meters per minute	This is expressed as total meters in a given minute and as an average during a specified period.
Average speed	This is the total distance covered by a player and divided by the total playing duration in hours. This is frequently measured in km per hour.
Maximal speed	The maximal speed reached for a one second sample period.
Speed zones or thresholds	Classified by Cummins et al. (19) as:
	Walking (0–7 $km \cdot h^{-1}$)
	Running at low speed (7–13 $km \cdot h^{-1}$)
	Running at medium speed (13–18 $km \cdot h^{-1}$)
	Running at high speed (18–21 $km \cdot h^{-1}$)
	Sprinting (>21 $km \cdot h^{-1}$)
Acceleration	Acceleration activity is measured as the change in GPS speed data using established statistical methods. To count as an acceleration, the increase in speed must take place for at least half a second with maximum acceleration in the period at least 0.5 m/s^2. The acceleration finishes when the player stops accelerating. Frequently, the number of accelerations is reported through specific zones.
Deceleration	Deceleration is the decrease in speed that takes place for at least half a second for an activity to be counted as deceleration. Also, the maximum deceleration in the period must be at least 0.5 m/s^2. The classification of decelerations by zone is based on the maximum deceleration in the period. Frequently, the number of decelerations is reported through specific zones.
Exertion index	This is calculated differently between brands. Exertion index according to Wisbey et al. (74) is based on the sum of a weighted instantaneous speed, a weighted accumulated speed over 10 seconds, and a weighted accumulated speed over 60 seconds.
Exertion index per minute	This is a measure of game intensity and is determined by dividing exertion index by playing time.
Longest continuous time above a specified speed	This is a measurement of the longest period the player stays above this speed, without dropping below this speed. Time is recorded even when the player enters a higher speed zone. This provides an indication of the longest continuous effort at varying speeds.
Time at steady state	This is measured as any time at a speed above 8 $km \cdot h^{-1}$ where the player's velocity does not alter by more than 1.5 $km \cdot h^{-1}$ within a 1-second sample period. This gives an indication of time spent at continual running speeds.
Efficiency	This is a measure of the work requirements for game involvement. It is measured by dividing the exertion index by total number of possessions.

(continued)

Table 1 (continued)	
Energy expenditure	The energy expenditure metric gives the total energy associated with running only, including accelerating and decelerating activity measured in kcal. It is based on the level of activity and scaled by the weight of the player in kilograms, set in the player profile screen. This metric and that of HMLD are derived from the work of Osgnach et al. (55).
High metabolic load distance (HMLD)	HMLD is the distance (meters) traveled by a player when his/her metabolic power (energy consumption per kilogram per second) is above the value of 25.5 W/Kg.
Metrics derived from integrated accelerometer	
Impacts	Impacts are frequently identified as maximum accelerometer magnitude values above 2*g* in a 0.1-s period and reported as maximum values and cumulative over a specific period.
Dynamic stress load (DSL)	Dynamic stress load is the total of the weighted impacts, which is based on accelerometer values of magnitude above 2*g*. It weights the impacts using an approach similar to that used in the speed intensity or heart rate exertion calculations, with the key concept being that an impact of 4*g* is more than twice as hard on the body as an impact of 2*g*. Statsports (www.statsports.com) note that impacts are a mixture of collisions and step impacts while running. For team sports such as soccer, these peak impacts may increase as a player fatigues during match-play.
Total load	Total load gives the total of the forces on the player over the entire activity period based on accelerometer data alone. It uses the magnitude of the accelerometer values taken in 3 directions, sampled 100 times per second. The total is scaled by 1,000 to give manageable values.
Step balance	Using the accelerometer data, sampled at 100 Hz in each of the 3 directions, step balance is defined as the average peak impact on each step for the left and right feet.

GPS = global positioning system.

team sport. As noted earlier, before we can confidently rely on these data, the validity and reliability of such devices need to be established. To date, it does seem that practitioners can have confidence that 10-Hz GPS devices have, in general, acceptable levels of reliability and validity for many metrics measured.

Early studies on accelerometer use in team sports reported acceptable reliability levels both within and between devices (8). However, a recent work from Alexander et al. (2) cautioned that accelerometer use may not be accurate during maximal acceleration and high-speed running. The authors assessed a commonly used 100-Hz triaxial accelerometer integrated within a wearable device. They compared the accelerometer-derived metrics for impact and speed with a dual-beam timing system as well as a video-capture system when professional team sport players completed 3 × 40 m maximal-sprint efforts on an indoor synthetic running track. The accelerometer data were recorded as the raw output and filtered using a variety of filtering techniques. The authors reported that the accelerometer could not accurately measure average acceleration values during high-speed running, and significantly overestimated average acceleration values during both 0–10 m and 10–20 m segments, regardless of the filtering technique used. The authors concluded that until GPS-integrated accelerometers incorporate gravity compensation formula in their algorithms, the usefulness of any accelerometer-derived algorithm is questionable (2).

Although GPS provides a potentially useful tool for the strength and conditioning coach to measure several workload metrics (Table 1), it is important to note that there is still concern regarding the precision of certain GPS-derived metrics (6,9,10). For example, the dynamic stress load is calculated in the GPS software as a weighted score using a combination of accelerometer and GPS data along with impacts (64). This external load metric is intended to reflect the total body load impact weighted to dominant and nondominant limbs over the duration of the physical activity. This metric, although appealing as a workload metric, has not been validated in field studies. Yet, the potential of using this metric has been demonstrated in that it has been associated with risk of injury and may be used in an injury predictive model (42). Nevertheless, although the potential of using such metrics is evident, more applied research is required in establishing the reliability and validity of these metrics.

WORKLOAD DEMANDS CONVENIENTLY DESCRIBED

Clearly, the previous approach to match analysis when using notational or time-motion analysis was a labor-intensive one and required several hours of analysis before presenting feedback (43). The time efficiency of using GPS is a very welcome technology addition to the team support staff. This now allows for the immediate compilation and presentation of relevant metrics, thereby facilitating more immediate feedback to coaching staff and players. In fact, it has been argued that when considering the alternative practices for player tracking and subsequent feedback, some errors may be an acceptable trade-off for both the time-efficient and ease of use of GPS devices (43,53).

USES OF GLOBAL POSITIONING SYSTEM–DERIVED METRICS

Quantifying player workload requires analysis of all the activities a player undertakes during a training and competitive period (57). To facilitate this, GPS metrics are used during a variety of physical activity sessions or units. For example, GPS-derived data are used to quantify competitive and noncompetitive match play, training-related activities such as small-sided games, technical and tactical preparation units, on-field team fitness routines, on-field specific individual fitness, or rehabilitation routines.

GLOBAL POSITIONING SYSTEM–DERIVED METRICS

Table 1 describes some of the commonly used measurements or metrics of physical training, practice, and match play derived from GPS and accelerometer technology. Note that the table is not an exhaustive one, rather an example of metrics used in team sports (19,33,64,73,74). Also note that some metrics have not been assessed regarding validity and many metrics are defined differently depending on the unit's brand (48).

TOTAL DISTANCE

Over the past 10 years, the demands of amateur and professional match play have been well established using GPS technology (11,49,58,60,67,68). Studies report that players can cover a distance of between 8,500 and 13,000 m using various locomotion intensities during match play (20,58). Research has also shown that the physical activity profile can be different depending on playing position (47), age of player (11), and team tactical formation (67).

SPEED ZONES

The speed activity profile of players may be categorized into zones typically using 5 absolute speed zones as described in Table 1 (19). Although these zones are commonly used, they are not standardized even within a given sport (19,48). Cummins et al. (19) reported that speed zone criteria often varied widely within and between sports. As a result, recent studies have proposed a more individualized approach to speed thresholds based on a systematic and detailed profiling of acceleration and maximum velocity testing of players (50,52,54). This development in the individualized application of GPS technology and its integration with field testing facilitates a more individualized profiling that has the potential to better inform a player's specific workload.

IMPACT METRICS

Until recently, GPS devices did not allow for the quantification of important sport-related events such as the impact associated with the take-off when jumping and landing, as well as the impact occurring when falling to the ground or when tackling, jostling, and blocking (10). GPS technology now features triaxial accelerometers integrated into the GPS unit (8,35,48). This integration of technologies has allowed for the quantification of additional important impact metrics associated with contact sports especially (1,3,8,9,13,54,56). Frequently, accelerometer values are reported as G-force and less commonly as meters per second^2 and these metrics are now reported by many popular GPS/accelerometer devices (33,64). This additional workload quantification inevitably adds to the broader understanding of workload. For example, it allows for greater insight into position-specific match play preparation with threshold levels being determined that are appropriate for the player and his or her position (15).

The usefulness of accelerometer-related metrics has been evident in recent studies. For example, Cormack et al. (15) assessed the relationship between accelerometer-derived impact load per minute and neuromuscular fatigue in elite team sport players. The authors reported an association between fatigue and vertical axis impact, thus providing a potential use and support for the application of accelerometer load–derived data in player workload and recovery monitoring. More recently and within soccer, Abade et al. (1) described training session body impact data for elite age grade players during a 9-week period of training. Although the authors noted that their results showed high variability between training sessions across the age grades, the use of accelerometer-derived data added to the overall description of the players' workload during this phase of the season.

DIFFERENT TEAM FORMATIONS

Tactical performance plays an important role in soccer and different team formations are used by teams both as a standard formation and as adjustments during the game (22,67). These formations can significantly affect the game-related tasks players will need to achieve and subsequently, the physical capacities they will need to be able to perform these tasks. Only recently the impact of different formations on overall workload and specific metrics has been reported (67). Using GPS, Tierney et al. examined 5 common playing formations used in elite-level under 18 and under 21 team match play over the course of a season (67). The metrics described included total distance, high-speed running, high metabolic load distance, high-speed accelerations, and decelerations. The authors reported that all positions within a 3-5-2 formation elicited higher total distances (10,528 ± 565 m, $P = 0.05$), greater high-speed running distance (642 ± 215 m, $P = 0.001$), and greater high metabolic load distance (2025 ± 304 m, $P = 0.001$) than all other formations. Also, the authors reported above average acceleration and deceleration profiles (34 ± 7, $P = 0.036$ and 57 ± 10, $P = 0.006$, respectively) for a 3-5-2 formation. The authors concluded that all positional physical characteristics are influenced by the demands of playing different formations.

Tactical and technical factors have been reported to be related to overall team success (22,23). Di Salvo et al. (22) reported that although physical performance metrics impact on match outcome, overall, technical and tactical effectiveness of the team rather than high levels of physical performance are more important in determining success in soccer. Therefore, it is evident that systems which assist in the quantification of technical and tactical approaches and events be integrated with physical workload analysis for a more holistic representation of performance.

POSITION-SPECIFIC DEMANDS

The use of GPS and related technology has allowed for a convenient and cumulative approach to player positional profiling in terms of workload (67,68). For example, Torreño et al. (68) used an integrated 5-Hz GPS tracking device and a 100-Hz accelerometer to quantify the position-specific demands of soccer players. The authors noted the benefits of such position-specific monitoring and concluded that training activities should focus on the level of physical and physiological demands based on the individual player profile during match play. They elaborated that many training drills can elicit similar internal loads (HR-based) compared with actual match play providing an optimal physiological training stress. For greater effectiveness, the authors noted that each team should have its own physiological and mechanical demands associated with soccer match play during official games, measured with the same technology that these players are monitored with during training sessions.

WEEKLY WORKLOAD DESCRIBED

Before the common use of GPS in monitoring workload, it is arguable whether precise workload monitoring in the immediate days during match week was a standard feature of team sports (37). However, since the introduction of affordable and reliable GPS technology in professional soccer and other team sports, a more thorough and complete workload profile is now a feature of in-season on-field training and practice (60). This was a positive development in player workload management. The potential of such monitoring is reflected in the specific daily workloads leading into a competitive match that are now monitored by soccer teams.

Coutinho et al. (17), for example, described the time-motion and physiological performance profiles of age-grade soccer players during a typical week of a competitive season. The data were captured using a 15-Hz GPS device and divided into postmatch (session after the match), prematch (session before the match), and middle week (average of remaining sessions). Differences in the various training/practice days were reported for the different age grades. The older age group displayed relatively higher body impacts with impacts above 10 G being reported. Furthermore, the prematch data presented 35–100% less workload values than the middle-week data. Understanding the weekly workload variations according to the competition and the developmental ages of the players can, according to the authors, contribute to optimizing both short- and mid-term planning. In addition, Stevens et al. (65) describe the workload tapering approach that is either intentionally or unintentionally used in the week leading into match play. The authors draw attention to the fact that nonstarters may actually not be challenged sufficiently in physical work during match week. This has implications for players training programmes and match readiness preparation. Thus, monitoring of all players can be facilitated by GPS technology use on an on-going basis.

PLAYER WORK:RECOVERY MONITORING–INTEGRATED WITH OTHER KEY METRICS

Integrating GPS- and MEMS-derived metrics with other standardized physical and physiological testing as well as psychological data may provide a more complete profile of the stress status of the player. For example, Watson et al. (70) reported that in female adolescent soccer players, lower mood scores and higher acute training load as derived from GPS workload tracking are factors associated with an increased injury risk. The authors note that monitoring well-being and training load may facilitate intervention that may reduce the risk of in-season injury and illness. Such metrics could also be further complemented using other internal system variables such as HR monitoring and HR variability, the latter reflecting a metric of the status of the autonomic nervous system. In addition, metrics reflecting other internal or biological systems including neuromuscular, endocrinal, and immunological systems coupled with psychological (i.e., mood or well-being status) as well as lifestyle profiling (i.e., sleep duration and quality) hold the potential to attain a more complete monitoring profile (31,32,42,70).

INJURY RISK–REDUCTION POTENTIAL

Clearly, the full potential of GPS and related technology is yet to be comprehensively investigated and realized. This is arguably true from an injury risk–reduction perspective when GPS-derived data are combined with historical and prospective injury-related data as well as other psychoemotional responses such as mood (13,28,70). Nevertheless, studies have investigated the association between physical workload using data derived from GPS technology and from retrospective and prospective injury data surveillance (13,28,30,59). Coughlan et al. (16) suggested that GPS data used in conjunction with video analysis can help clarify the mechanism of many injuries. This integration of technologies can no doubt be of assistance to the support team in understanding the factors that may be associated with injury during match play and training. Added to this potential, Gabbett and Ullah (28) reported that higher distances and high-speed running are variables or metrics associated with injury in elite sports. In addition, Colby et al. (13) examined the association between overall physical workload using GPS and accelerometer-derived measurements and injury risk in elite team sport players during a season. The authors reported that from an injury risk perspective, their findings supported consideration of several GPS/accelerometer running load variables. They noted that cumulative weekly loads could be closely monitored with 3-weekly loads most indicative of a greater injury risk across both pre-season and in-season phases. More recently, Windt et al. (72) highlighted the apparent training-load injury paradox within team sport players. The authors reported that additional pre-season training sessions were associated with a reduction in the odds of injury in the subsequent training week and further, with a lower percentage of games missed due to injury during the in-season. The authors concluded that maximizing participation in pre-season training may protect elite team players against in-season injury.

Within soccer, a theoretical predictive model of injury derived from GPS metrics has been proposed (42). The author examined the incidence of intrinsic injury, defined as an injury not related to collision or contact, and several GPS-related metrics. The study demonstrates that key GPS metrics aggregated over a weekly workload can offer workload and temporal guidelines that assist in better workload-recovery practices that seek to reduce injury risk. There are some practical limitations to the study and one is the limitation of the application of such predictive models, given that contact is an inevitable part of the game. Other limitations relate to the rigorous process required in establishing an association between injury risk factors and injury risk–reduction practice (4). Nonetheless, the research is of interest as it is among the first to report the potential of such modeling techniques in soccer. Other related wearable technologies offer potential for more in-depth and critical workload evaluation as well as injury rehabilitation workload monitoring (19). These may include wearable electromyographic (EMG) technology. Together, GPS and EMG wearable technologies highlight the potential benefit of such technological integration in establishing workloads that are on the one hand, tolerable to the player, but also allow for thresholds to be determined that may assist in reducing the risk of injury and in assisting in the return to play program after injury (19,51).

ACTUAL USE OF GLOBAL POSITIONING SYSTEM AND MICROELECTROMECHANICAL SENSORS TECHNOLOGY IN INJURY RISK–REDUCTION MANAGEMENT

To what extent such integration of injury data and GPS/MEMS-derived workload metrics are recorded and analyzed in team sport is not clear (35). Having the technology alone does not ensure that such data are recorded, analyzed, and used to inform better player management practice. Also, it is clear that not all team sport coaches will regularly monitor workload and player response to such workloads (35). This may be due to a number of factors and Halson (35) notes that resources in the form of time, money, or the human resources needed to collect, process, and analyze the data are all issues that may limit the use of player monitoring systems. An important point made by Halson (35) is that there are no guarantees that monitoring training load will result in successful performances. In addition, a lack of knowledge or experience with monitoring techniques or the inability to interpret derived data can result in an impediment to implement a practical and sustainable monitoring system. In conjunction, the reality may be that many teams do not have a clear rationale identifying why monitoring is occurring, what is to be monitored, how often monitoring will occur, and how the data are interpreted and presented to the coaching staff and players. Halson (35) also notes that the ability and opportunity to implement change and provide feedback is critical to a successful monitoring system and if this does not occur, any attempts at monitoring are not sustainable.

POTENTIAL TO TRACK SPORT OR GAME CHANGES OVER TIME

As previously discussed, studies have described the changing nature of the game of soccer at the professional level (5,22). To do so, the authors used a multicamera, stadium-based, computerized tracking system (Prozone Sports Limited, Leeds, United Kingdom). Such tracking systems are becoming popular especially at the top tier of professional socccer and have been shown to be valid and reliable (21). The initial setup cost, the fixed nature of the system within a given stadium, the absence of such a system in all physical and technical training areas, and the lack of impact-related outputs are all factors that may limit stadium-based system use. As evidenced earlier, all physical workload regardless of where it occurs needs to be recorded and reported to quantify the total workload of a player. Therefore, the portability associated with GPS tracking is a positive feature of this system as it allows locomotor metrics from most all outdoor physical exercise to be recorded and reported (45).

Although no long-term comparative GPS-based studies have been reported in soccer, GPS-based technology has been shown to be useful in tracking the changing nature of other team sports, notably Australian Rules Football (73,74). Wisbey et al. examined the demands of elite-level Australian Rules Football based on GPS data collection with the cooperation of 16 clubs (73,74). Interestingly, the comparison of data collected on different brands of GPS devices showed similar work rates but differences in accelerations and surges. Thus, the accuracy of the data is questioned, given the use of different GPS brands. On a positive note, the changes in certain metrics do facilitate an analysis of the collective changes occurring over several seasons in the sport. Therefore, the capability to track changes in match play workload over several seasons when using GPS tracking systems is well supported.

With respect to the use of different tracking systems, some issues deserve attention if data from both a fixed camera system and a GPS system are to be combined (5,21). The fixed system differs in the manner in which data are captured and in which it categorizes metrics such as speed and acceleration/deceleration zones (4,19,22). Such standardization issues are important to address before a valid representation of total workload can be quantified using a combination of systems. On this point, the author is unaware of any published research which compares locomotor and other work-related metrics derived from stadium tracking systems and GPS-derived metrics and a comparative study investigating this would be useful and beneficial.

LIMITATIONS OF GLOBAL POSITIONING SYSTEM TECHNOLOGY

Surprisingly, few studies report issues in signal reception, whereas in practice, this can be a common problem when using GPS tracking (13,20,45). Colby et al. (13) report that, on occasions, GPS data were deemed unreliable because of an intermittent signal where insufficient connecting satellites were detected. On such occasions, the authors ensured that workload data were predicted by calculating individual player averages for drills completed. This does demonstrate the need to have alternative methods to record work that is actually completed when satellite signal reception is problematic.

Many practitioners may use a combination of methods to report overall workload; yet, few studies report a combination of GPS data and other methods of physical activity workload reporting such as session RPE and duration (13). For example, Coutinho et al. (17) provided no description or report of any indoor-related work completed by the subjects in their study. Other studies may also not report all physical workload due to this limitation (60,65). As a result, there is need to use more traditional workload-reporting formats such as RPE and session duration (26) not only for indoor aerobic and anaerobic exercise but also for resistance training (49,66). To assist in indoor workload quantification, the advent of commonly available and reliable linear position transducers now allows for a more precise quantification of indoor resistance training–related workload (36). Some players may pursue physical recreation pastimes and again, this is a further physical workload that might be included in all physical workload-monitoring systems.

Another limitation of GPS technology is that, in its popular format, it can only track outdoor physical activity. Clearly, there is a need to monitor all physical activities including indoor activities if a more complete representation of overall workload is to be reported. GPS manufacturing and distribution companies are working to overcome this limitation associated with GPS tracking (33,64). For example, local positioning systems which use accelerometer, gyroscope, and magnetometer capability are currently promoted to provide several locomotor and impact metrics in an indoor environment (64). However, more research is required to establish the device's accuracy, especially during high-speed running efforts (2).

To ensure better reception and consequently more accurate data capture, differential GPS is sometimes though not always used (13,20). More recent advances of GPS and wireless communication technology are now in use (64). These advances are based on augmented satellite signal reception using ultra-wideband positional beacons placed strategically within a stadium or training/competition arena, which are reported to augment satellite signal reception (64). Peer-reviewed research reporting the accuracy and reliability of such ultra-wideband augmented technology is yet to be completed when using such device systems.

In addition to the factors previously noted, other factors are considered to impact on the precision and accuracy of GPS tracking (43,44,48,51). For example, Malone et al. (48) note that in addition to device sampling rate, positioning and fitting of devices and data filtering methods can affect the measures obtained from GPS and MEMS devices. The authors encourage researchers to report device brand or model, sampling frequency, number of satellites locked onto, horizontal dilution of precision and software/firmware versions, in any published research. An understanding of the impact of such factors on a unique GPS session is also important for the practitioner or scientist who will eventually be responsible for reporting and interpreting GPS- and MEMS-derived data.

LIMITATIONS IN GLOBAL POSITIONING SYSTEM USE

A GPS-related limitation with respect to use is that few studies have used

GPS technology to inform tactical and technical performance criteria (67). Arguably, this may also reflect the lack of integration with other technologies that describe tactical and technical elements of match play. In the absence of an integration of GPS and tactical/technical event description, other technologies are often used to complement GPS-derived metrics so that a more comprehensive evaluation of performance workload can be attained. For example, Nic (53) notes that most if not all professional soccer teams use some form of video feedback from a tactical/technical perspective. This concept has been advanced with virtual reality biofeedback technologies being used in professional team settings (www.beyondsports.nl). It is possible that the integration of GPS with such technology has the potential to create a more holistic and broader understanding of the physical, technical, and tactical demands of the sport. The limitation for such use may not actually be a technical one, but rather a more human limitation, where coaching and performance knowledge, as well as analytical and communication skills are insufficient in deriving meaningful interpretation from such integrated data.

THE NEED FOR CAUTION

Buchheit et al. (10) caution the coach and user when comparing data collected with different brands or units or when data are analyzed with different software versions (Table 2). This, according to Buchheit et al., is problematic especially when dealing with historical data collected on a large number of players (10). Researchers have reported differences between devices even of the same model, suggesting that it is prudent that a player be monitored with the same device (18). By contrast, research from Castellano et al. (12) found small variations between devices, with a coefficient of variation of 1.3 and 0.7% in runs of 15 and 30 m, respectively. These researchers concluded that it is not always necessary to monitor players with the same device. In a more recent study, Beato et al. (6) reported that external load variables such as total distance and high-speed running distance may be underestimated by GPS tracking even when using a 10-Hz sampling rate. This underestimation according to the authors increases in short-distance tracks as well as during on-field–based scenarios including change of direction activities. The authors state that these limitations should be considered even in sport science research, especially because they could affect the estimates of accelerations, decelerations, and metabolic power during short shuttle running and change of direction activities, with consequent underestimation of total energy expenditure (EE).

With reference to EE, Brown et al. (9) reported that GPS tracking using the metabolic power model of EE does not accurately estimate EE in field-sport movements or over an exercise session consisting of mixed locomotor activities interspersed with recovery periods. However, GPS tracking, is able to provide a reasonably accurate estimation of EE during continuous jogging and running (9). Nagahara et al. (52) caution that although GPS tracking technology has merit, the more traditional means of assessing sprint velocity should be preferred compared with GPS-derived velocities. The authors reported both overestimation and underestimation for both 5- and 20-Hz GPS tracking systems when measuring maximum velocity during a running sprint.

The above evidence is not intended to be biased toward negating the positive impact of GPS-derived data. It merely attempts to caution the practitioner as to the limitations of GPS tracking as it is currently used (Table 2).

Table 2
Issues concerning GPS use in sport and recommendations to offset limitations

Issue concerning GPS	Recommendation to resolve
Systems using a sampling rate of 1 or 5 Hz may be less reliable and valid especially where high-speed running is concerned (20,40,43,61).	Select device with a sampling frequency of 10 Hz (40,43,61).
Comparing metrics derived from different brand devices may be problematic (10,47).	Use only the same GPS brand (51).
Changes in software may create practical problems in using historical data as the new software may not be completely compatible with the older software (10,48).	Ensure compatibility, should software options change (48).
Energy expenditure calculations derived from GPS systems may not be valid for intermittent team sport activities but may be appropriate for steady-state jogging or running (6).	Use established systems for assessing athlete maximum velocity and energy expenditure (2,9,52).
GPS may underestimate high-speed running especially in short-distance tracks and during change of direction (2,6).	Use metrics that have established validity (10). Wear the same GPS tracking unit (61).

These are derived and informed from a number of sources.

GPS = global positioning system.

SUMMARY

The introduction of GPS technology to monitor the physical demands of match play and all outdoor-related physical practice, training, and general activity in the early 2000s represented a significant step change in the way in which team sport physical workload was recorded and assessed. In the mid-2000s, various studies examined the reliability and validity of the devices used to track external workload, and many reported reliability and validity concerns. This was related chiefly to the limited sampling frequencies for 1- and 5-Hz devices. The advances in sampling frequency since then to include a 10-Hz sampling frequency resulted in greater confidence in the precision of GPS devices to track player physical work-related metrics. Although there are still concerns regarding the precision of both GPS tracking and MEMS devices in tracking high-speed activities as well as change of direction and other more novel metrics, as derived from algorithms calculated from accelerometer data, GPS technology has made a clear statement as to its usefulness in player workload monitoring and to a lesser extent, in overall performance and welfare management. As GPS technology and its software/firmware advances and integration with MEMS technology has progressed, it is clear that the practitioner or analyst recording, analyzing, and presenting these metrics needs to be both well informed of their limitations and potential. Furthermore, support staff should ensure a clear rationale for technology use and application within the club or team setting. This, then, is more likely to facilitate a positive environment that allows for decisions about player recovery, practice, and training workload to be implemented.

Although the future for GPS technology looks promising, there is a need to embrace a broader and more holistic approach to workload monitoring. The limitation of GPS technology in monitoring only outdoor exercise and its current incapability to monitor resistance training–related exercise is a limitation. Here, other MEMS technologies can play an important role, provided their validity and reliability are established and acceptable, and provided that manufacturers and service providers work closely with the end user in establishing the limitations of use as well as the beneficial uses of integrated systems.

Clearly, there is a need to identify reliable, valid, and meaningful metrics that are not only external workload and GPS-derived but that also include internal and psychological metrics, as well as technical and tactical elements. There is also a need to integrate all workload-related monitoring systems so that unnecessary and irrelevant data can be minimized. Future research should focus on identifying the training and match play metrics that may allow for a valid injury predictive model, thus facilitating a reduced risk of injury and individualized workload thresholds based on optimal work:recovery processes.

The use of GPS and related technologies, when the rationale of use is agreed and articulated, can offer positive outcomes to both support staff and players. This is predicated on the end users of such technology appreciating the potential and limitations of such devices and software. Finally, if the potential of GPS and related technologies is to be realized, there are many challenges to all stakeholders. Nonetheless, with the skills and competencies to report, present, interpret, and apply the metrics derived from such devices, the potential for better player welfare and performance management in such technologies can be realized.

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