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SYSTEMATIC REVIEW

# Global Positioning Systems (GPS) and Microtechnology Sensors in Team Sports: A Systematic Review

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**Abstract**

*Background* Use of Global positioning system (GPS) technology in team sport permits measurement of player position, velocity, and movement patterns. GPS provides scope for better understanding of the specific and positional physiological demands of team sport and can be used to design training programs that adequately prepare athletes for competition with the aim of optimizing on-field performance.

*Objective* The objective of this study was to conduct a systematic review of the depth and scope of reported GPS and microtechnology measures used within individual sports in order to present the contemporary and emerging themes of GPS application within team sports.

*Methods* A systematic review of the application of GPS technology in team sports was conducted. We systematically searched electronic databases from earliest record to June 2012. Permutations of key words included GPS; male and female; age 12–50 years; able-bodied; and recreational to elite competitive team sports.

*Results* The 35 manuscripts meeting the eligibility criteria included 1,276 participants (age 11.2–31.5 years; 95 % males; 53.8 % elite adult athletes). The majority of manuscripts reported on GPS use in various football codes: Australian football league (AFL; $n = 8$), soccer ($n = 7$), rugby union ($n = 6$), and rugby league ($n = 6$), with limited representation in other team sports: cricket ($n = 3$), hockey ($n = 3$), lacrosse ($n = 1$), and netball ($n = 1$). Of the included manuscripts, 34 (97 %) detailed work rate patterns such as distance, relative distance, speed, and accelerations, with only five (14.3 %) reporting on impact variables. Activity profiles characterizing positional play and competitive levels were also described. Work rate patterns were typically categoriszed into six speed zones, ranging from 0 to 36.0 km·h$^{-1}$, with descriptors ranging from walking to sprinting used to identify the type of activity mainly performed in each zone. With the exception of cricket, no standardized speed zones or definitions were observed within or between sports. Furthermore, speed zone criteria often varied widely within (e.g. zone 3 of AFL ranged from 7 to 16 km·h$^{-1}$) and between sports (e.g. zone 3 of soccer ranged from 3.0 to <13 km·h$^{-1}$ code). Activity descriptors for a zone also varied widely between sports (e.g. zone 4 definitions ranged from jog, run, high velocity, to high-intensity run). Most manuscripts focused on the demands of higher intensity efforts (running and sprint) required by players. Body loads and impacts, also summarized into six zones, showed small variations in descriptions, with zone criteria based upon grading systems provided by GPS manufacturers.

*Conclusion* This systematic review highlights that GPS technology has been used more often across a range of football codes than across other team sports. Work rate pattern activities are most often reported, whilst impact data, which require the use of microtechnology sensors such as accelerometers, are least reported. There is a lack of consistency in the definition of speed zones and activity descriptors, both within and across team sports, thus underscoring the difficulties encountered in meaningful comparisons of the physiological demands both within and between team sports. A consensus on definitions of speed

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zones and activity descriptors within sports would facilitate direct comparison of the demands within the same sport. Meta-analysis from systematic review would also be supported. Standardization of speed zones between sports may not be feasible due to disparities in work rate pattern activities.

## 1 Introduction

Global positioning system (GPS) is a satellite-based navigational technology originally devised for military purposes. A number of informative, technical reviews on GPS [1–3] have previously been published outlining how this technology enables three-dimensional movement of an individual or group to be tracked over time in air-, aquatic-, or land-based environments. The recent development of portable GPS units has permitted wider application of this technology in a variety of settings, including sport, thus providing an additional means for describing and understanding the spatial context of physical activity. First utilized for athlete tracking in 1997 [4], GPS technology is now increasingly used in team sport settings to provide sports scientists, coaches, and trainers with comprehensive and real-time analysis of on-field player performance during competition or training.

GPS technology has been used extensively in rugby league, rugby union, Australian football league (AFL), cricket, hockey, and soccer, with only limited research available in netball, hockey, and lacrosse. Current literature provides an array of information on the activity profile of field sport athletes. By measuring player movements, GPS can be used to objectively quantify levels of exertion and physical stress on individual athletes, examine competition performances, assess different positional workloads, establish training intensities, and monitor changes in player physiologic demands [5]. Player movement patterns and activity profiles (external loads) can be used in addition to tactical information and physiological responses (internal load) to characterize competitive match play [5]. From its introduction, GPS was used to measure basic components of player movement patterns, speed, and distance travelled and the number of accelerations and decelerations. The integration of GPS with a triaxial accelerometer enables the capture of information on work rate patterns and physical loads. The triaxial accelerometer measures a composite vector magnitude (expressed as a G-force) by recording the sum of accelerations measured in three axes ($X$, $Y$, and $Z$ planes) [6]. In addition, the number and intensity of physical contacts and collisions between athletes and objects or surfaces can be quantified by body load and impact measures. Body load (measured as G-force) is the collation of all forces imposed on an athlete, including acceleration/deceleration, related changes of direction and impacts from both the player-to-player collision and contact with the ground (foot strikes and falls) [7]. GPS technology allows for further analysis of speed and impact characteristics by classification into six activity bands known as speed and impact zones, respectively. Zone one indicates the lowest, whilst zone six indicates the highest level of effort or impact [8]. These details can be utilized to analyze training or game settings and compare player performance or session intensity.

There is an abundance of literature examining the validity and reliability of GPS for the measurement of movement in the football codes, hockey, and cricket. The gold standard criterion method used to investigate GPS validity for distance is to measure a course with a trundle wheel or tape measure and, for speed, use of timing gates at the start and finish [9] or a speed gun [10]. GPS devices are currently manufactured with 1-, 5-, and 10-Hz sampling rates (the speed at which the unit gathers data). The literature suggests that GPS with a higher frequency rate provides greater validity for measurement of distance. When comparing the precision of distance acquisition between a 1- and a 5-Hz GPS, the standard error of a standing start 10-m sprint was 32.4 and 30.9 %, respectively [11]. By contrast, a 10-Hz GPS demonstrated a 10.9 % standard error over a 15-m sprint [9]. Recently, it has been reported that GPS devices at 1 Hz may be unable to record movements taking <1 s to complete [12]. The newer 10-Hz units are capable of measuring the smallest worthwhile change in acceleration and deceleration, whereas the 5-Hz unit is unable to do so [10]. The greater errors associated with measurement of distance with the 1- and 5-Hz versus the 10-Hz GPS devices indicate that the sampling rate may be limiting the accuracy of distance measurements and velocity.

The speed of a movement impacts the validity of the GPS-measured distance. The earliest validation of a GPS device (GPS 45, Garmin) showed various walk and run velocities (2–20 $km \cdot h^{-1}$) were highly correlated ($r = 0.99$) with a chronometer [4]. A more recent study [13] shows GPS distance measurement error to be lowest during walking ($\sim 1.8$ $ms^{-1}$; standard error of estimate [SEE] 0.7 %) and highest during running ($\sim 6$ $ms^{-1}$; SEE 5.6 %). Similarly Johnston et al. [12] reported that GPS is capable of measuring work rate patterns performed at velocities <20 $km \cdot h^{-1}$; however, recommended caution when analyzing work rate patterns at velocities >20 $km \cdot h^{-1}$. These results indicate that movement velocity impacts upon accuracy, with GPS reported as a valid method for measurement of distance travelled at low to moderate but not high speeds.

The validity of distance measures improves with longer duration activities [11]; for example, the coefficient of variation (CV) diminished from 32.4 to 9.0 % for sprint distances of 10 and 40 m, respectively. The CV was further reduced to 3.8 % for a range of velocities completed over a 140-m modified team-sport running circuit [11].

The factors of sampling frequency, distance, and speed, which affect GPS validity, similarly affect the reliability of GPS. The impact of sampling frequency still remains unclear; for example, the CV of a linear soccer task has been reported as 4.4–4.5 % for a 1-Hz GPS and 4.6–5.3 % for a 5-Hz [14]. However, another study [11] reported the CV of a 10-m sprint as 77 and 39 % for 1 and 5 Hz, respectively. More recently, a higher sampling rate of 10 Hz has demonstrated improved reliability during the constant velocity and acceleration or deceleration phase (CV <5.3 and <6 %, respectively) [10]. Whilst the data are currently ambiguous and may be explained through the use of different GPS manufacturers and models [9], it would seem that an increased sample rate appears to improve the reliability of GPS measures.

The reliability of GPS decreases with the increased velocity of movement. The CV of walking for a 5-Hz GPS was 1.4–2.6 %, whilst the CV of sprinting over a 20-m distance was 19.7–30 %. Similarly, CVs of 30.8 and 77.2 %, respectively, for walking and sprinting over a 10-m distance were noted with a 1-Hz GPS [11]. The reliability of GPS devices is also negatively affected by movements requiring changes in direction. The CV for gradual and tight change of direction movements at walking pace has been reported as 11.5 and 15.2 %, respectively [11]. The tight change of direction movements may demonstrate a decreased reliability due to the increased number of speed changes performed [11].

The re-test reliability between GPS devices is consistent. Waldron et al. [6] examined the re-test reliability between GPS units, finding random errors between two tests ranging from 0.56 to 1.64 $km{\cdot}h^{-1}$ and small mean biases ($-0.01$ to $-0.14$ $km{\cdot}h^{-1}$) for all sprint intervals.

Overall, studies conclude that GPS devices have an acceptable level of validity and reliability for assessing movement patterns at lower speeds and over increased distance efforts. The decreased reliability of GPS units to accurately measure movement patterns during short-duration, high-speed, straight-line running, and efforts requiring changes in direction may limit both accuracy and reliability for assessing these aspects in team sports. However, GPS units with increased sampling frequency demonstrate improved reliability and validity and can be utilized in the monitoring of physical activity in situations such as team sports, so long as caution is taken when interpreting individual sprints and rapid changes in both direction and velocity. Use of GPS for quantifying impacts in collision sports is still relatively new and so further research on the validity and reliability for this purpose is warranted.

Although many studies have examined the GPS application within specific team sports, a comprehensive documentation of movement patterns and physiological demands of team sports has not been undertaken. Furthermore, the rapidly evolving utilization of GPS in the football codes, through the application of player profiles to investigate collision impacts, match fatigue, and injury risk, may inform all team sports.

Therefore, the aim of this study was to conduct a systematic review to collate the considerable depth and scope of reported GPS measures within individual sports in order to present the contemporary and emerging themes of GPS application within team sports.

## 2 Methods

### 2.1 Design

Studies investigating the use of GPS systems to monitor the position, speed, or distance of an athlete during outdoor training or competition settings within team sports were eligible for inclusion in the review. A systematic search of electronic databases (MEDLINE, SPORTdiscus, CINAHL, Web of Science, Scopus, EMBASE, Cochrane, and Google Scholar) was performed from the earliest record to June 2012. All study designs (e.g. randomized controlled trials, cohort cross over, observational) were included. The search strategy combined terms covering the topics of device (GPS), population (male and female, 12–50 years, able bodied, recreational to elite), and activity (sport, team sport, exercise, training, physical activity, rugby, AFL, football, rugby union, rugby league, soccer, basketball, hockey, and cricket). Studies were included if athletes were monitored using GPS systems and at least one of the following GPS outcomes was reported: distance, velocity/speed, acceleration, impacts, or body load.

### 2.2 Selection of Studies

After eliminating duplicates, search results were screened independently by two researchers (CC, CW) against eligibility criteria. References that could not be eliminated by title or abstract were retrieved and independently evaluated for inclusion. Reviewers were not masked to the title or authors of the publications. Disagreements were resolved by discussion or via a third researcher (RO). Abstracts and conference papers from annual meetings were not included due to not meeting the rigour of outcome measures. In cases where journal articles contained insufficient information, attempts were made to contact authors to obtain missing details. Reference lists of all retrieved papers were manually searched for other potentially eligible papers. Papers from all languages were included, but were excluded if a translation could not be made.

### 2.3 Data Extraction

Data relating to the participant characteristics (age, sex, height, mass, and level of competition/athletic calibre), GPS unit (brand, model, speed, and distance recording frequency), and work rate patterns were extracted by two researchers (CC, RO). Work rate patterns included speed zone identification (zones 1–6), time spent in zones (min), and speed ($km \cdot h^{-1}$). Distance covered was extracted as either total distance (m) over the competition or training session, distances covered in each zone, or average maximal or total sprint distance (m). Sprint duration (min) over the competition or training session was also extracted in addition to the number of acceleration and decelerations ($m \cdot s^{-2}$), impact (G), and body load (G). Studies reporting speed in $m \cdot min^{-1}$ were converted to $km \cdot h^{-1}$. Authors were contacted to provide data if reported only in graphical form. When data were unavailable, two researchers (CC, RO) estimated mean and standard deviation (SD) in duplicate using a ruler.

### 2.4 Assessment of Methodological Quality

The quality of included studies was independently assessed by two researchers (CC and RO) using the modified assessment scale of Downs and Black [15]. Of the 27 criteria, 12 that logically applied to the study designs included in this review were used. No studies were eliminated and no additional subgroup analysis was undertaken on the basis of methodological quality. A meta-analysis was not performed, as study designs were heterogeneous and unable to be pooled.

### 2.5 Statistics

All data are presented as mean or mean (SD) unless otherwise specified.

## 3 Results

### 3.1 Identification and Selection of Studies

The original search netted 7,333 studies. After the removal of duplicates and screening, 43 studies remained. One of these was unable to be translated and was excluded; seven studies were eliminated based on the eligibility criteria. The flow of the papers from potentially relevant to inclusion is displayed in Fig. 1. One author was contacted and provided mean and SD of data presented graphically in the manuscript as median and range [16].

### 3.2 Study Characteristics

There were a total of 1,276 participants in the included manuscripts, with individual study numbers ranging from 3 to 179. Manuscripts mainly described young (age 11.2–31.5 years) males (95.2 %), with 32 studies exclusively recruiting male, three exclusively female, and none of mixed sex (Table 1). Of the 35 papers, 18 (51.4 %) report on elite adult athletes, whilst eight (22.9 %) report on children/adolescent athletes.

The team sports included AFL ($n = 8$) [17–24], soccer ($n = 7$) [16, 25–30], rugby union ($n = 6$) [31–36], rugby league ($n = 6$) [5, 8, 37–40], cricket ($n = 3$) [41–43], hockey ($n = 3$) [44–46], netball ($n = 1$) [47], and lacrosse ($n = 1$) [48]. There was a strong bias towards description of football codes (AFL, rugby union, rugby league, and soccer), with the majority of all studies (26 of 35) [5, 8, 17–24, 29–32, 35, 37–45, 47, 48] conducted in Australian sports settings. Papers demonstrated varied use of GPS, with 25 [5, 8, 16–20, 22, 24–28, 33–38, 40–43, 45, 46] studies examining competition match variables, eight [21, 23, 29–32, 47, 48] examining training variables, and three reporting on both training and competition variables [32, 39, 44].

### 3.3 Methodological Quality

The scores for the assessment of methodological quality ranged from 6 to 10 across the 12 items assessed (See Electronic Supplementary Material, T1). The main quality issue was the provision of exact $P$ values. Three [16, 18, 43] studies failed to provide a clear description of participants. One criterion required that a hypothesis, aim, or objective was stated; only four studies identified an hypothesis [5, 8, 20, 40].

### 3.4 Analysis of Physiological Outcomes

All 35 manuscripts, apart from one [8], reported on various GPS variables of movement ($n = 34$; 97 %) [5, 16–48], with only five manuscripts (14.3 %) [8, 33, 34, 36, 39] evaluating impact variables.

#### *3.4.1 Work Rate Patterns*

Movement variables included distance covered (m), mean and maximum velocity ($km \cdot h^{-1}$), acceleration and deceleration ($m \cdot s^{-2}$), impact (G), and body load (G).

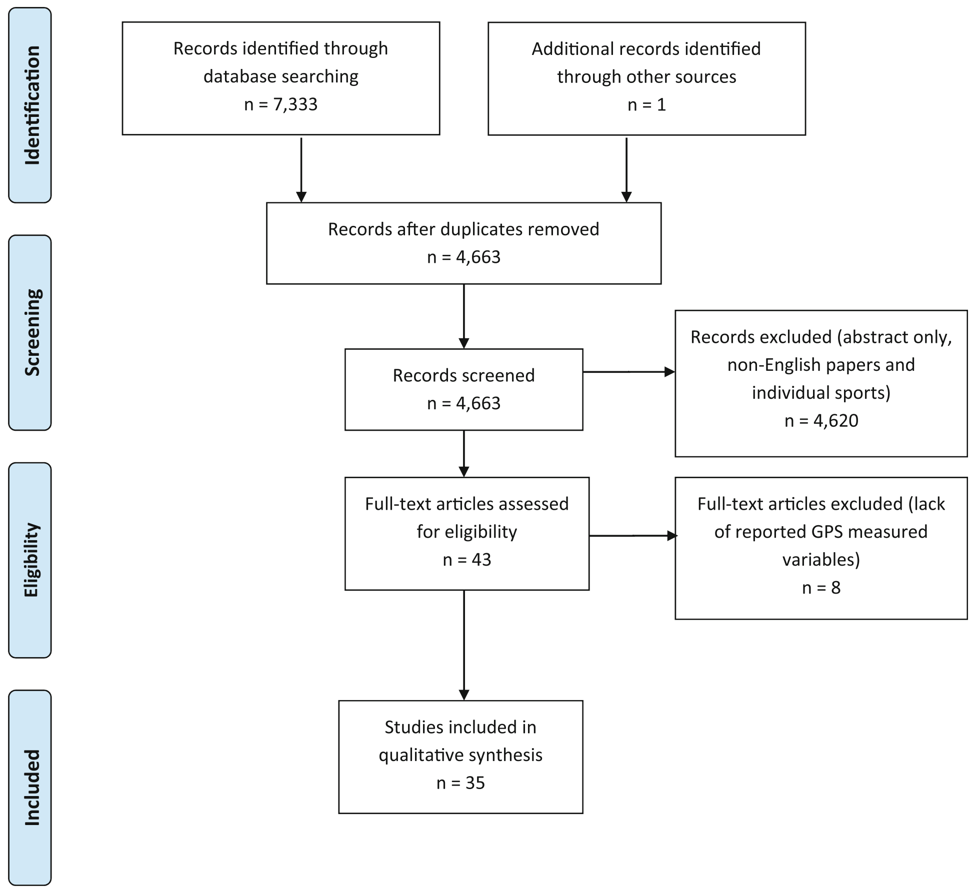


**Fig. 1** Study selection flow chart. *GPS* global positioning system

**Table 1** Characteristics of studies

| Sport | Sample size | % Male | Age range (years) | Athletic calibre | Reference |
|---|---|---|---|---|---|
| AFL | 348 | 100 | 16.2–28.9 | Elite, subelite, junior | [17–24] |
| Rugby Union | 188 | 100 | 14.0–28.6 | Elite, semi-professional, junior | [31–36] |
| Rugby League | 287 | 100 | 16.9–31.5 | Elite | [5, 8, 37–40] |
| Soccer | 286 | 95.8 | 11.2–20.0 | Elite, semi-professional, elite under 19, elite junior, junior | [16, 25–30] |
| Cricket | 96 | 100 | 19.3–24.9 | Elite | [41–43] |
| Hockey | 55 | 70.9 | 18.0–29.7 | Elite | [44–46] |
| Netball | 9 | 0 | 18.0–27.2 | State league 1 | [47] |
| Lacrosse | 7 | 100 | 18.5–21.3 | Collegiate division 1 | [48] |
| Overall | 1,276 | 95.2 | 11.2–31.5 | | |

*AFL* Australian Football League

*3.4.1.1 Total Distance* Total distance travelled (Fig. 2) was, historically, one of the first GPS variables to be monitored and thus the most commonly reported variable in the studies included in this review. Cricket players covered the greatest distance per competition game, with a fast bowler in One Day International cricket covering 15,903 m [41–43], followed by elite AFL players covering a total distance of 12,939 m [17–20, 22, 24]. Soccer consistently demonstrated a higher distance travelled per game than rugby union and rugby league.

Athletic calibre and age impacted upon total distance. Elite [33] and junior [32] rugby union forwards covered 5,853 and 3,511 m, respectively, with elite players covering 40 % further distance. Similarly in soccer, under 18 years players covered 8,867 m [27], an additional 27.2 % distance compared with the 6,459 m observed in under 13 years players [27].

Positional differences were evident within each sport, for example, backs in both rugby league [37, 39, 40] and rugby union [32–34] covered greater distances than

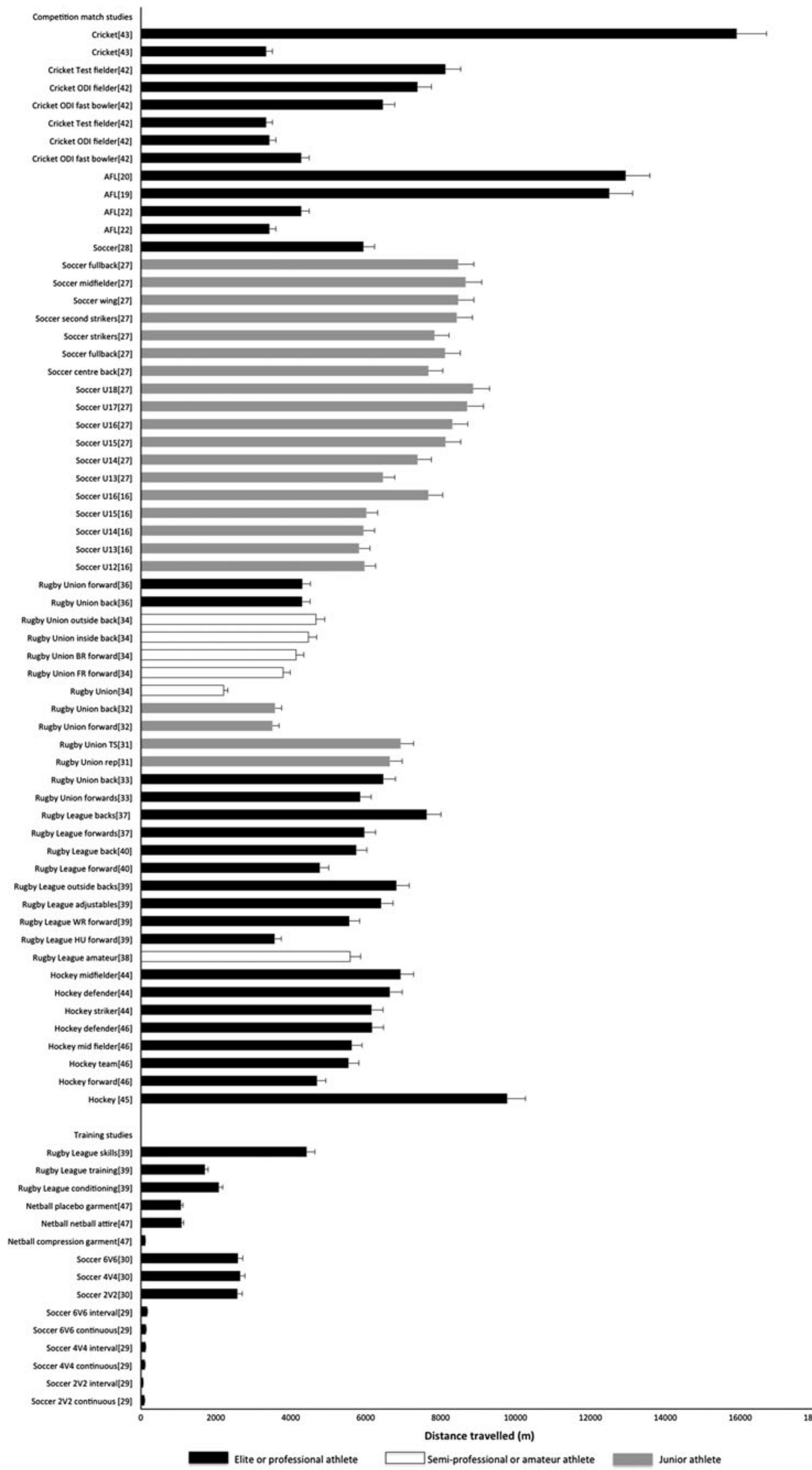


**Fig. 2** Total distance covered during competitive matches or training [16, 19, 20, 22, 27–34, 36–40, 42–47]. Values expressed as mean (SD). *AFL* Australian Football League, BR back row, *FR* front row, *HU* hit up, *ODI* one day international, *Rep* representative, *TS* talent squad, *Ux* under x years, *WR* wide running, *2v2* 2 versus 2 players, *4v4* 4 versus 4 players, *6v6* 6 versus 6 players

forwards; however, the margin of difference was less in rugby union. McLellan et al. [40], reported that elite rugby league backs covered 5,747 m or 16.9 % greater distance than forwards (4,774 m). By comparison, in rugby union, backs covered 7.6 % more distance than forwards (6,471 and 5,853 m, respectively) [33]. Similarly in AFL, Brewer and colleagues [19] found that mid-fielders and small forwards/backs covered greater total distances than other positions, with ruckmen recording the lowest distances.

*3.4.1.2 Relative Distance* Relative distance or total distance travelled per minute of competition game time ($m{\cdot}min^{-1}$) may provide a more accurate reflection of match intensity than total distance covered, as it takes into account the event time. Additionally, distance is only a measure of volume, whilst relative distance is a measure of intensity. Only eight [16, 22, 35–39, 45] manuscripts reported on relative distance (Fig. 3). Although few papers address this, positional differences were apparent when examining the distance covered per minute, showing similarities to total distance. A difference of 7.2 % relative distance was evident between elite rugby union forwards and backs (66.7 vs. 71.9 $m{\cdot}min^{-1}$, respectively) [36]. The impact of age on distance travelled per minute was also observed in soccer, where under 16 years players covered 115.2 $m{\cdot}min^{-1}$, an additional 10 % relative distance compared with that of under 13 years players (103.7 $m{\cdot}min^{-1}$) [16].

*3.4.1.3 Work Rate Patterns by Speed Zones* Work rate patterns were further categorized into six speed zones, ranging from 0 to 36 $km{\cdot}h^{-1}$, and each of these zones was linked with a description of the activity (e.g. walking through to sprinting). There were large variations in the range of speeds for each zone, both within and across sports. The greatest variations were observed between sports, for example, the zone 4 speeds reported were hockey [44–46] and soccer [16, 25–30] (7–18 $km{\cdot}h^{-1}$), cricket [41–43] (13–14 $km{\cdot}h^{-1}$), rugby union [31–36] (12–21 $km{\cdot}h^{-1}$), rugby league [5, 8, 37–40] (14.1–20 $km{\cdot}h^{-1}$), and AFL [17–24] (14–20 $km{\cdot}h^{-1}$). Furthermore, zone 4 definitions ranged from jog, stride, run, high velocity, to high-intensity run, both within and between the sports. Cricket, where all manuscripts were from a singular authorship [41–43], was the only sport where speed zones and descriptors were consistently applied across studies. In AFL papers, zone 3 speeds varied from 7 to 16 $km{\cdot}h^{-1}$ (Table 2). The majority of papers (30 [85.7 %]) concentrated upon the high-intensity efforts and distances covered in zones 5 and 6. Analysis of the higher intensity zones was apparent in AFL [17, 18, 20, 21, 24], rugby league [5, 37, 38, 40], rugby union [32–36], soccer [16, 25–30], cricket [41–43], hockey [44–46], and lacrosse [48].

*3.4.1.4 Impact, Body Load, and Collision* Only five manuscripts (14.3 %) reported on impact variables (Table 3 and Electronic Supplementary Material, T2) in rugby league [8, 39] and rugby union [33, 34, 36]. Impact intensity was generally graded into six impact zones based upon the grading system provided by GPS manufacturers or in accordance with work by Cunniffe et al. [36]. Small variation in impact range was observed between football codes, with three manuscripts [8, 33, 36] reporting on six impact zones and one manuscript [39] only reporting on four. Cunniffe et al. [36] monitored impacts in only two rugby union players, where the forward experienced 3.8 times more frequent impacts during a single competition game than the back. By comparison, the back showed slightly greater loads than the forward (52 %) in the first half, whereas the forward recorded a significantly higher body load in the second half of competition games than the back (66 %). Similarly in rugby league [8], the forwards sustained 63 more impacts (7.3 %) than the backs.

*3.4.1.5 Acceleration and Deceleration* Acceleration is another measure of high-intensity exertions in team sport. Only five studies quantified acceleration across three team sports (AFL [17, 21], rugby union [33, 35], and hockey [44]) in the contexts of training drills [21, 44] and matches [17, 33, 35]. Manuscripts investigated the physical demands of accelerations of rugby union playing positions [33] and compared the physical efforts in regular competition matches against the physical efforts of finals [17] and international matches [35]. The latter was the only paper to quantify deceleration demands [35]. The limited availability of acceleration and deceleration data can mostly be attributed to the inability of GPS to accurately measure these variables, until the introduction of 10-Hz GPS units.

## 3.5 Sport-Specific Summary of Global Positioning System (GPS) Studies in Team Sports

### *3.5.1 Australian Football League (AFL)*

The eight AFL manuscripts included 348 male participants. The studies included elite ($n = 292$; aged 18.7–28.9 years), sub-elite ($n = 26$; aged 19.1–25.9 years), and elite junior ($n = 30$; aged 15.9–17.2 years) athletes. All AFL studies examined the work rate patterns of high-intensity running or sprinting in addition to distance covered at various speeds (see Electronic Supplementary Material, T3). Two manuscripts reported distance measures [22, 23]. Piggot and colleagues [23] examined training load and injury levels throughout 15 weeks of pre-season training. Weekly

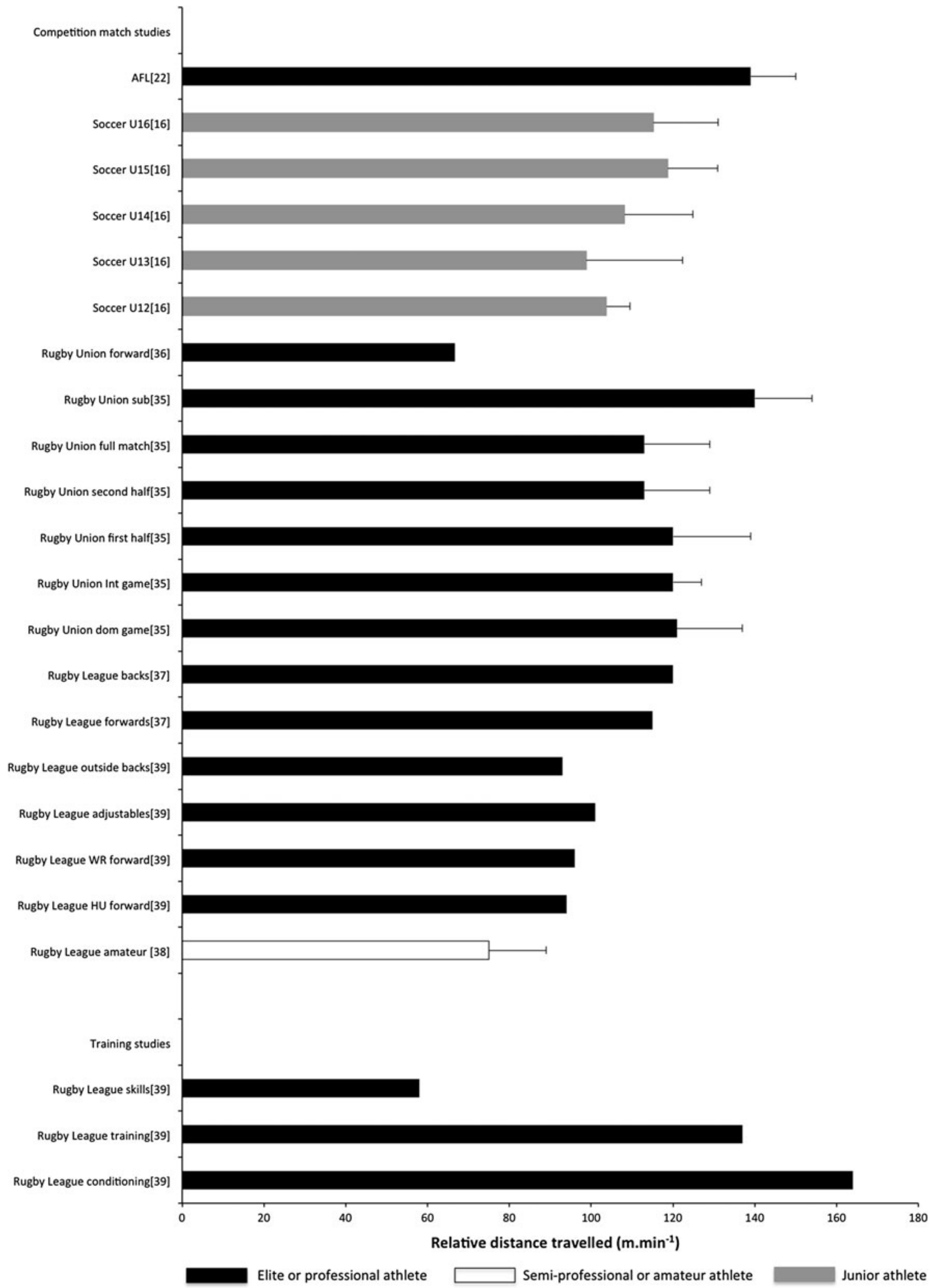


**Fig. 3** Relative distance (distance travelled per minute) in competitive matches or training [16, 22, 34–39]. Values expressed as mean (SD). *AFL* Australian Football League, *Dom* dominant, *HU* hit up, *Int* international, *Sub* substitute, *Ux* under x years *WR* wide running

**Table 2** Zone classification of work rate patterns in team sports

| References | Zone 1 | | Zone 2 | | Zone 3 | | Zone 4 | | Zone 5 | | Zone 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed (km·h$^{-1}$)[a] | Description | Speed (km·h$^{-1}$)[a] | Description | Speed (km·h$^{-1}$)[a] | Description | Speed (km·h$^{-1}$)[a] | Description | Speed (km·h$^{-1}$)[a] | Description | Speed (km·h$^{-1}$)[a] | Sprinting |
| Australian Football League (AFL) | | | | | | | | | | | | |
| Farrow et al. [21] | | | | | 7.2–14.4 | Moderate velocity | >14.4 | High velocity | | | >20.0 | Sprint |
| Brewer et al. [19] | | | | | | | >15.0 | High-intensity run | 20.0–23.0 | Higher-speed running | >23.0 | Sprint |
| Aughey and Falloon [18] | | | | | | | 15.2–18.0 | Jog | >18.0 | | >25.0 | |
| Coutts et al. [20] | 0–0.7 | Standing | 0.7–7.0 | Walk | 7.0–14.4 | Jog | 14.4–20.0 | Run | 18.0–24.9 | Run | 24.9–36.0 | Sprint |
| Wisbey et al. [24] | 0–0.8 | | 8.0–12.0 | | 12.0–16.0 | | 16.0–18.0 | | 18.0–21.6 | | >18.0 | Sprint/ maximum intensity |
| Aughey [17] | | | 7.2–10.8 | | | | 14.4–18.0 | | | | >18.0 | Sprinting |
| Rugby Union | | | | | | | | | | | | |
| Hartwig et al. [31] | 0–1.0 | Stationary | 1.0–7.0 | Walk | 7.0–12.0 | Jog | 12.0–21.0 | Stride | 81.0–95.0 % $V_{max}$ | Sprinting | >21.0 | Sprint |
| Cunniffe et al. [36] | 0–6.0 | Standing, walking | 6.0–12.0 | Jogging | 12.0–14.0 | Cruising | 14.0–18.0 | Striding | | | | |
| Hartwig et al. [32] | 0–1.0 | Stationary | 1.0–7.0 | Walking | 7.0–12.0 | Jogging | 12.0–21.0 | Striding | 18.0–20.0 | High-intensity running | >21.0 | Sprint |
| Venter et al. [34] | 0–1.0 | Standing | <20 % $V_{max}$ | Walking | 20–50 % $V_{max}$ | Jogging | 51–80 % $V_{max}$ | Striding | | | 96–100 % $V_{max}$ | Maximum sprint |
| Higham [35] | | | 0–7.2 | | 7.2–12.6 | | 12.6–18 | | 18.0–21.6 | | >21.6 | |
| Suárez-Arrones et al. [33] | 0.1–5.9 | Standing, walking | 6.0–11.9 | Jogging | 12.0–13.9 | Cruising | 14.0–17.9 | Striding | 18.0–19.9 | High-intensity running | >20 | Sprinting |
| Rugby League | | | | | | | | | | | | |
| McLellan et al. [5, 40] | 0–6.0 | Standing/ walking | 6.1–12 | Jogging | 12.1–14.0 | Cruising | 14.1–18.0 | Striding | 18.1–20.0 | High-intensity running | >20.1 | Sprint |
| Austin and Kelly [37] | 0–12 | Standing, walking, or jogging | 12–14 | Cruising | 14–18 | Striding | 18–20 | High-intensity running | 20–24 | Sprinting | >24 | High-intensity sprinting |
| Duffield et al. [38] | | | | | <14.4 | Low-speed activity | >14.5 | High-speed running | | | >20 | Very-high speed running |
| Gabbett et al. [39] | 0–3.6 | Low speed | >3.6 | High speed | | | | | | | | |
| Soccer | | | | | | | | | | | | |
| Barbero Alvarez et al. [26] | 0.0–0.4 | Standing/stop | 0.5–3.0 | Walk | 3.1–8.0 | Low-intensity running or trotting | 8.1–13.0 | Medium intensity running | 13.1–18.0 | High-intensity running | >18.0 | Sprint |
| Hill-Haas [29] | 0–6.9 | | 7.0–9.9 | | 10.0–12.9 | | 13.0–15.9 | | 16.0–17.9 | | >19.1 | Sprinting |

**Table 2** continued

| References | Zone 1 | | Zone 2 | | Zone 3 | | Zone 4 | | Zone 5 | | Zone 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed ($km \cdot h^{-1}$)[a] | Description | Speed ($km \cdot h^{-1}$)[a] | Description | Speed ($km \cdot h^{-1}$)[a] | Description | Speed ($km \cdot h^{-1}$)[a] | Description | Speed ($km \cdot h^{-1}$)[a] | Description | Speed ($km \cdot h^{-1}$)[a] | Sprinting |
| Hill-Haas et al. [30] | 0.0–0.4 | Standing/stop | | | | | 7.9–12.9 | Jogging | 13.0–17.9 | Cruising | | Sprinting |
| Castagna et al. [25] | 0–0.4 | Standing | 0.4–3.0 | Walking | 3.0–8.0 | Jogging | 8.0–13.0 | Medium-intensity running | 13.0–18.0 | High-intensity running | >18.0 | Sprinting |
| Casamichana Castellano [28] | 0–3.9 | Stationary–walking | | | 4.0–6.9 | Jogging | 7.0–12.9 | Quick running | 13.0–17.9 | High-intensity running | >18.0 | Sprinting |
| Bucheit et al. [27] | | | | | <13 | Low-intensity running | 13.1–16.0 | High-intensity running | 16.1–19.0 | Very high-intensity running | >20.0 | Very high intensity |
| Harley et al. [16] | | Standing | | Walking | | Jogging | | Running | | High-speed running | | |
| Cricket | | | | | | | | | | | | |
| Petersen et al. [41–43] | | | | Standing/walking | 7.2–12.6 | Jogging | 12.6–14.4 | Running | 14.4–18.0 | Striding | | |
| Hockey | | | | | | | | | | | | |
| Gabbett [44] | 0–3.6 | Low intensity | | | 3.6–10.8 | Moderate intensity | 10.8–18 | Moderate intensity | 18–25.2 | High intensity | | |
| Macutkiewicz and Sunderland [46] | 0–0.6 | Standing | | Walking | 6.1–11.0 | Jogging | 11.1–15.0 | Running | 15.1–19.0 | Fast running | | |
| Jennings et al. [45] | 0.36–15 | Lower speed activity | | | | | | | >15 | Hig-speed running | | |
| Lacrosse | | | | | | | | | | | | |
| Duffield et al. [48] | | | | | <7.0 | Low-intensity activity | 7.0–14.4 | Moderate intensity activity | >14.5 | High-intensity run | | |

$V_{max}$ maximum velocity

[a] Except where otherwise stated

**Table 3** Game impacts and body loads in team sports [8, 33, 34, 36][a]

| References | Sample, age (years) [mean (SD)] | Variable | Zone 1, light (5–6 G) | | Zone 2, light–mod (6–6.5 G) | | Zone 3, mod–heavy (6.5–7 G) | | Zone 4, heavy (7–8 G) | | Zone 5, very heavy (8–10 G) | | Zone 6, severe (>10 G) | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | B | F | B | F | B | F | B | F | B | F | B | F | B | F |
| Rugby Union | | | | | | | | | | | | | | | | |
| Cunniffe et al. [36] | $n = 2$, 5 (3.6) | Impacts [$n$, mean] | 349 | 563 | 328 | 398 | 55 | 143 | 38 | 101 | 24 | 56 | 4 | 13 | 798 | 1,274 |
| | | Body load (G) [$n$, mean] | | | | | | | | | | | | | 31,402 | 119,103 |
| | | Body load/min (G) [$n$, mean] | | | | | | | | | | | | | 376 | 1,426 |
| Suarez-Arrones et al. [33] | $n = 9$, 25.9 (4) | Impacts [$n$, mean (SD)] | 382 (129) | 501.6 (106) | 326 (173) | 341.3 (219) | 54.3 (28.9) | 161.6 (107) | 29.8 (9) | 143.1 (122) | 35.2 (26) | 66.6 (48) | 6.3 (4) | 10.4 (5) | 883 | 1,225 |
| Venter [34] | $n = 17$, 18.5 (0.5) | Impacts [$n$, mean (SD)] | | | | | | | | | | | 8 (4.58) | 12.16 (3.18) | 683.4 (295.04) | 474.33 (295.04) |
| Rugby League[b] | | | | | | | | | | | | | | | | |
| McLellan et al. [8] | $n = 17$, 19.0 (1.3) | Impacts [$n$, mean (SD)] | 214 (126) | 215 (80) | 154 (105) | 146 (68) | 334 (195) | 392 (151) | 50 (31) | 47 (24) | 26 (14) | 29 (14) | 20 (5) | 21 (8) | 795 (145) | 858 (125) |
| | | Impacts [$n$/min, mean (SD)][c] | | | | | | | | | | | | | 10 (2) | 11 (2) |

[a] All studies reported on elite subjects in match situations

[b] See also Electronic Supplementary Material T2

[c] Impacts [n/min, mean (SD)] for zones 4–6 were 1.2 (0.5) for B and 1.2 (0.6) for F

*B* outside backs (centres and wingers), *F* forwards, *mod* moderate, *SD* standard deviation distances averaged 11.3 km, with weekly recorded peaks between 15.4 and 15.8 km, and a week 5 nadir of 6.0 km. Mooney et al. [22], investigated the relationship between physical capacities and match performance, reporting the total relative distance of 139.0 ± 11.1 m·min$^{-1}$, whereas the relative distance at high intensity was 40.6 ± 9.6 m·min$^{-1}$.

The studies in AFL demonstrate the wider use of GPS utilization for monitoring the physical demands of playing positions during competition game quarters and the finals as well as in training situations. Six manuscripts reported competition [17–20, 22, 24] and two [21, 23] appraised training data. Activity profiles from training showed that open drills proved more physically demanding than closed [21], with ~20 % more moderate-velocity efforts in open drills.

#### 3.5.2 Rugby League and Rugby Union

Rugby league ($n = 6$) [5, 8, 37–40] and rugby union ($n = 6$) [31–36] manuscripts were grouped together due to the similar nature of the codes (see Electronic Supplementary Material, T4). These manuscripts included 470 junior to elite male athletes; rugby league (elite: $n = 276$, aged 16.9–31.5 years; amateur: $n = 11$, aged 18–22.6 years) and rugby union (junior: $n = 135$, aged 14–18 years; semi-professional: $n = 26$, aged 18–29.9 years; elite: $n = 21$, aged 18.5–28.6 years). Two manuscripts did not report on movement demand variables. Hartwig and co-authors [31] compared distance in match performance of junior rugby union players (schoolboys, talent, and representative squads) (Fig. 2). McLellan et al. [8] explored the intensity, number, and distribution of impacts associated with collisions in rugby league competition matches. Interestingly, recent research within these two codes has progressively further investigated the demands of impacts and collisions on players using GPS (Table 3).

The work-to-rest ratio by positional play evaluated in one study [5] indicated that rugby league forwards completed slightly more work than backs (1:7 and 1:6, respectively). Conversely, a study in rugby union [36] indicated that backs produced marginally more work than forwards (1:5.7 and 1:5.8, respectively). Similar to AFL, all six papers from these football codes reported on movement demand variables. However, by comparison, rugby union papers focused largely on distance travelled over the game as opposed to sprint distance and time within each speed zone. The football codes demonstrate an increased utilization for monitoring both training and game situations, demonstrating similarities with AFL. Nine manuscripts reported exclusively on competition matches [5, 8, 33–38, 40], one exclusively on training [31] and two on combined training and game-based data [32, 39] (see Electronic Supplementary Material, T4).

#### 3.5.3 Soccer

The seven studies in soccer included 286 participants from six male ($n = 274$) and one female ($n = 12$) teams. The studies reported on junior ($n = 28$; aged 11.2–16.2 years), elite junior ($n = 232$; aged 13.0–18.0 years), elite under 19 ($n = 16$; aged 15.7–16.9 years), and semi professional ($n = 10$; aged 22.0–23.0 years) athletes. In regard to work rate patterns, the soccer studies were similar to those in AFL, with a focus upon sprint time and sprint distance measures (see Electronic Supplementary Material, T5). As with other football codes, the soccer manuscripts reported on both training and game data, with five manuscripts reporting exclusively on game [16, 25–28] and two exclusively on training variables [29, 30].

#### 3.5.4 Cricket

The three cricket manuscripts reported on 96 male, elite ($n = 42$; aged 19.3–24.9 years), State ($n = 42$; aged 23.8–30.4 years), and international ($n = 12$; aged 26.2–33.4 years) participants. The studies examined the work rate patterns of speed, distance, sprint distance, and the number of high-intensity efforts at the higher speeds (see Electronic Supplementary Material, T6). In contrast to the football codes, the cricket manuscripts only report on competition-based GPS variables [41–43]. The observed consistency of speed zone definitions and descriptors in these studies is the result of singular authorship.

#### 3.5.5 Hockey, Lacrosse, and Netball

Five manuscripts reported on 71 participants and covered the remaining team sports of hockey ($n = 55$ elite; aged 18.0–29.7 years) [44–46], lacrosse ($n = 7$; National division, aged 18.5–21.3 years) [48], and netball ($n = 9$; elite State level, aged 18–27.2 years) [47]. Because of the limited number of manuscripts in these sports, they are summarized together in the Electronic Supplementary Material, T7 . Three [44, 46, 47] of the four papers report exclusively on female athletes ($n = 48$ participants; 67.6 %) in netball and hockey.

GPS capability was used in elite hockey to assess the influence of international competitions [45] and playing position [46] and compared game-based training versus competition [44] on player activity profiles. Two studies utilized GPS to evaluate the efficacy of distinct interventions on exercise performance. They examined part-body pre-cooling procedures on physiological responses to lacrosse training in the heat [48] and the effect of compression garments on physiological demand and sprint performance in a simulated game-specific circuit for netball [47] (see Electronic Supplementary Material, T7).

## 4 Discussion

To our knowledge, this is the first systematic review evaluating the application of GPS technology to classify work rate patterns and physical impact demands across team sports. The review clearly demonstrates that existing GPS classification definitions vary widely both within and between sports. Lack of uniformity in movement demand descriptors and classification of speed zones limits comparisons within the same team sport. Consensus on a consistent GPS movement, physical demand, and external work criteria for individual team sports may help facilitate comparisons within individual sporting disciplines and levels of participation. The literature for GPS use in team sports remains limited and is strongly biased towards adult male athletes participating in football codes (AFL, rugby league, rugby union, and soccer). The majority of the data have been collected in competition game situations, with limited training data available, perhaps attributable to the fact that many professional teams are reluctant for such information to be placed in the public domain.

### 4.1 Zone Classifications

Clarity and consistency of speed zones and movement pattern definitions within a team sport facilitates precise comparison and analysis of performance between players, teams, levels of competition, and seasons. Furthermore, with speed and impacts divided into the six activity bands, the upper zones (4–6) provide more insightful information about the physical stressors and demands experienced by players. It is important to note that GPS reliability is reduced with increased movement intensity >20 km·h$^{-1}$ [3]. It is likely this uncertainty is due to the rapid changes in velocity that are apparent in movements performed at higher speeds [11]. Although GPS reliability is reduced with increased movement intensity, validity is improved through increased distance; for example, the standard of error is reduced by 67 % when comparing sprinting over 40- and 10-m distances [11]. However, a 5-Hz non-differential GPS has been reported by Portas et al. [14] to be a reliable method (CV 55 %) of monitoring overall distance during multiple sprint team sports-specific movements. However, due to the variability of exercise activity, GPS devices, sample rates, and statistical methods applied, direct comparison of GPS validity within team sports is difficult [9].

Movement demand classifications across all sports are derived from the manufacturer or modified from rugby union [49]. Classifications from rugby union potentially fail to adequately reflect the demands of other football codes (e.g., zone 1 speed criteria ranged from 0 to 5.9 km·h$^{-1}$ in rugby union and from 0 to 12 km·h$^{-1}$ in rugby league, whilst zone 6 ranged from >18 to 36 km·h$^{-1}$ in AFL). Activity descriptors also varied, with zone 2 descriptions ranging from jogging and walking in rugby union to jogging and cruising in rugby league.

Abt and Lovell [50] suggested that, as players differ in the speed at which they begin to run at high intensity, there is a need for individualized high-intensity speed thresholds and an absolute maximum intensity threshold of 15 km·h$^{-1}$. Waldron and colleagues [6] highlight that players are influenced not only by the field position they possess, but also by the possibility that positional playing groups display different speed characteristics (e.g., in rugby league, forwards are slower than backs and adjustables) [5, 37, 39]. The difference in field position and speed characteristics prevents the development of an arbitrary sprint zone classification, whilst the suggestion of individualized speed zones poses both a logical and a logistical problem in speed zone determination [6].

### 4.2 Distance and Relative Distance

Reporting of the GPS parameter total distance covered per game or training session provides for little comparison between team sports. Comparing distance travelled in sports may only be meaningful when reference to the time spent in activity or game play is made; for example, elite AFL players covered 12,939 m per game in comparison with 4,302 m by elite rugby union backs [36], suggesting AFL players [20] covered 67 % greater distance. However, when the time spent in activity was accounted for, AFL players recording a relative distance of 139 m·min$^{-1}$ [22] in fact covered 48 % more ground than rugby union backs, with a relative distance of 71.9 m·min$^{-1}$ [36]. Thus, the time on field is most certainly a key metric to include, enabling qualification of distance covered not only between but also within sports.

The significance of using the relative distancemetric was identified in a recent review [9]. Although cricket fast bowlers appeared to run greater distances than AFL players, the calculated relative distances revealed a higher work intensity in AFL (63 and 109 m·min$^{-1}$ for cricket and AFL, respectively).The use of estimated game time (i.e. via use of the game and rule durations) presents a limitation to this approach. Only a minority of included manuscripts have reported the actual player match time (time on field including stoppages). Data should be reported relative to precise field time and not include time on the bench (e.g. from injury or substitution) in order to minimize the margin of error when reporting distance per minute.

Stoppages account for 33 % of the overall match time in senior elite rugby league matches, with an average of 48 s per stoppage [51]. The majority of manuscripts to date have failed to account for player time on the field in competition or training sessions. Reporting of distance relative to match time is strongly recommended. Increased ease and ability of GPS devices in allowing users to take account of various stoppages in play (i.e. injury or interchange) could further facilitate this reporting.

### 4.3 Positional Play

Some studies that inform this review have compared the physical demands by player position. The work-to-rest ratio by positional play was investigated in one rugby league [5] and one rugby union [36] manuscript. Rugby league forward playing positions completed more work than back playing positions (1:7 and 1:6, respectively), whilst rugby union showed backs to produce slightly more work than forwards (1:5.7 and 1:5.8, respectively). The distance in maximal speed by positional play has also been explored in rugby league [5], where backs attained a 20 % higher maximal sprint speed than forwards (30.6 and 24.5 km·h$^{-1}$, respectively). It should be noted that the findings might be attributed to the field position and individual sprint characteristics of positional groups [6]. Sprint performance appears to be influenced through field position, whereby outside backs are presented with large areas of open space in which to develop locomotion, in comparison with forwards, who are more often in closer proximity (10 m) [6] to the opposition and involved in increased contacts [52], which diminishes their opportunity to generate higher speeds.

The GPS metric of distance has also been explored in regards to positional play in hockey [44]. The distance covered at high-intensity running showed midfielders covered more ground per match (77 m) than strikers (46 m) and defenders (52 m), due to greater game involvement moving the ball up and down the field as the link between defensive and attacking players. Positional play data enable the provision of position-specific training programs and targets such as distance and maximal speeds. Further positional data allows for player performance to be evaluated against positional-specific established benchmarks.

### 4.4 Specific Application and Usefulness of GPS Metrics

Although GPS metrics provide quantitative data on a range of physical demand variables in team sports, the relative load on players may be difficult to compare across sports due to differences in the interchange of players, game durations, and conditions. Specific metrics may have greater application in some team sports than others. The accuracy of GPS for evaluating impact and collision data has not been fully examined. GPS devices do not have the capacity to measure the forces upon the body without integrated accelerometer sensing devices [53]. When combined with a triaxial accelerometer, information relating to the physical loads and impacts can be measured through the acceleration and deceleration forces experienced by the player. Although the work rate patterns such as speed and distance are automatically detected and reported by GPS technology, the analysis of loads experienced through tackles or collisions is relatively complex. One GPS unit (Catapult Sports™) equipped with tackle detection technology, allows for the detection of tackles; however, it is limited by the fact that the technology does not distinguish between the types of tackles, such as whether it is a multiple player tackle, or the position of contact to the player. Complete analysis of tackle and contact events still requires manual pairing of GPS loads and video footage. Measurement of attack- and defence-specific impact events would allow for the evaluation and quantification of the loads sustained through individual tackles, the cumulative load experienced through a game, training session, or season and the forces experienced during injury.

### 4.5 Global and Sport-Specific Use of GPS

The available literature on GPS use in team sports demonstrates a strong bias to Australian studies (20 of 27 manuscripts, 74.1 %), indicating that its use, certainly for research, has proliferated. This could be due to a number of the publications emanating from the same research groups. It may also be that the application of GPS to team sports favors popular sports in Australia, such as AFL, rugby league, rugby union, and cricket, or that local or researcher interest in the technology has encouraged greater use in these disciplines. Limited research within soccer may possibly be attributed to the soccer federation not permitting the use of GPS within professional competition matches. However, it is clear that GPS technology has a more logical application to certain team sports than others. Sports in which there is movement across a substantial distance of varied speed and player-to-player contact or collisions likely lends itself to monitoring by GPS compared with other team sports such as water polo or volleyball. Use of GPS in stadiums with high walls and curved roofs may provide unreliable data because fewer satellites are available to triangulate signals from devices. GPS is also less reliable for indoor sports and for those where short distances and changes in direction are predominant [54]. Although this technology is less able to attain satellite connections when used indoors and therefore unable to provide the parameters of distance or speed, newly developed GPS units equipped with new indoor functions are currently being assessed within indoor sports such as basketball to examine the player load and heart rate zones throughout training and game situations.

### 4.6 Use of GPS Across Different Age Groups and Levels of Athletic Calibre

The varying age of athletes from junior/prepubescent to post pubescent adults may require the addition of age-appropriate speed zones so as to more accurately reflect the work rate patterns of both pre and post pubescent athletes. Speed zone classifications defined and designed around post pubescent adult athletes may not be suitable for, or adequately reflect the competition or training demands of, prepubescent athletes due to the inherent physiologic, biomechanical, and metabolic differences during exercise. Compared with adults, children and young adolescents exhibit a lower energy reserve between submaximal and maximal aerobic exercise; that is, an increased cost of locomotion—for a given running speed, they will work at a higher percent of their maximal aerobic capacity [55]. Metabolic differences between children/prepubescent adolescents and adults during exercise are due to three physiological factors. Children/prepubescent adolescents have lower walking/running economy due to shorter legs requiring a higher stride frequency and smaller stride length [56]. They also display less efficient running mechanics (higher peak ground reaction forces, greater braking forces, greater vertical movements) [55, 57] and less efficient co-contraction of antagonist muscles where there is a less than optimal neuromuscular control to synchronize action between muscle groups [58]. Furthermore, they have a mass–speed imbalance, where the lighter child cannot effectively match their load to an imposed speed of movement [59, 60]. Energy costs associated with exercise decline steadily throughout childhood and into late adolescence [61].

The varying calibre of athletes from non-elite to elite may also require the addition of reduced speed zone brackets, reflective of the athlete's differing ability and skill level. Although these data were informed by a relatively small body of literature [32] in rugby union, it was seen that semi-professional [34] forward players covered 17.3 m during sprinting, whilst junior forward players covered 28.8 % less distance with 12.3 m of sprinting.

### 4.7 Use of GPS Within Training and Competition

The football codes demonstrate an increase in GPS utilization for monitoring both training and game situations. AFL training data indicate activity profile differences within the demands of open and closed drills, where open drills prove more physically demanding. However, these were just drills from one club and one manuscript [21], such that more research is needed to adequately describe the demands of different training drills using GPS. This detailed understanding of training drills and match demands enables for the provision of individually tailored training programs that more accurately reflect competition demands and ensures athletes reach optimal training targets. It may be of value to report the time of year in which training has occurred, as sports are periodized, with athletes training less and at lower intensities during the season or when recovering from injury, than during the pre season. The major benefit of GPS technology within competition settings is the lightweight, unintrusive nature of the monitoring units with the ability to provide real-time movement demand information (e.g. distance and speed) to coaches and training staff.

In competition settings, the provision of realistic impact and load data has eluded sports scientists for some time. Currently, the only mechanism available for in-depth analysis of tackle and collision events is to manually label impact data through cross referencing video footage with the GPS and accelerometer measurements. This is a time-consuming process, which needs to take place for each individual player, making it impossible to provide coaches with real-time tackle or impact information [49].

### 4.8 Use of GPS with Injuries

The use of GPS metrics and training practices should represent a balance between developing the individual for the specific and positional demands of team sports, and the maximum training load that can be sustained by the individual before a marked increase in the likelihood of injury [62]. Piggott et al. [23] observed that with professional athletes, 42 % of illnesses and 40 % of injuries could be explained by a preceding spike in training load [23]. The optimal amount of training should not exceed an individual's exercise tolerance and capability for recovery. A recently developed injury-prediction model showed that rugby league players exceeding a training threshold were at significantly higher risk of soft tissue injuries [63]. Accordingly, GPS technology can be used to inform and regulate training loads for individual athletes at crucial parts during the competitive season. Further research into this area is warranted.

### 4.9 Use of GPS and Fatigue

Research is emerging on the monitoring of fatigue through GPS. Higham and colleagues [35] examined the movement patterns between full match and substitute players, showing that substitute players exhibited a substantially greater work rate than players who played the entire match. Substitutes were seen to cover 24 % greater distance per minute, and an additional 110 and 123 % greater distance at 5–6 and >6 $m \cdot s^{-1}$, respectively. The authors suggest that players pace their activity throughout a match so as to mitigate fatigue later in the match and that the replacement of one or more players at a key stage of a match could potentially influence a match result.

The ability of GPS to monitor activity demands and fatigue development during a soccer match has recently been examined [64]. The game–fatigue index (the difference in high-intensity running between the first and last 15 minutes of the game) was 49.9 + 25.7 and 44.7 + 27.2 %, for different GPS devices, and not significantly different from either a video-based time–motion analysis system or a semi-automatic multiple-camera system. Whilst this study proposes that GPS is a valid measure of fatigue development, it has also recently been reported [65] that pacing strategies are difficult to discern from time–motion data. The use of the initial 15-min phase of the match as a criterion for match-related fatigue is highly questionable, thereby providing a stimulus for more robust analytic approaches to research into the measurement of fatigue in the field.

### 4.10 Comparison of GPS with Other Technologies Assessing Time–Motion Analysis

This review has not reported on the evaluation or comparison of GPS with other technologies assessing movement patterns as it is beyond the scope of this review. No 'gold standard' method for determining movement patterns and workload in sport has been ascertained [64]. Two studies [64, 66] have compared GPS with other technologies, such as video capture and semi-automated image recognition systems, in assessing work rate patterns. These studies observed that the absolute agreement between measurements produced from each of the systems is not well established. Randers et al. [64] compared four match-analysis methods (two different GPS systems, video capture, and semi-automated multiple-camera image-recognition systems) during the same football match. The findings highlighted that although similar performance decrements were detected, between-system differences in absolute running distances covered were present. The authors cautioned that differences in performance measurements should be taken into account when comparing results collected by different methods of time–motion analysis systems.

### 4.11 Limitations

A limitation of this review revolves around the comparison of speed zones and classifications due to the large variability of descriptors used. The validity and reliability of different GPS devices used and their many variables may be a major contributor. There is a strong sex bias in the studies to recruitment of male athletes, so the results may not be generalizable to females. Speed zone classifications defined and designed around post pubescent adult athletes may not be suitable for, or adequately reflect the competition or training demands of, prepubescent or adolescent athletes due to the inherent physiologic differences. Another limitation is that some manuscripts informing this review report on small sample sizes (fewer than ten) of athletes from within a team or training institution; whereby results may not be representative of the entire population. Additionally, there is a possible bias towards Australian research (26 of 35 studies). The start of 2012 saw a surge in research in rugby league and rugby union. Although these latest papers [8, 33, 34, 39] show an increased trend for analysing the contact events through quantification of impact loads, the use of the resultant G force as a precise measure of player-to-player collisions is yet to be explored and determined.

### 4.12 Future Directions

The introduction of and improvements in GPS technology have provided for a shift from descriptive studies of movement patterns to comparisons between levels of competition, training, and match situation work rate patterns of distance, speed, and speed zones. The use of GPS parameters to detect injury, fatigue, and overtraining could determine the timing of return to play, inform provision of supplementary or complementary conditioning, or help to better characterize training drills.

The physiological demands and characteristics of junior and subelite athletes should be investigated so as to define modified speed zones that more accurately reflect the age and skill level of these athletes. Further utilization of GPS technology in junior athletes may facilitate the development of younger players. The GPS variables can also be used to formulate rule modifications, age limits, or training/competition parameters of junior to elite athletes. In addition, GPS measurements may inform coaches and trainers of methods for the introduction and preparation of younger players to the impacts experienced at elite level. By monitoring the physiological stress on each athlete, GPS technologies allow sports scientists, coaches, and trainers to optimize and individualize training and potentially diminish the incidence of injury.

Finally, the use of live analysis will provide instantaneous feedback to coaches of player work rate patterns in order to monitor fatigue and allow for adjustments to player performance or effect of player rotations. Future research on impact classification zones, player impacts, and body loads within game and training situations is warranted. Quantification of these parameters to coaches in real-time could provide data for instantaneous modification to play and tactical substitutions based upon loads, impacts, and the physiological limits of players, as well as improve injury surveillance of athletes.

## 5 Conclusion

GPS utilization within the sporting context has facilitated collection of metrics that describe the physical demands and impacts on players, both at training and in competition settings. Use of the technology for this purpose is still relatively new and evolving. This review provides insight into the depth and span of its use within team sports and some of the existing limitations with the metrics reported, and with high-speed running involving rapid directional changes.

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