Tracking Systems in Team Sports: Back to Basics

Lorena Torres-Ronda [1], **Jo Clubb** [2 3], **Emma Beanland** [4]

[1]Spanish Basketball Federation, Spain
[2]Global Performance Insights, UK; University of Technology Sydney, Australia
[3]University of Technology Sydney, Australia
[4]Sports Performance, Buffalo Bills, Buffalo, U.S.

Technology | Monitoring systems | External load | Data | Sport science

Headline

The desire to deepen the understanding of sports performance has led to the proliferation of technology. Within this, tracking technology enables the objective capture of work completed by athletes independent of their internal characteristics, which is labelled external load (1). Such data enables practical applications that include quantifying physical demands, objectifying training prescription, monitoring individual training load, and assisting with rehabilitation.

Aim

Several types of tracking systems have emerged since the 1970s, while include notational analysis (2), multi-camera systems (3), and microtechnology devices (4). Professionals tasked with managing these systems have a responsibility to understand data collection, processing, and analysis as it pertains to athlete preparation within their specific setting.

In order to select and utilise impactful technologies, understanding the methodologies, requirements, and differences between systems should be thorough. Knowledge of hardware (e.g., satellites/anchors, receivers/devices, network requirements) and software (e.g., system operation, firmware version, metric definition) will better prepare users to understand the subsequent advantages and disadvantages of the data. During the technology selection process, practitioners should consider the context, regulations, and culture of their specific sport and organisation. Thereafter, practitioners must be knowledgeable in data collection, processing, analysis, visualisation, and communication, in order to transform data into meaningful and actionable information for athlete management.

In this paper, we provide an overview of the emergence and development of different tracking systems. Considerations for a systematic approach to data processing and collection are also presented.

Types of Tracking Systems

In the following section, the methodologies of the most commonly utilised player tracking technologies within team sport settings are discussed. By means of comparison, Table 1 provides an overview of these characteristics. Here, we define tracking systems as those that quantify external load within the training environment. Therefore, monitoring systems that quantify internal load (e.g., heart rate), track segmental movements (e.g., force plates or motion capture) or capture training load response (e.g., subjective wellness) are not included.

Global Positioning Systems

Global Positioning Systems (GPS) provide measures of displacement, velocity, and acceleration by using a satellite network, which was initially used by the US Department of Defense, and have since been validated for use in sport (5). A GPS device constantly receives the exact time, based on the atomic clock, via radio signals transmitted by these satellites at the speed of light (6). The difference in time between the satellite and GPS receiver is used to calculate the signal travel time and therefore, distance from the satellite to each receiver (6). A minimum of four satellites is required (nine is preferred) to calculate the exact position via trigonometry, expressed as latitude and longitude (7).

Once the position is known, the displacement over a given epoch can be used to calculate instantaneous speed (velocity of a movement) (5). Velocity is calculated via the Doppler-shift method, which refers to a change in frequency of the satellite signals caused by the movement of the receiver (8). Doppler-shift is frequently preferred to positional differentiation (the derivative of distance caused by the change in device location) owing to greater accuracy and lower error (9). Using the Doppler-shift method, distance and acceleration can be derived from velocity (10).

There are three key factors that influence GPS quality: i) the line of sight from GPS receiver to satellite, ii) the signal strength and iii) the horizontal dilution of precision (HDoP) (11). The line of sight is affected by structural interferences (e.g., stadium obstructions) as GPS signal will not travel through metal or concrete (7). The signal strength is determined by both the number of satellites connected to the receiver and their orientation within the atmosphere, with a signal greater than 40 decibels ideal (12). Manufacturers have attempted to improve data quality through the integration of both the United States GPS and the Russian GLONASS (GLObal NAvigation Satellite System), which together doubles the number of available satellites. Finally, the HDoP refers to the geometrical arrangement of satellites, whereby one satellite is positioned directly overhead and the others are evenly spaced, with less than 1.0 representing ideal positioning (11).

GPS validity and reliability can be compromised by movements that require shorter durations, higher velocities and/or more complexity (5). Such movements may be the most critical to a sporting context, as well as being the most physically demanding. Therefore, practitioners are presented with a paradox in that the most vital movements may be the least accurately quantified. In an attempt to address this, hardware improvements, including higher sampling frequencies (13), updated GPS chipset and antenna providers, and more powerful microprocessors have enhanced the quality of GPS data (7). Additionally, manufacturers frequently release enhanced firmware that control hardware operation, but practitioners should be aware such changes may affect the data output (10).

Optical Tracking Systems

Optical tracking (OT) uses multiple cameras placed around the playing environment to collect computer video analysis that determines the 2-dimensional coordinates (2D; x, y) and trajectories of all moving objects (3). The camera setup, including position, orientation, zoom, and field of vision, are fixed upon installation to ensure an all-encompassing vision of the playing area, with at least two cameras covering every area (14). Sampling frequencies vary between systems with between 10 and 25 Hz reported (3, 15). Early OT was semi-automated as it required operators to code activities (3). However, more recent solutions utilise machine learning and computer vision techniques to calculate location data without the need of manual operators (16). By employing a camera system, OT does not require the athletes to wear any technology, which is especially pertinent in sports that prevent the use of these in competition.

Despite the appeal of a non-invasive solution, OT presents some limitations (Table 1) (17). Given the system permanence, teams may be limited to competition and/or home venue data. Users may not receive tracking data until 36 hours after competition, due to post-event processing, although some systems now offer real-time analysis (17). Despite extensive research on early OT accuracy (3, 14), more recent technology has been introduced into sporting competition despite a lack of peer-reviewed precision research (16).

Table 1. Comparison of Characteristics Across Different Tracking Systems.

	GPS	OT	LPS	IMU
METHODOLOGY	The travel time of radio signals transmitted by the satellites to GPS tags/devices.	Camera system around the playing environment tracks coordinates	Anchors placed around the environment triangulates radio signals with tags	Multiple microsensors detect movement on the body upon which they are placed
MEASUREMENT	Displacement, distance via known time between Satellite and GPS tag. Velocity via Doppler-shift. Acceleration derived from velocity	Trajectories of moving objects from which distance, speed, and acceleration are derived	Reception time of signal used to determine location from which distance, speed, and acceleration are derived	Accelerometer = acceleration Gyroscope = angular velocity Magnetometer = orientation
SAMPLING FREQUENCIES	1-15 Hz (Greater than 10 Hz recommended)	10-25 Hz		Raw accelerometry data at 500-1000 Hz, reported as 100 Hz
DIMENSIONS	2D (x,y)	2D (x,y)	2D (x,y) 3D (x,y,z)*	3D Triaxial (x,y,z)
PLAYING OBJECT TRACKING	In progress	Yes	Yes	#N/A
SETTING	Outdoor	Indoor, Outdoor	Indoor, Outdoor	Indoor, Outdoor
PORTABILITY	Yes	Lacking	Lacking	Yes
KEY LIMITATIONS	Accuracy in movements that require shorter durations, higher velocities and/or more complexity	High costs, demanding infrastructure requirements, lack of portability, post-event processing, lack of peer-reviewed validity and reliability studies	Susceptibility to potential electronic interference and/or signal instability, lack of portability	Alone will not provide detail of global movement tasks regarding overall distance/speed.

Local Positioning Systems

Local positioning systems (LPS) provide location information on an object or a person within a space covered by a local area network (15, 18). In sport settings, LPS triangulate signals between anchors placed in an elevated position and electronic tags worn by the athlete. The system provides information about athlete position at a given time by their 2D or, in some cases, 3-dimensional (3D) coordinates.

Radio Frequency Identification

Radio frequency identification (RFID) technology has been commercially available since the 1970s however, it was not until the early 1990s that it entered sport, initially for timing mass running events. RFID refers to a wireless system composed of antennae (or anchor nodes) that emit radio waves, and tags that return signals to communicate their identity

(17). The reception time between the antennae and tag is synchronised and used to determine location, with the data immediately processed by a central computer (17) . Types of RFID systems differ by radio frequency signal; low- (30-500 KHz), high- (3-30 MHz), ultra-high-, and microwave frequency (including ultra-wideband; see below).

The advantages of RFID include commensurate performance across indoor and outdoor venues (19) and advances in accuracy and processing speed over other tracking devices (20). However, as with other LPS, RFID is most reliable when the system is permanent therefore, it lacks portability and requires installation that can be costly (21). When a compatible portable system is available, it can involve a time-consuming setup and requires calibration for 3D data. Additionally, if a playing implement is used and not endowed with a tag, it is not possible to provide tactical information related to the object.

Ultra-wideband Local Positioning System

Ultra-wideband (UWB) is a type of RFID that transmits short pulses via radio signals, specifically, using a bandwidth greater than 500 MHz or greater than 25% of the centre carrier frequency (21). It provides greater precision than other RFID systems, owing to better ability of the signal to pass through obstacles and greater resistance to interference (21). UWB also provides lower power consumption, higher data rate transmission and may cost less than alternatives (22).

Inertial Measurement Units

Inertial measurement units (IMU) typically consist of an accelerometer, a 3D gyroscope (to determine angular velocity) and/or a magnetometer (to measure the orientation with the Earth). Most athlete IMU contain a triaxial piezoelectric linear accelerometer that measures 3D (anterior-posterior, medial-lateral, and vertical) acceleration of the body or body segment to which the sensor is placed, expressed as G-force (where 1 G = 9.81 m.s^{-2}) (23).

In order to provide timely data processing, accelerometers usually report sampling at 100 Hz (24), however often the raw data sampling is much higher (e.g., 500 Hz – 1000 Hz). The signal obtained from the sensor is usually filtered to reduce noise. Physical activity can be obtained by classifying the volume and intensity of the signal in a specific time interval (25). In addition, manufacturer-specific, vector-magnitude metrics derived from the triaxial accelerometer, such as PlayerLoad$^{\text{TM}}$ or BodyLoad$^{\text{TM}}$ (26), are often used to represent external load (23).

The combination of data from accelerometers, gyroscopes, and magnetometers, coupled with increased sampling rates and machine learning, is increasing the accuracy of fine movement detection (27). As such, the ability to capture locomotor activities such as sprinting and changes of direction (28), as well as sport-specific movements, including rugby collisions (29), ice hockey strides (30) and specific skill-based activities (31), have been enhanced. The detection of such demands, along with the ability to derive these measures while both indoors and outdoors, highlight a number of advantages of IMU over other technologies.

Data Processing

Often not enough attention is placed on the data processing techniques that calculate the myriad of metrics available via tracking technology. Filtering, threshold selection, and effort detection rules are important components for defining high-speed and high-intensity efforts, which are of great interest to practitioners given their association with neuromuscular demands, performance outcomes and fatigue (32, 33). However, these definitions are often not included within the literature and there exists a lack of uniformity across and within sports. Becoming familiar with these settings will enable practitioners to select settings relevant to the context of their environment.

A

Reference	HS Threshold (km/h)	VHS Threshold (km/h)
Buchheit et al. (35)	14.4	19.8
Dwyer & Gabbett, (38)	19.4	22.0
Linke et al. (15)	20.0	25.0
Lovell & Abt (41) (Ab)	14.4	19.8
Lovell & Abt (41) (Rel)	11.3	14.8
Varley et al. (36)	19.4	25.2

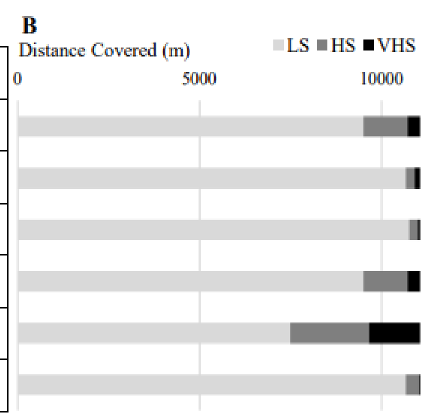

Fig. 1. Select high-speed running thresholds (A) from a group of studies with similar subjects (sport, sex) and (B) a visual comparison of distance within corresponding bands applied to a single hypothetical tracking file.
Ab = absolute thresholds; Rel = relative thresholds; LS = low speed band (light grey); HS = high-speed (dark grey); VHS = very high-speed (black)

Filtering

Raw, unfiltered data is subject to a degree of noise that adds error to a signal. Therefore, to accurately analyse velocity or acceleration data, filtering is required to ensure the signal resulting from human motion is detected (34). A variety of filters can be applied to velocity data however, manufacturers may not disclose information regarding the technique used. Acceleration derived from velocity is also smoothed at a time interval set within the software (e.g., 0.2-0.5 s), whereby the wider the time interval, the greater the smoothing of the data.

Most manufacturers recommend frequent updates to apply bug fixes, feature enhancements and filtering improvements and yet, slight adjustments to these settings can have a notable effect on data output (10, 35). While filtering is often discussed in relation to GPS, it is important to note that OT and LPS may also use filtering techniques that merit consideration.

Thresholds and Bands

Velocity and acceleration efforts, particularly those at greater magnitudes, are of interest to practitioners given the increased importance on match outcomes and energetic demands of such movements respectively (36, 37). Threshold selection refers to a series of lower and upper limits that define a band, which are commonly set across metrics (38). These bands allow for qualitative descriptors to be assigned, typically based on a form of intensity (e.g., very low, low, moderate, high, and very high) (39). However, there is a lack of consensus in defining these thresholds and consequently large discrepancies exist, even within the same sport (37) (Figure 1).

Traditionally, thresholds have been determined arbitrarily by using absolute measures however, growing interest exists in individualised thresholds (40). An overestimation of high-speed distance has been demonstrated with an absolute threshold compared to individualised thresholds, determined by a treadmill test to exhaustion (41). However, Lovell and Scott (2018) highlighted the additional challenge practitioners face in obtaining an appropriate and up-to-date maximum value for each individual to apply to relative thresholds (42).

While manufacturers may now enable both absolute and relative threshold settings, it is important practitioners assess the demands of their sport and population when selecting appropriate bands. Manufacturer defaults may not always be applicable for practitioners within their sporting context. While, equal bandwidth thresholds, such as 5km/h bands, have been advised (37), new data mining techniques provide a potential avenue for defining more appropriate band settings, although meaningful differences in outputs between different statistical approaches remain (7, 42).

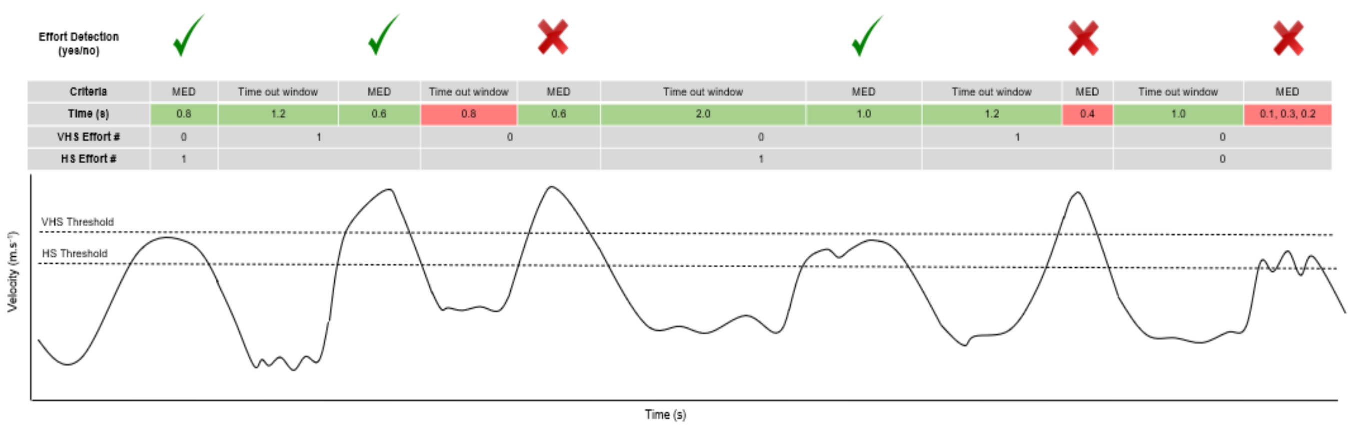

Fig. 2. Acceptance criteria demonstrated for velocity effort detection where, 1) minimum effort duration, or 'dwell time', is set at 0.5 seconds, and 2) time out window is set to greater than 1 second. Note, these time windows are for illustration only and may differ accord to manufacturer. Green shows the acceptance criteria is met; Red shows that it is not. HS = high-speed; VHS = very high-speed

Effort Detection

While distance-aggregates within bands require only a lower and upper threshold limit, effort detection requires multiple rules. These may include determining time periods for the minimum effort duration (MED) and a time out window between efforts (Figure 2). The MED, or 'dwell time', determines the minimum duration by which the athletes must exceed a threshold to count as an effort (10). A MED of 0.5 s has been suggested to detect high-speed running efforts (37). Historically, detection has required a one or two band drop below the current threshold post-MED to register an effort. A time out window can specify the minimum time required to elapse before an effort is counted as a separate effort to the previous one. These rules are an attempt to ensure potential erroneous spikes are not incorrectly captured as efforts and to avoid multiple effort detection for what is in reality a single effort, as velocity or acceleration may oscillate around a threshold. It is imperative practitioners seek out these settings to understand how their system is defining efforts, especially when integrating data from different systems.

Data Collection and the Need for Systematic Process

Having "unpacked the black box" (7) to understand data processing techniques employed, the onus is now on the practitioner to establish a consistent approach to their workflow. Their primary responsibility is to ensure their process enables accurate data collection, especially if decisions around player management are to be based upon such information. Furthermore, promoting clean and organised data will enable more time to be spent on analysis, interpretation and communication. A summary of these considerations is shown in Table 2.

Pre-session Considerations

Despite that manufacturers often deliver systems in an immediately operational state, it is imperative to review the settings before use. It is recommended to review features such as the synchronisation time (especially when receiving new tags), system modes (e.g., indoor/outdoor), and the data processing settings discussed in section 3. Practitioners may wish to document their preferred settings and data collection steps, in order to ensure a replicable workflow, especially if other colleagues may also be tasked with running the system.

Considerations relating to tag setup in preparation for tracking a session are provided in Table 2. Since questionable between-device reliability has previously been demonstrated, it is recommended to assign the same tag to the same athlete where possible (11, 35). Practitioners should build time into their workflow prior to the session to allow them to validate tag switch on, athlete mapping, and anchor/satellite visibility.

The specific location of the tag on the athlete can vary depending on the manufacturer and the algorithms used for calculating metrics. For garment setup, it is worth noting that while custom-built pockets in jerseys have become commonplace, they may increase incidental unit movement, as demonstrated by increases in accelerometer loads across standardised running, agility, and tackling drills, compared to data collection via manufacturer-provided vests (43). This provides an example of an accuracy-practicality trade-off, whereby practitioners should give pause to the most practical solution for their setting without too much loss in precision.

Table 2. Checklist for Promoting Clean Tracking Data.

Session Time Point	Considerations for Practitioners
System Setup	Have I reviewed the manufacturer instructions?
	Have I reviewed, where available, the filtering and smoothing utilised by this manufacturer?
	Have I determined and set suitable thresholds/bands and effort detection settings for my population?
	Have I tested the system operation and data collection process prior to use with athletes?
	Where necessary, have I synchronised the time on all tags?
Pre-session	Is every tag charged, mapped and labelled for the assigned athlete? Where possible, have I used the same tag for the same athlete?
	Is every tag set to turn on at a sufficient time before the session? Where automated turn-on not possible, have I planned when and how I will switch the tags on?
	Is the garment suitable sized for the assigned athlete and holding the tag in the correct position and/or orientation?
Within-session	Have I verified tag switch on prior to or at the start of the session?
	Have I created the drills with accurate start and stop times?
	Have I managed each athlete correctly (e.g., benching, rehab, extra workload, etc.)?
	Have I correctly named and categorised the session and drills according to a systematic typology? Can I use a pre-populated list in the software or on the computer?
Post-session	Have I checked for errors and removed bad data?
	Have I logged data precision information (e.g., signal strength, HDoP) and software and firmware versions?
	Have I successfully integrated the data with reporting and/or data management systems?

In-session Considerations

While tracking a session, there are often software features available that can promote clean data, minimise administrative time after the session, and facilitate insightful and efficient data analysis. Firstly, there is an opportunity to label the sessions with attributes that assist in retrospective analysis by describing the session (see Table 3).

A drill typology opens potential avenues for analysis, including workload comparison (44), assessing readiness by normalising drill outputs by player (45), and monitoring athlete response using standardised drills (46). Table 4 outlines potential categories and associated examples from a range of sports that may be considered. Maintaining consistency in naming structure, including the case used (e.g., upper, lower, sentence), is advised. Where possible, it is recommended to set up a pre-populated list of drill categories and/or names, to enable uniformity and speed-up naming. For the aforementioned applications to be accurate, the drill timings and participants need to be precisely aligned.

Perhaps the greatest challenge facing the practitioner during a session within the team setting is tracking each individual. Athletes may need removing from a drill or entire session if they cease to participate, to ensure data is not skewed by a missing participant. Alternatively, athletes regularly carry out extra drills before and/or after the main team session, which should be captured for longitudinal load monitoring. Such work should be labelled appropriately to allow for removal from analysis when only structured, coach-led training is of interest. This also applies to athletes undergoing rehabilitation, who should have their sessions captured and named in a consistent manner that enables inclusion or exclusion from analysis as required.

Table 3. Examples of Session Level Attributes.

Category	Examples
Session Type	Game/Match, Training/Practice, Rehabilitation, Fitness Test
Category	D+1/D-2, G-3, Strength, Day Before Game
Location	Pitch 1, Field 2, Main Court, Rink 2, Indoor, Stadium
Surface	Grass, Synthetic, Sand, Court
Equipment	Boots/Cleats, Trainers/Sneakers, Pads, Helmets

D = Day; G = Game

Table 4. Examples of Drill Typology

Category	Examples
Type	Team, Individual, Technical, Tactical, Physical, Rehabilitation
Drill/Period	Warm-up, Possession, Shooting, 3rd Down, Scrimmage, Defensive
Numbers	10v10+GKs, 7v7, 9 on 7, 1 on 1s, 5v5+5+GK, Individual
Space	80x50yd, 30x20m, Half Court, Full Court, Penalty Area
Descriptors	Coach encouragement, Walk-through, Two-touch

GK= Goalkeepers

Post-session Considerations

Where the workflow detailed above is attentively followed, the post-session data management processes should be streamlined. Nevertheless, practitioners should investigate the quality of the data post-session for errors and spikes. Where the system allows, descriptive information relating to the data quality (e.g., GPS signal strength and HDoP) should be logged.

Tracking data may be integrated with an athlete data management system to allow for analysis and communication alongside other sources of information. The practitioner should consider how missing data (e.g., for a specific drill due to an error with the system or a completely missing session due to a device not working/being worn) will be handled, particularly for the purposes of longitudinal load monitoring. Interested readers are directed to a review by Broman and Woo (47) in which data organisation techniques (e.g., variable names, categories, and units, managing date formats, structuring tidy data, and using a data dictionary) are discussed.

Practical Applications

- While practitioners may be tempted to dive straight into tracking data analysis, this article demonstrates the importance of understanding the characteristics of different systems and settings.
- Each technology differs in how it tracks athletes and subsequently, each offers varying advantages and disadvantages for tracking external load. In particular, how a technology and/or manufacturer processes the data should be considered within the sporting context.
- The filtering processes, velocity/acceleration thresholds for band selection, and effort detection rules should be explored, given that the manufacturer-specific defaults may not be best suited for the specific sport, team, or athlete(s) in question.
- The potential applications for tracking data will only be enabled if a systematic process to data collection is employed. This process can include utilising a pre-session checklist, along with a sport-specific typology for session and drill classification, to ensure consistent and accurate collection.

Twitter: Lorena Torres-Ronda (@lorenatorres07), Jo Clubb (@JoClubbSportSci), Emma Beanland (@EmmaBeanland1)

References

1. Halson SL. Monitoring training load to understand fatigue in athletes. Sports Med. 2014 Nov;44 Suppl 2:S139-47.

2. Reilly T, Thomas V. A motion analysis of work-rate in different positional roles in professional football match-play. J Hum Mov Stud. 1976;2:87–97.

3. Castellano J, Alvarez-Pastor D, Bradley PS. Evaluation of research using computerised tracking systems (Amisco and Prozone) to analyse physical performance in elite soccer: a systematic review. Sports Med. 2014 May;44(5):701-12.

4. Whitehead S, Till K, Weaving D, Jones B. The Use of Microtechnology to Quantify the Peak Match Demands of the Football Codes: A Systematic Review. Sports Med. 2018 Nov;48(11):2549-75.

5. Aughey RJ. Applications of GPS technologies to field sports. Int J Sports Physiol Perform. 2011 Sep;6(3):295-310.

6. Larsson P. Global positioning system and sport-specific testing. Sports Med. 2003;33(15):1093-101.

7. Malone JJ, Lovell R, Varley MC, Coutts AJ. Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. Int J Sports Physiol Perform. 2017 Apr;12(Suppl 2):S218-S26.

8. Schutz Y, Chambaz A. Could a satellite-based navigation system (GPS) be used to assess the physical activity of individuals on earth? Eur J Clin Nutr. 1997 May;51(5):338-9.

9. Townshend AD, Worringham CJ, Stewart IB. Assessment of speed and position during human locomotion using nondifferential GPS. Med Sci Sports Exerc. 2008 Jan;40(1):124-32.

10. Varley MC, Jaspers A, Helsen WF, Malone JJ. Methodological Considerations When Quantifying High-Intensity Efforts in Team Sport Using Global Positioning System Technology. Int J Sports Physiol Perform. 2017 Jan 04:1-25.

11. Jennings D, Cormack SJ, Coutts AJ, Aughey RJ. GPS analysis of an international field hockey tournament. Int J Sports Physiol Perform. 2012 Sep;7(3):224-31.

12. Witte TH, Wilson AM. Accuracy of non-differential GPS for the determination of speed over ground. J Biomech. 2004 Dec;37(12):1891-8.

13. Scott MT, Scott TJ, Kelly VG. The Validity and Reliability of Global Positioning Systems in Team Sport: A Brief Review. J Strength Cond Res. 2016 May;30(5):1470-90.

14. Di Salvo V, Collins A, McNeill B, Cardinale M. Validation of Prozone ®: A new video-based performance analysis system. Int J Perf Anal Spor. 2006 2006/06/01;6(1):108-19.

15. Linke D, Link D, Lames M. Validation of electronic performance and tracking systems EPTS under field conditions. PloS one. 2018;13(7):e0199519.

16. McLean BD, Strack D, Russell J, Coutts AJ. Quantifying Physical Demands in the National Basketball Association-Challenges Around Developing Best-Practice Models for Athlete Care and Performance. Int J Sports Physiol Perform. 2019 Apr 1;14(4):414-20.

17. Carling C, Bloomfield J, Nelsen L, Reilly T. The role of motion analysis in elite soccer: contemporary performance measurement techniques and work rate data. Sports Med. 2008;38(10):839-62.

18. Woellik H, Mueller A, Herriger J. Permanent RFID Timing System in a Track and Field Athletic Stadium for Training and Analysing Purposes. Procedia Engineering. 2014;72:202-7.

19. Sathyan T, Shuttleworth R, Hedley M, Davids K. Validity and reliability of a radio positioning system for tracking athletes in indoor and outdoor team sports. Behav Res Methods. 2012 Dec;44(4):1108-14.

20. Carling C, Williams AM, Reilly T. Handbook of Soccer Match Analysis: A Systematic Approach to Improving Performance. J. Sports Sci. Med. 2006;5(1):171.

21. Angrisani L, Arpaia P, Gatti D. Analysis of localization technologies for indoor environment. IEEE International Workshop on Measurement and Networking (M&N. 2017:1-5.

22. Alarifi A, Al-Salman A, Alsaleh M, Alnafessah A, Al-Hadhrami S, Al-Ammar MA, et al. Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances. Sensors (Basel, Switzerland). 2016 May 16;16(5).

23. Boyd LJ, Ball K, Aughey RJ. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. Int J Sports Physiol Perform. 2011;6(3):311-21.

24. Barrett S, Midgley A, Lovell R. PlayerLoad: reliability, convergent validity, and influence of unit position during treadmill running. Int J Sports Physiol Perform. 2014 Nov;9(6):945-52.

25. Migueles JH, Cadenas-Sanchez C, Ekelund U, Delisle Nyström C, Mora-Gonzalez J, Löf M, et al. Accelerometer Data Collection and Processing Criteria to Assess Physical Activity and Other Outcomes: A Systematic Review and Practical Considerations. Sports Med. 2017 Sep;47(9):1821-45.

26. Gómez-Carmona CD, Pino-Ortega J, Sánchez-Ureña B, Ibáñez SJ, Rojas-Valverde D. Accelerometry-Based External Load Indicators in Sport: Too Many Options, Same Practical Outcome? Int J Environ Res Public Health. 2019;16(24):5101.

27. Gurchiek R, Rupasinghe Arachchige Don H, Watagoda L, McGinnis R, Werkhoven H, Needle A, et al. Sprint Assessment Using Machine Learning and a Wearable Accelerometer. J Appl Biomech. 2019 01/24;35:1-16.

28. Meylan C, Trewin J, McKean K. Quantifying Explosive Actions in International Women's Soccer. . Int J Sports Phy Perf. 2017:310-5.

29. Hulin BT, Gabbett TJ, Johnston RD, Jenkins DG. Wearable microtechnology can accurately identify collision events during professional rugby league match-play. J Sci Med Sport. 2017 Jul;20(7):638-42.

30. Douglas A, Johnston K, Baker J, Rotondi MA, Jamnik VK, Macpherson AK. On-Ice Measures of External Load in Relation to Match Outcome in Elite Female Ice Hockey. Sports (Basel). 2019 Jul 16;7(7).

31. Chambers R, Gabbett TJ, Cole MH, Beard A. The Use of Wearable Microsensors to Quantify Sport-Specific Movements. Sports Med. 2015 Apr 3;45(7):1065-81.

32. Bishop D, Girard O, Mendez-Villanueva A. Repeated-sprint ability - part II: recommendations for training. Sports Med. 2011 Sep 1;41(9):741-56.

33. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability - part I: factors contributing to fatigue. Sports Med. 2011 Aug 1;41(8):673-94.

34. Wundersitz DW, Gastin PB, Richter C, Robertson SJ, Netto KJ. Validity of a trunk-mounted accelerometer to assess peak accelerations during walking, jogging and running. Eur J Sport Sci. 2015;15(5):382-90.

35. Buchheit M, Allen A, Poon TK, Modonutti M, Gregson W, Di Salvo V. Integrating different tracking systems in football: multiple camera semi-automatic system, local position measurement and GPS technologies. J Sports Sci. 2014 Dec;32(20):1844-57.

36. Varley MC, Gabbett T, Aughey RJ. Activity profiles of professional soccer, rugby league and Australian football match play. J Sports Sci. 2014 Dec;32(20):1858-66.

37. Sweeting AJ, Cormack SJ, Morgan S, Aughey RJ. When Is a Sprint a Sprint? A Review of the Analysis of Team-Sport Athlete Activity Profile. Front Physiol. 2017 2017-June-20;8(432).

38. Dwyer DB, Gabbett TJ. Global positioning system data analysis: velocity ranges and a new definition of sprinting for field sport athletes. J Strength Cond Res. 2012 Mar;26(3):818-24.

39. Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. J Sci Med Sport. 2010 Jan;13(1):133-5.

40. Reardon C, Tobin DP, Delahunt E. Application of Individualized Speed Thresholds to Interpret Position Specific Running Demands in Elite Professional Rugby Union: A GPS Study. PLoS One. 2015;10(7):e0133410.

41. Lovell R, Abt G. Individualization of time-motion analysis: a case-cohort example. Int J Sports Physiol Perform. 2013 Jul;8(4):456-8.

42. Lovell R, Scott D, Park L. Soccer velocity thresholds: do we really know what's best? Science and Medicine in Football. 2019 01/02;3:85-6.

43. McLean BD, Cummins C, Conlan G, Duthie G, Coutts AJ. The Fit Matters: Influence of Accelerometer Fitting and Training Drill Demands on Load Measures in Rugby League Players. Int J Sports Physiol Perform. 2018 Sep 1;13(8):1083-9.

44. Schelling X, Torres L. Accelerometer Load Profiles for Basketball-Specific Drills in Elite Players. J. Sports Sci. Med. 2016 Dec;15(4):585-91.

45. Lacome M, Simpson B, Buchheit M. Monitoring training status with player-tracking technology. Still on the road to Rome. Part 2. Aspetar J. 2018 06/21;7:64-6.

46. Lacome M, Simpson BM, Cholley Y, Lambert P, Buchheit M. Small-Sided Games in Elite Soccer: Does One Size Fit All? Int J Sports Physiol Perform. 2018 May 1;13(5):568-76.

47. Broman K, Woo K. Data organization in spreadsheets. Am Stat. 2018;72.1:2-10.