Chapter

Review of Ultra-Wide Band in Team Sports

José Pino-Ortega and Markel Rico-González

Abstract

The use of valid, accurate and reliable systems is fundamental to warrant a high-quality data collection and interpretation. In 2015, FIFA created a department of Electronic Performance and Tracking systems, collecting under this name the more used tracking systems in team sport setting: high-definition cameras, Global Positioning Systems, and Local Positioning Systems. To date, LPS systems proved to be valid and accurate in determining the position and estimating distances and speeds. However, it is hypothesized that between LPS, ultra-wide band (UWB) is the most promising technology for the future. Thus, this chapter was aimed to make an update about UWB technology in sport: the FIFA's regulation, manufacturer that provide this technology, the research articles that assessed validity and reliability of UWB technology, and the criteria standard for the use of this technology.

Keywords: electronic performance and tracking systems, local positioning systems, UWB, technology, accuracy

1. Introduction

Since the monitoring of match performance is now considered a fundamental part of contemporary team sport's players development, professional soccer clubs invest significant amount of money to nurture elite players [1]. Overall, the quantification of both internal and external training and match load are useful in a practical context to aid game understanding and decision making in relation to individual and collective physical training content and prescriptions [1, 2].

Today, training load monitoring is made thanks to Electronic Performance and Tracking Systems (EPTS) [3, 4], which are classified into three types based on different technologies: Global Positioning Systems (GPS) or Global Navigation Satellite Systems (GNSS) [5–7], semi-automatic video camera systems (VID) [8], and Local Positioning Systems (LPS) [9]. The fact that GPS/GNSS and LPS were not allowed during official competition, together with VID are non-invasive technologies, were the main reasons to VID has been the most used EPTS before 2014. However, the acceptance of the use radio-frequency based technologies during competitions, some installation difficulties of VID, and the possibility to add additional microelectromechanical sensors (MEMS) makes that radio-frequency technologies have become most common in team sport settings [4]. However, since some scientific validity and reliability studies have compared LPS and GPS/GNSS based EPTS [10–12], and they have shown high precision measures using LPS, the use of LPS seems to grow in the future [4, 13, 14].

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Indoor positioning wireless technologies are classified into infrared, radio-frequency (Radio frequency identification (RFID), Wi-Fi, Bluetooth and ultra-wide band [UWB]), and ultrasound systems [13]. Among different types of wireless indoor positioning systems, UWB is a promising technology for indoor positioning and tracking [13] and also for outdoor venues where there is no possibility of the surrounding infrastructure interfering in the results [3, 13, 14]. Therefore, the aim of this review was to make an update about UWB technology in sport.

2. Safe and accuracy certificates of UWB in team sports

International Federation of Amateur Football (FIFA) organized an event in which EPTS of those manufacturers that wish an official assessment of its devices´ security may be evaluated under standards and common conditions. All of these providers´ devices evaluated positively are certified with International Match Standard (IMS) license and published in the FIFA's website [15]. In addition, FIFA offer a second certificate under the name "FIFA Quality" certificate, in which manufacturers show the accuracy of their devices against a *Gold Standard* registration system. **Tables 1** and **2** show those manufacturers that provide UWB technology-based devices with IMS or "FIFA Quality" certificates.

Manufacturer	Brand	Test Institute
REALTRACK SYSTEMS SL	WIMU PRO	Victoria University
STATSports Group LTD	APEX POD	Sports Labs Ltd.
Catapult Sports	VECTOR	Sports Labs Ltd.

Table 1.
UWB manufacturers with IMS certificate.

FIFA Quality certificate			
Manufacturer	**Brand**	**Test Institute**	**Certification period**
Catapult Sports	VECTOR (LPS)	Victoria University	05-FEB-20 23-JAN-22
REALTRACK SYSTEMS SL	WIMU PRO	Victoria University	29-NOV-19 23-JAN-22

Table 2.
UWB manufacturers with FIFA quality certificate.

3. UWB in scientific articles

Based on a recently published systematic review about the validity and reliability of LPS technology [9], and additional one added due to its recently publication [16], it may be summarized that three studies used UWB technology with 6 antennae around the field and, in general, 18 Hz [10, 17–19], and one used UWB technology with 8 anchors and 33 Hz [16]. All of them belong to three different manufacturer: Realtrack Systems [10, 17, 18], KINEXON [20], and Ubisense [19].

3.1 Validity of UWB technology

Realtrack Sytems´ UWB (WIMU PRO™, RealTrack Systems, Almeria, Spain) was tested in indoor context to assess its validity, revealing 5.2 cm (0.97%) and 5.8 cm (94%) of mean absolute error (MAE) of all estimations in x- and y- position, respectively [17] (**Table 3**). The same system, in outdoor field showed a MAE of 9.57 cm in x-axis positioning and 7.15 cm in y-axis positioning [18] (**Table 3**). A third study assess the validity of an UWB during linear, circular and zig-zag drills in soccer training in walking and running intensities [10]. The authors showed a bias (%) of 0.55 to 5.85% for determining distance covered, and, moreover, a bias between −0.56 and 0.67 for determining mean velocity [10]. Additionally, this system has been compared with an GNSS revealing lower MAE than satellite-based system (**Table 3**). Athlete tracking technology is continually improving due to developments in microprocessors, data processing, and software [21]. Hence, Realtrack System have provide a new modified UWB with height antennae and 33 Hz, which has been recently compared against a real-measure [16]. The authors showed that the mean difference (MD) was less than 4 cm and in 95% of the cases was between 1 cm and 7 cm. the magnitude of the differences was expressed as 0.28% with real measures as the reference. %CV was less than 1% in all cases (**Table 3**). Despite the fact that Realtrack System (Almería, Spain) has published most of the article, an alternative brand of UWB (Ubisens Series 7000 compact tag) was also tested for its accuracy [19]. The authors also showed sufficient accuracy to test positions of players independently of the length of the recorded runs (**Table 5**). Summarizing, all manufacturers that provide UWB technology have showed acceptable accuracy levels for monitoring the position of players in team sports settings (**Tables 3–5**).

3.2 Reliability of UWB technology

Four studies [16–18, 20] aimed to assess the reliability of LPS based on UWB technology. Hoppe et al., (2018) assessed the reliability calculating the differences between the KINEXON ONE UWB devices of each positioning system (i.e. the between device reliability) though typical error. They found typical errors between 0.1 (criterion variable of 10 m jogging with jump) and 1.7 (criterion variable of 129.6 m entire circuit). The LPS revealed good reliability for the entire distance covered, walking over 10 m and sprinting with change of direction, sprinting over 30-m, sprinting over 5–20 m and theoretical maximal force and horizontal power [20]. In addition, Hoppe et al., [20] compared the results of GPS and UWB, and despite some contradictorily results, comparisons of reliability between the GPS and LPS was mainly favorable to LPS [20].

Regarding to the other commercial UWB based device from RealTrack Systems was tested for its intra- and inter-unit reliability [17]. These tests assisted with understanding the degree of error and the amount of variation between the units. A Mann–Whitney U test was performed to compare differences in the differently designed routes and between devices (i.e. the variation in data measured in one participant or another). Inter-unit reliability (i.e. the difference in using one device or another) was determined using Hopkins's reliability spreadsheet to calculate the percentage typical error of measurement and the intra-class correlation coefficient (ICC) values. The intra-unit reliability of UWB in mean velocity varied between 0.895 and 0.999 of ICC (95% of confidence interval) and the low and upper (for inter-unit variability) ranged between −0.09 and 0.42%. In the case of distance covered, the typical error of UWB varied between 0.94 and 4.87% and the lower and upper bias was between

Ref.	Article's information	Outcomes	What this Document Add?
Bastida-Castillo et al. [10]	• Aim: accuracy/reliability • Environment: outdoor. • Algorithm: TDOA. • Number of anchors: 6 • Sampling frequency: 18 Hz. • Gold Standard: timing gates and real measurement. • Drill: linear, circular and zig-zag course.	• *Distance covered* = bias: 0.57–5.85%; Test–retest reliability %TEM: 1.19; Inter-unit reliability bias: 0.18. • *Velocity* = *b*ias: 0.09; ICC: 0.979; bias: 0.01.	• In static conditions and over prolonged periods of time UWB is more accurate than GPS. • GPS accuracy was slightly more affected by the speed and type of displacement than UWB technology. • Intra- and inter-unit reliability was acceptable for both systems analyzed.
Bastida-Castillo, et al. [17]	• Aim: accuracy/reliability. • Environment: indoor. • Algorithm: TDOA. • Number of anchors: 6 • Sampling frequency: 18 Hz. • Gold Standard: Fixed reference lines of basketball court. • Drill: (1) static position; (2) perimeter markings of the court; (3) middle line of court; (4) exterior perimeter of the painted lines; (5) circle 6.75 m line.	• MAE of all estimations for the x-position of 5.2 ± 3.1 cm and for the y-position of 5.8 ± 2.3 cm. • Inter-unit reliability and ICC = 0.65 (x coordinate) and 0.85 (y coordinate).	• Position estimations are very precise and acceptable for tactical analyses. • The error of the position estimations does not change significantly across different courses. • The use of different devices does not significantly affect the measurement error.

Ref.	Article's information	Outcomes	What this Document Add?
Bastida-Castillo, et al., [18]	• Aim: accuracy. • Environment: outdoor. • Algorithm: TDOA. • Number of anchors: 6 • Sampling frequency: 18 Hz. • Gold Standard: GIS. • Drill: (1) perimeter of the field; (2) halfway line; (3) centre circle; (4) perimeter of the penalty area; (5) semicircle penalty area; (6) *SSG* (7 vs. 7).	• MAE = 9.57 ± 2.66 cm (x coordinate) and 7.15 ± 2.62 cm (y coordinate). • *SSG:* For tactical variables, differences between UWB and GPS reached 8.31% (ES = 0.11).	• UWB-20 Hz has been recommended as accurate technology for estimating position of players on the pitch, while GPS-10 Hz has substantial limitations. • Significance differences reported in tactical analysis between GPS and UWB that the error of using one system or another can mean a difference of more than 8%. • Test–retest reliability and inter-unit reliability were good for the two systems assessed.
Pino-Ortega et al., [16]	• Aim: accuracy/reliability. • Environment: indoor. • Algorithm: TDOA. • Number of anchors: 8 • Sampling frequency: 33 Hz. • Gold Standard: real measurement. • Drill: over the lines of the court (linear course).	• The MD was less than 4 cm and in 95% of the cases was between 1 cm and 7 cm, the reference being the real measure. The magnitude of the differences was expressed as 0.28% with real measures as the reference. %CV was less than 1% in all cases. • It is remarkable that %CV was less than 1% in all cases, in going, coming back and in total. • Besides, inter-unit, test–retest and inter-subject analysis did not influence the reliability results.	• An eight antennae UWB system can be considered suitable for locomotion and positioning in an indoor environment.

Table 3.
Studies that assess validity or reliability of Realtrack systems´ UWB (Almería, Spain) (adapted from Rico-González et al. [9]).

Ref.	Article's information	Outcomes	What this Document Add?
Hoppe et al., [20]	• Aim: accuracy/reliability. • Environment: indoor. • Brand: 1.0, Munich, Germany. • Algorithm: not defined. • Number of anchors: 12 • Sampling frequency: 18/20 Hz. • Gold Standard: not defined. • Drill: Specific circuits: walking, jogging, and sprinting sections that were performed either in straight-lines or with changes of direction.	• *Distance covered* UWB 18 Hz: TEE: 1.6–8.0%; CV: 1.1–5.1% UWB 20 Hz, TEE: 1.0–6.0%; CV: 0.7–5.0% • *Sprint* UWB 18 Hz, TEE: 4.5–14.3%; CV: 3.1–7.5% UWB 20 Hz, TEE: 2.1–9.2%; CV: 1.6–7.3% • *Relative loss of data sets due to measurement error* UWB 18 Hz = 20.0% UWB 20 Hz = 15.8%	• Overall, 20 Hz UWB had superior validity and reliability than 18 Hz UWB and 10 Hz GPS.

Table 4.
Studies that assess validity or reliability of KINEXON's UWB (Munich, Germany) (adapted from Rico-González et al. [3]).

Ref.	Article's information	Outcomes	What this Document Add?
Leser et al., [19]	• Aim: accuracy. • Environment: indoor. • Brand: Ubisens Series 7000 Compact Tag. • Algorithm: TDOA/AOA. • Number of anchors: 6 • Sampling frequency: 4.17 ± 0.01 Hz per-tag. • Gold Standard: trundle wheel. • Drill: *Runs* in the center of the playing field and at the borders; *Matches* (5 vs. 5 + 1 player (without ball contact) leading a trundle wheel).	• *Runs* = difference with trundle wheel: 8.25 ± 4.07%; 95% LoA: 0.27–16.22%). • *Match* = MD = 3.45 ± 1.99%; 95% limits of agreement = −0.46–7.35%.	• UWB had enough accuracy for time-motion analysis.

Table 5.
Studies that assess validity or reliability of Ubisense's UWB (Munich, Germany) (adapted from Rico-González et al. [3]).

−2.65 and 2.06%. Thus, it was concluded that the UWB was reliable for distance covered and mean velocity [17]. Another study testing inter-unit reliability of UWB of the RealTrack system presented ICC values of 0.65 and 0.88 for x- and y-axis, respectively [17]. In the last published article using a develop device of this provider, Pino-Ortega et al., found remarkable that %CV of a 33 Hz and 8 antennae UWB was less than 1% in all cases, in going, coming back and in total. Besides, inter-unit, test–retest and inter-subject analysis did not influence the reliability results. Therefore, both KINEXON ONE and Realtrack Systems provide a reliable device for measures in sport settings (**Tables 3** and **4**). The characteristics of Realtrack Systems´, KINEXON ONE's and Ubisense's UWB devices have been summarized in **Table 6**.

	REALTRACK Wimu Pro	KINEXON	Ubisense
Sampling rate	< 55 Hz	10–1000 Hz	Not fixed
N° anchors	6–12	6–16	Scalable
GPS integrated	Yes	No	No
Triaxial accelerometer	4 sensors <1000 Hz	200 Hz	—
Triaxial gyroscope	3 sensors <1000 Hz	200 Hz	—
Triaxial magnetometer	160 Hz	20 Hz	—
Battery life	5	6	—
HR data available	Compatible with 3rd party sensors	Compatible with 3rd party sensors	No
Thresholds for each player?	Yes	Yes	Yes
Real-data available	Yes	Yes	Yes
Raw data available	Yes	Yes	Yes
Visualization platform	Software; App; Online	Software; Online	Software; Online
Technology based	ANT+	—	—

Table 6.
Characteristics of devices based on UWB (extracted from Serpiello [22]).

4. Principles for positioning detection

Radio-frequency EPTS are based on quite similar principles of use for positioning detection [13, 14, 21], however, UWB replace satellite navigation networks by a set of antennae installed in a known positioning around the field in which the data are going to be recorded. Thus, UWB system calculate position of devices using: (1) the antennae set (which act as a reference system), and (2) the devices tracked (**Figure 1**). The communication stablished between antennae allows a detection of each device enclosed in a tight-fitty garment commonly located between each player´ scapulae. So, UWB is based on a wireless technology, which establish a communication in the absence of a physical medium [23]. Concretely, the reference system is composed by a set of antennae located around the field in which the measurements are going to be recorded. Though an algorithm (see 4.2. section) (e.g. Time Difference of Arrival (TDOA)), at least three antennae stablished a circumference around themselves, whose radius is defined by the distance between an antenna and the object [13]. It is known that player positioning is in any place of the circumference's perimeter. When at least three antennae stablish their computation, the circumferences perimeters meet in a common place, where the player is (**Figure 1**).

These communication is stablished using electromagnetic waves which carry data [23]. The values of the electromagnetic waves that allow positioning computation are measured over time, and represented by curves, called sinusoids [24]. These curves appear in a certain shape according to their values. Mathematically, these sinusoids are the result of the number of beats or cycles per second (frequency), the power of each frequency component (amplitudes), and the delay or advantage of a signal (phase), which describe the angular displacement of two sinusoidal functions [23, 25]. The key to transmitting the information is through the use of waves with more complex shapes, as a result of a combination of different sinusoids [25]. Depending on the frequency of these waves, indoor positioning wireless technologies are classified into different types (see introduction section).

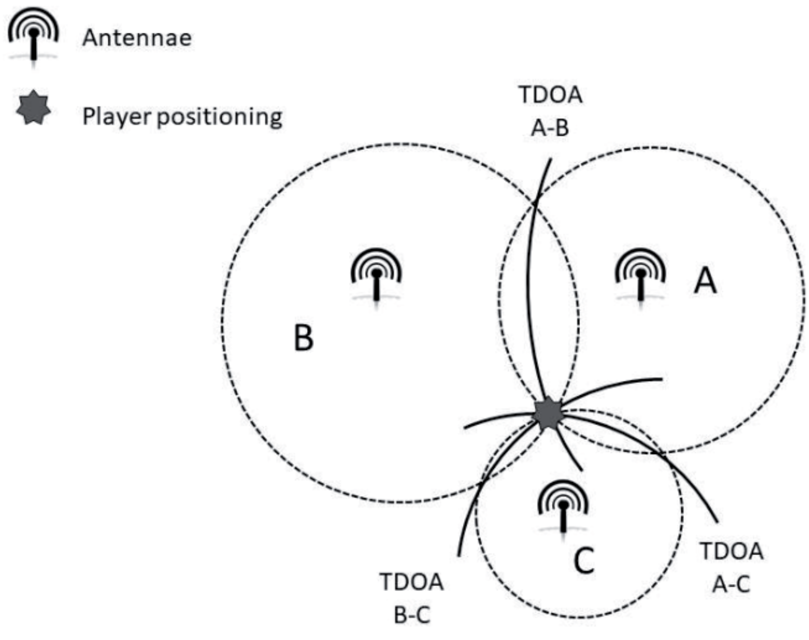

Figure 1.
Positioning using UWB technology.

The distances between antennae (node located in known positioning) and device (held by each player and located in unknown positioning) are computed by UWB positioning algorithms, clustered into different categories: angle of arrival (AOA), received signal strength (RSS); time difference of arrival (TDOA); time of arrival (TOA), and a hybrid algorithm [13]. An understanding of the accuracy, environment, estimation technique, space, and purpose of use of these algorithms is critical because of their differences and the appropriateness of their use in different situations [3, 13]. In brief, despite the fact that AOA algorithm has valid accuracy, AOA and RSS are more suitable than other methods for those systems based on a narrowband signals than with a high UWB bandwidth [3, 13]. Instead, TOA algorithm is suitable for those systems with bandwidth such as UWB. Regarding to the accuracy, small errors in AOA will negatively impact precision when the target object is far away from the base station. However, TOA and TDOA are more accurate relative to other algorithms because of the high time resolution of the UWB signals. In addition, due to hybrid algorithms combine the advantages of all algorithms, it seems to be the most effective solutions for UWB positioning systems [13].

The receiver and transmitter devices that these technologies contain are interconnected to avoid communication with interference from other devices [13]. The communication of the UWB system occupies a very large frequency band, at least 0.5 GHz, as opposed to more traditional radio communications which operate on much smaller frequency bands. On the other hand, since UWB is only allowed to transmit at very low power, its signal emits little noise and can coexist with other services without influencing them (Bastida-Castillo, Gómez-Carmona, De la Cruz-Sánchez, et al., 2019).

5. Limitations and future ways of the use of UWB in team sport

As was analyzed in this chapter, each manufacturer provides a different LPS based on different engineering specifications. Hence, the comparison between LPS provides a wide conclusion due to the comparison between two systems with different standards is difficult. However, since LPS measurement seems to be sensible by several factors such as temperature, humidity gradients, air circulation, pitch dimensions or infrastructure condition, among others [3, 13], the comparison between the outcomes of two studies should be made with caution, even though both of them were performed with the same UWB device. In fact, the same device has resulted in different outcomes in outdoor and indoor context, even in two indoor environments (see **Table 3**). In order to open a research way with the aim of unification all possible information about the use of UWB technology (among others) in the scientific articles´ methodology description, a survey has been published [3] based on the following literature: [5–7, 13, 14, 21, 26–34]. Recently, the information provided in articles has been analyzed based on the survey, and it has been highlighted a need to more detailed descriptions [3]. Accordingly, the items provided by the survey belongs to five quality metrics: (1) system accuracy and precision; (2) coverage and its resolution; (3) latency in making location updates; (4) building's infrastructure impact; and (5) effect of random errors on the system such as errors caused by signal interference and reflection [35]. This fact makes that the comparison between two studies may be unsuitable, at least, while the narrow information is reported. The sampling frequency, computation methods for velocity and acceleration, data exclusion and inclusion criteria, high-intensity bias due to random error, the time at which the data were extracted, technology lock, and data synchronization, and other factors such as the athlete's clothes, the number of reference point, environmental and infrastructure conditions, antennae installation and position, and measurement methods have also been mentioned for the use and description for UWB technology. However, the most of these questions has been addressed in other context such as engineering, and this survey focused in sport settings was based on theoretical framework. The unification of these information will allow a summary of future systematic reviews comparing the outcomes extracted with the same characteristics, and context.

6. Concluding remarks

Theoretically, UWB seems to be the most promising technology for team sports tracking monitoring, however, since it has not been compared against another LPS in team sport setting, it should be considered with caution. In any case, the devices based on UWB technology have shown a high degree of validity for all variables based on positioning (static positioning, time-motion, high speed running and collective tactical behavior). Specifically, Realtrack Systems (6 antennae/18 Hz) = bias (distance covered): 0.55–5.85%, bias (velocity): −0.56 - 0.67, and difference with other EPTS (collective tactical analysis): 8.31%; Realtrack Systems (8 antennae/33 Hz) = bias: 0.28%; KINEXON ONE = TEE: 1.0 ± 6.0%; Ubisense = bias: 8.25 ± 4.07%). Hence, all Realtrack Systems´, KINEXON ONE's and Ubisense systems´ UWB are considered a valid technology for sport settings. Moreover, Realtrack Systems´ and KINEXON ONE's UWB showed to be reliable (KINEXON ONE = TE: 1.7 cm; Realtrack Systems (6 antennae / 18 Hz) = ICC: 0.65 (x-axis) and 0.88 (y-axis); Realtrack Systems (8 antennae / 33 Hz) = %CV: <1%). Therefore, UWB is considered a valid and reliable EPTS in the field of load monitoring of team sports in both indoor and outdoor environments. However, although UWB has usually resulting in greater accuracy than other radio frequency systems at high intensity drills [10], special care should be taken when analyzing load indicators at high speeds or involving different trajectories.

To date, due to the low amount of information reported in the articles´ methodology sections [3], the comparison between outcomes extracted from devices with different characteristics, or in different environment should be made with caution. Therefore, we encourage the authors to explain the methodology about the use of UWB sensors, among others EPTS, based on recently published guideline [3].

Abbreviation list

ANT+	advanced and adaptive network technology
AOA	angle of arrival
EPTS	electronic performance and tracking systems
FIFA	International Federation of Amateur Football
GPS	global positioning systems
GNSS	global navigation satellite systems
Hz	Hertz
ICC	intraclass correlation coefficient
IFAB	International Football Association Board
IMS	International Match Standard
LPS	local positioning systems
MAE	mean absolute error
ME	mean difference
MEMS	microelectromechanical sensors
RFID	radio frequency identification
RSS	received signal strength
TE	typical error
TEE	typical error of estimate
TDOA	time difference of arrival
TOA	time of arrival
UWB	ultra-wide band
VID	semi-automatic video camera systems
%CV	% of coefficient of variation

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References

[1] Palucci Vieira LH, Carling C, Barbieri FA, Aquino R, Santiago PRP. Match running performance in young soccer players: A systematic review. Sports Medicine. 2019;**49**:289-318

[2] Rico-González M, Mendez-Villanueva A, Los Arcos A. Training load periodization in soccer with one official match a week: A systematic review. In: An Essential Guide to Sports Performance. New York: NOVA Science publisher; 2020. pp. 123-166

[3] Rico-González M, Los Arcos A, Rojas-Valverde D, Clemente FM, Pino-Ortega J. A survey to assess the quality of the data obtained by radio-frequency technologies and microelectromechanical systems to measure external workload and collective behavior variables in team sports. Sensors. 2020;**16**

[4] Rico-González, M., Pino-Ortega, J., Nakamura, F. Y., Moura, F. A., Rojas-Valverde, D., & Los Arcos, A. (2020). Past, present, and future of the technological tracking methods to assess tactical variables in team sports: A systematic review. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology* 175433712093202. https://doi.org/10.1177/1754337120932023

[5] Castellano J, Casamichana D. Deporte con dispositivos de posicionamiento global (GPS): Aplicaciones y limitaciones. Revista de Psicología del Deporte. 2014;**23**:10

[6] Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global Positioning Systems (GPS) and Microtechnology Sensors in Team Sports: A Systematic Review. *Sports Medicine,* 43(10), 1025-1042. https://doi. org/10.1007/s40279-013-0069-2

[7] Hausler, J., Halaki, M., & Orr, R. (2016). Application of Global Positioning System and Microsensor Technology in Competitive Rugby League Match-Play: A Systematic Review and Meta-analysis. *Sports Medicine,* 46(4), 559-588. https://doi.org/10.1007/s40279-015-0440-6

[8] Castellano J, Álvarez-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 Medicine. 2014;**44**:701-712

[9] Rico-González, M., Los Arcos, A., Clemente, F. M., Rojas-Valverde, D., & Pino-Ortega, J. (2020). Accuracy and reliability of local positioning Systems for Measuring Sport Movement Patterns in stadium-scale: A systematic review. Applied Sciences 10(17), 5994. https://doi.org/10.3390/ app10175994

[10] Bastida-Castillo, A., Gómez-Carmona, C. D., De la Cruz Sánchez, E., & Pino-Ortega, J. (2018). Accuracy, intra- and inter-unit reliability, and comparison between GPS and UWB-based position-tracking systems used for time–motion analyses in soccer. European Journal of Sport Science, 18(4), 450-457, https://doi.org/10.1080/174613 91.2018.1427796

[11] Linke, D., Link, D., & Lames, M. (2018). Validation of electronic performance and tracking systems EPTS under field conditions. PLoS One, 13(7), e0199519. https://doi.org/10.1371/journal.pone.0199519

[12] Rico-González M, Los Arcos A, Nakamura FY, Gantois P, Pino-Ortega J. A comparison between UWB and GPS devices in the measurement of external load and collective tactical. International Journal of Performance Analysis in Sport. 2020;**20**:10

[13] Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S.,

Al-Ammar, M., & Al-Khalifa, H. (2016). Ultra wideband indoor positioning technologies: Analysis and recent advances. Sensors, 16(5), 707. https://doi.org/10.3390/s16050707

[14] Leser, R., Baca, A., & Ogris, G. (2011). Local positioning systems in (game) sports. Sensors, 11(10), 9778-9797. https://doi.org/10.3390/s111009778

[15] FIFA. (2018). *About the IMS Standard for Wearable Tracking Devices. Football technology*. https://football-technology.fifa.com/en/media-tiles/about-the-ims-standard-for-wearable-tracking-devices/

[16] Pino-Ortega J, Bastida-Castillo A, Gómez-Carmona C, Rico-González M. Validity and reliability of an eight antennae ultra-wideband local positioning system to measure performance in an indoor environment. *Sports Biomechanics*, 2020. Article in Press.

[17] Bastida-Castillo, A., Gómez-Carmona, C., De la Cruz-Sánchez, E., Reche-Royo, X., Ibáñez, S., & Pino-Ortega, J. (2019). Accuracy and Inter-Unit Reliability of Ultra-Wide-Band Tracking System in Indoor Exercise. *Applied Sciences,* 9(5), 939. https://doi.org/10.3390/app9050939

[18] Bastida-Castillo, A., Gómez-Carmona, C. D., De La Cruz Sánchez, E., & Pino-Ortega, J. (2019). Comparing accuracy between global positioning systems and ultra-wideband-based position tracking systems used for tactical analyses in soccer. European Journal of Sport Science, 19(9), 1157-1165. https://doi.org/10.1080/17461391.2019.1584248

[19] Leser, R., Schleindlhuber, A., Lyons, K., & Baca, A. (2014). Accuracy of an UWB-based position tracking system used for time-motion analyses in game sports. European Journal of Sport Science, 14(7), 635-642. https://doi.org/10.1080/ 17461391.2014.884167

[20] Hoppe, M. W., Baumgart, C., Polglaze, T., & Freiwald, J. (2018). Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. PLoS One, 13(2), e0192708. https://doi.org/10.1371/journal.pone.0192708

[21] Malone, J. J., Lovell, R., Varley, M. C., & Coutts, A. J. (2017). Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. *International Journal of Sports Physiology and Performance*, 12(Suppl 2), 18-26. https://doi.org/10.1123/ijspp.2016-0236

[22] Serpiello, F. (2019). *Compare GPS - upper price tier.* Compare Sports Tech. https://www.comparesportstech.com/compare-gps-tracking-systems

[23] Rico-González, M., Los Arcos, A., Nakamura, F. Y., Moura, F. A., & Pino-Ortega, J. (2020). The use of technology and sampling frequency to measure variables of tactical positioning in team sports: A systematic review. Research in Sports Medicine, 28(2), 279-292. https://doi.org/10.1080/15438627.2019.1660879

[24] Jovanov, E., Milenkovic, A., Otto, C., & de Groen, P. C. (2015). A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. *J NeuroEngineering Rehabil*, 2(1), 6. https://doi.org/10.1186/1743-0003-2-6

[25] Winter DA. (2009). Biomechanics and Motor Control of Human Movement. 4. Ed. Hoboken, NJ: John Wiley & Sons, Inc., Hoboken, New Jersey; 2009

[26] Adesida, Y., Papi, E., & McGregor, A. H. (2019). Exploring the Role of Wearable Technology in Sport

Kinematics and Kinetics: A Systematic Review. *Sensors,* 19 (7), 1597. https://doi.org/10.3390/s19071597

[27] Aughey, R. J., & Falloon, C. (2010). Real-time versus post-game GPS data in team sports. Journal of Science and Medicine in Sport, 13(3), 348-349. https://doi.org/10.1016/j.jsams.2009.01.006

[28] Chambers, R., Gabbett, T. J., Cole, M. H., & Beard, A. (2015). The Use of Wearable Microsensors to Quantify Sport-Specific Movements. *Sports Med,* 45(7), 1065-1081. https://doi.org/10.1007/s40279-015-0332-9

[29] Chen, K. Y., Janz, K. F., Zhu, W., & Brychta, R. J. (2012). Redefining the Roles of Sensors in Objective Physical Activity Monitoring: *Medicine & Science in Sports & Exercise,* 44: S13–S23. https://doi.org/10.1249/MSS.0b013e3182399bc8

[30] Hennessy, L., & Jeffreys, I. (2018). The current use of GPS, Its Potential, and Limitations in Soccer: *Strength and Conditioning Journal,* 40(3), 83-94. https://doi.org/10.1519/SSC.0000000000000386

[31] Jackson BM, Polglaze T, Dawson B, King T, Peeling P. Comparing global positioning system and global navigation satellite system measures of team-sport movements. International Journal of Sports Physiology and Performance. 2018;**13**(8):1005-1010. DOI: https://doi.org/10.1123/ijspp.2017-0529

[32] Niu X, Li Y, Zhang H, Wang Q, Ban Y. Fast thermal calibration of low-grade inertial sensors and inertial measurement units. Sensors. 2013;**13**(9):12192-12217. DOI: https://doi.org/10.3390/s130912192

[33] Pons, E., García-Calvo, T., Resta, R., Blanco, H., López del Campo, R., Díaz García, J., & Pulido, J. J. (2019). A comparison of a GPS device and a multi-camera video technology during official soccer matches: Agreement between systems. PLoS One, 14(8), e0220729. https://doi.org/10.1371/journal.pone.0220729

[34] Treviño G. Trilateración: Sismos, GPS, rayos y teléfonos celulares, y la XIX Olimpiada de Ciencias de la Tierra. GEOS. 2014;**34**(2):15

[35] Wu H, Marshall A, Yu W. Path planning and following algorithms in an indoor navigation model for visually impaired. In Proceedings of the Second International Conference on Internet Monitoring and Protection, ICIMP. 2007:38-48