Review

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Concurrent validity and reliability of global positioning systems for measuring intense running and peak speed performance: a systematic review

Supplementary Information

The online version of this article (https://doi.org/10.1007/s12662-025-01023-2) contains supplementary material, which is available to authorized users.

Introduction

Sprinting performance and peak speed are two athletic determinants that support human running performance in different individual and team sports (Haugen, Seiler, Sandbakk, & Tønnessen, 2019). While peak speed is a determinant in the 100- and 200-m dash (Healy, Kenny, & Harrison, 2022; Majumdar & Robergs, 2011), running above $25\,\text{km/h}^{-1}$ (sprinting threshold in soccer) is highly important in soccer to sustain match demands in intense scenarios (Andrzejewski, Chmura, Pluta, Strzelczyk, & Kasprzak, 2013; Gualtieri, Rampinini, Dello Iacono, & Beato, 2023). Therefore, monitoring sprinting performance and peak speed is crucial not only to determine the overall load occurring during training and competitive scenarios (Malone et al., 2018), but also to determine the maximum level of a player aiming to standardize the training process (Barbero-Álvarez, Coutts, Granda, Barbero-Álvarez, & Castagna, 2010; Miguel, Oliveira, Loureiro, García-Rubio, & Ibáñez, 2021). If proper identification of the sprinting demands and peak speed is done, then it is possible to adjust the training process and determine individualized thresholds of training while controlling the external load stimulus imposed on each player (Haugen, Tønnessen, Hisdal, & Seiler, 2014; Massard, Eggers, & Lovell, 2018).

To properly identify sprinting performance and peak speed in sports environments, different approaches can be used (e.g. radar gun, laser systems, video-analysis, timing gates or photocells, optoelectronic system, video-based mobile applications) (Romero-Franco et al., 2017). Usually, radar guns and laser devices are considered the gold standard for monitoring speed while running (Beato, Devereux, & Stiff, 2018b). However, in the context of field-based sports, more important than controlling instantaneous speed is to determine the accumulated distance while sprinting or, alternatively, the frequency of peak speed achieved (Haugen & Buchheit, 2016). Therefore, microelectromechanical systems such as global positioning systems (GPS) have become popular devices for controlling running load in training and competitive scenarios of different individual and team sports (Crang et al., 2020).

Despite the extensive use of GPS for monitoring sprinting distances and peak speed in different sports, it is critical for sports scientists and coaches to know the accuracy and precision of each model and brand. In fact, erroneous interpretations of human performance can be made based on the imprecision or inac-

Table 1 Eligibility criteria

PICOS	Inclusion criteria	Exclusion criteria
1—Population	Tests were conducted in human intense running actions or peak speed ($\geq 19.8\,\text{km/h}^{-1}$) in any sport context	The tests were not conducted in human running actions (e.g. swimming sprinting, rowing sprinting)
2—Intervention/ Exposure	Test of GPS and estimates intense running and/or peak speed ($\geq 19.8\,\text{km/h}^{-1}$)	Other instruments than GPS (e.g. photocells, radar gun, mobile applications) and estimates other speed thresholds ($< 19.8\,\text{km/h}^{-1}$), acceleration, or deceleration
3—Comparator	In the case of concurrent validity, GPS was compared with: (i) photocell, (ii) radar gun, (iii) other microelectromechanical system, (iv) mobile application, and/or (v) video-camera analysis or optoelectronic system	Was not compared with one of the following possibilities: (i) photocell; (ii) radar gun; (iii) other microelectromechanical system; (iv) mobile application; and/or (v) video-camera analysis or optoelectronic system
4—Outcomes	In the case of concurrent validity, one of the following measures was included: (i) typical error, (ii) mean absolute error, (iii) correlation coefficient, and (iv) standard error of the estimate, (v) mean absolute percentage error (MAPE), (vi) root mean square error (RMSE), (vii) coefficient of determination (R^2). Validation methods based on artificial intelligence were not considered	For concurrent validity, the outcomes presented are not typical error, mean absolute error, correlation coefficient, or standard error of estimate. Validation methods based on artificial intelligence were excluded
	In the case of reliability, one of the following measures was included: (i) intraclass correlation test, (ii) coefficient of variation, (iii) standardised typical error, and (iv) standard error of measurement	For reliability, the outcomes presented are not (i) intraclass correlation test, (ii) coefficient of variation, (iii) standardised typical error, and (iv) standard error of measurement
5—Study design	Only peer-reviewed observational, cross-sectional, and longitudinal studies that assess the validity or reliability of devices were included	Experimental studies, case studies, opinion pieces and nonpeer-reviewed articles were excluded
6—Others	Only original and full-text studies written in English. Chest/back-mounted inertial navigation system	Written in a language other than English. Article types other than original (e.g. reviews, letters to editors, trial registrations, proposals for protocols, editorials, book chapters and conference abstracts). Foot-mounted inertial measurement unit

GPS global position system, *PICOS* (P) population, (I) intervention/exposure, (C) comparator, (O) outcomes, (S) study design

curacy of the measurement instruments, and this should be avoided by systematically testing the concurrent validity and reliability of the instruments (Denegar & Ball, 1993; Hopkins, 2000). In the particular case of sprinting and/or peak speed, this can be more critical since it is working closer or in maximal intensity, thus possibly increasing the bias of instruments (Rampinini et al., 2014). This is particularly relevant because errors may accumulate in cases of monitoring the sprinting distance or miss the detection of maximal speed in field-based tests.

While some systematic reviews have been published on the validity and reliability of GPS for monitoring distance covered (Hoppe, Baumgart, Polglaze, & Freiwald, 2018; Pino-Ortega, Oliva-Lozano, Gantois, Nakamura, & Rico-González, 2021; Scott, Scott, & Kelly, 2016), no systematic review has centred on the summary of evidence on the concurrent validity and reliability of GPS for measuring intense running and peak speed performance. Considering the relevance of ensuring a summary of evidence regarding the concurrent validity and reliability of different models and brands for monitoring intense running and peak speed performance, the aims of this study were twofold: (1) to identify and summarize studies that have examined the concurrent validity of microelectromechanical devices for measuring intense running and peak speed performance and (2) to identify and summarize studies that have examined the reliability of microelectromechanical devices for measuring intense running and peak speed performance.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines were followed to write this systematic review (Page et al., 2021) as well as the guidelines for performing systematic reviews in sport science (Rico-González, Pino-Ortega, Clemente, & Arcos, 2021). The protocol of the systematic review was a priori registered in the International Platform of Registered Systematic Review and Meta-Analysis Protocols with the number INPLASY202160007 and the DOI number https://doi.org/10.37766/inplasy2021.6.0007.

Eligibility criteria

The inclusion and exclusion criteria can be found in ▣ **Table 1** based on the PICOS strategy (Methley, Campbell, Chew-Graham, McNally, & Cheraghi-Sohi, 2014).

The screening process related to the analysis of the title, abstract, and reference list of each study to locate potentially relevant studies was independently executed by two of the authors (A.M. and E.M-P.). Moreover, both authors reviewed the full version of the included papers in detail to identify which article met the inclusion criteria. In addition, a search within the reference lists of the included records was performed to add more relevant studies. In case of discrepancies, a discussion was conducted using the participation of a third author (R.O.). Possible errata for the included articles were considered.

Abstract

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Concurrent validity and reliability of global positioning systems for measuring intense running and peak speed performance: a systematic review

Abstract

The current systematic review aimed to analyse studies on the concurrent validity and reliability of microelectromechanical devices for measuring intense running and peak speed performance. A systematic review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, using EBSCO, PubMed, Scielo, Scopus, SPORTDiscus and Web of Science. Keywords and synonyms were entered in various combinations in the title, abstract, or keywords: ("Global positioning system" OR "Global Navigation Satellite System" OR "GPS") AND (Validity OR Accuracy OR Reliability OR Precision OR Repeatability OR Reproducibility OR Consistency) AND ("sprint" OR "peak speed" "top seed" OR "maximal speed"). The risk of bias was assessed using the Appraisal tool for Cross-Sectional Studies. From 839 studies, 20 were systematically analysed. It was found that 16 global positioning system (GPS) models were considered valid and 12 were considered reliable for measuring intense running and/or peak speed performance. Intense running performance in GPS with lower sampling rate (e.g. ≤ 5 Hz) acquisition demonstrated reduced validity and reliability in nonlinear movement patterns as well as movement intensity increases. Some limitations of the evidence, including the conditions associated with exercise testing and the benchmark and device used, varied between studies. In addition, the data of the algorithms used by GPS can affect the interpretation of the results. Thus it would be advisable to use higher sampling rates.

Keywords
Accuracy · High-speed · Sensors · Sports · Sprint

Information sources and search

The following electronic databases were used to search for relevant publications on February 21, 2024: Web of Science, PubMed, and SPORTDiscus (EBSCO). Keywords and synonyms were entered in various combinations in the title, abstract, or keywords: ("Global positioning system" OR "Global Navigation Satellite System" OR "GPS") AND (Validity OR Accuracy OR Reliability OR Precision OR Repeatability OR Reproducibility OR Consistency) AND ("sprint" OR "peak speed" "top seed" OR "maximal speed"). In addition to the automatic search, the reference lists of the studies retrieved were manually searched to identify potentially eligible studies not captured by the electronic searches.

Data collection process

EndNote (Clarivate Analytics, Philadelphia, PA, USA) was used to manage the bibliographic data and streamline the process of organizing references. The software allowed to systematically categorize the articles based on inclusion and exclusion criteria. Two authors (A.M. and E.M-P.) independently reviewed the references, and in cases of discrepancies, a third author (R.O.) was consulted to resolve any conflicts. The inclusion and exclusion process followed the guidelines recommended by the Cochrane Consumers and Communication Review Group (Ryan, Synnot, Prictor, & Hill, 2021).

Data items

The following main outcomes were extracted for concurrent validity studies: (i) typical error, (ii) mean absolute error, (iii) correlation coefficient and (iv) standard error of the estimate. For reliability, the following main outcomes were extracted: (i) intraclass correlation test (ICC), (ii) coefficient of variation (CV), (iii) standardized typical error and (iv) standard error of measurement. In addition, to the above-mentioned main outcomes, the following information was extracted from the included articles: (i) experimental design, procedures and setting of each study, number of participants (*n*), age group (youth, adults or both), sex (men, women or both), training level (untrained, trained) and sport; (ii) characteristics of the GPS and comparator (for cases of concurrent-validity).

Study risk of bias assessment

The Appraisal tool for Cross-Sectional Studies (AXIS) was used to assess bias in the study design (Downes, Brennan, Williams, & Dean, 2016). This was applied by two authors of this study (A.M. and R.O.). The assessment process was conducted independently. After that, both authors compared results, and any disagreement regarding the results was discussed and decided in agreement. AXIS is a tool composed by 20-item to access bias quality of cross-sectional studies. Before conducting the bias assessment, a prescreening process was applied to evaluate the general quality of the studies, ensuring that only studies with sound methodologies were considered. With the application of the AXIS tool, it was possible to identify whether the studies included in the present systematic review presented appropriate study designs, and consequently, a higher representation of how valid and/or reliable intense running and peak speed variables are. The AXIS assesses the quality of cross-sectional studies based on the following criteria: clarity of aims/objectives and target population; appropriate study design and sampling framework; justification for the sample size; measures taken to address nonresponders and the potential for response bias; risk factors/outcome variables measured in the study; clarity of methods and statistical approach; appropriate result presentation, including internal consistency; justified discussion points and conclusion; discussion of limitations; and identification of ethical approval and any conflicts of interest (Downes et al., 2016). Since questions 7, 13 and 14 were not applicable to the

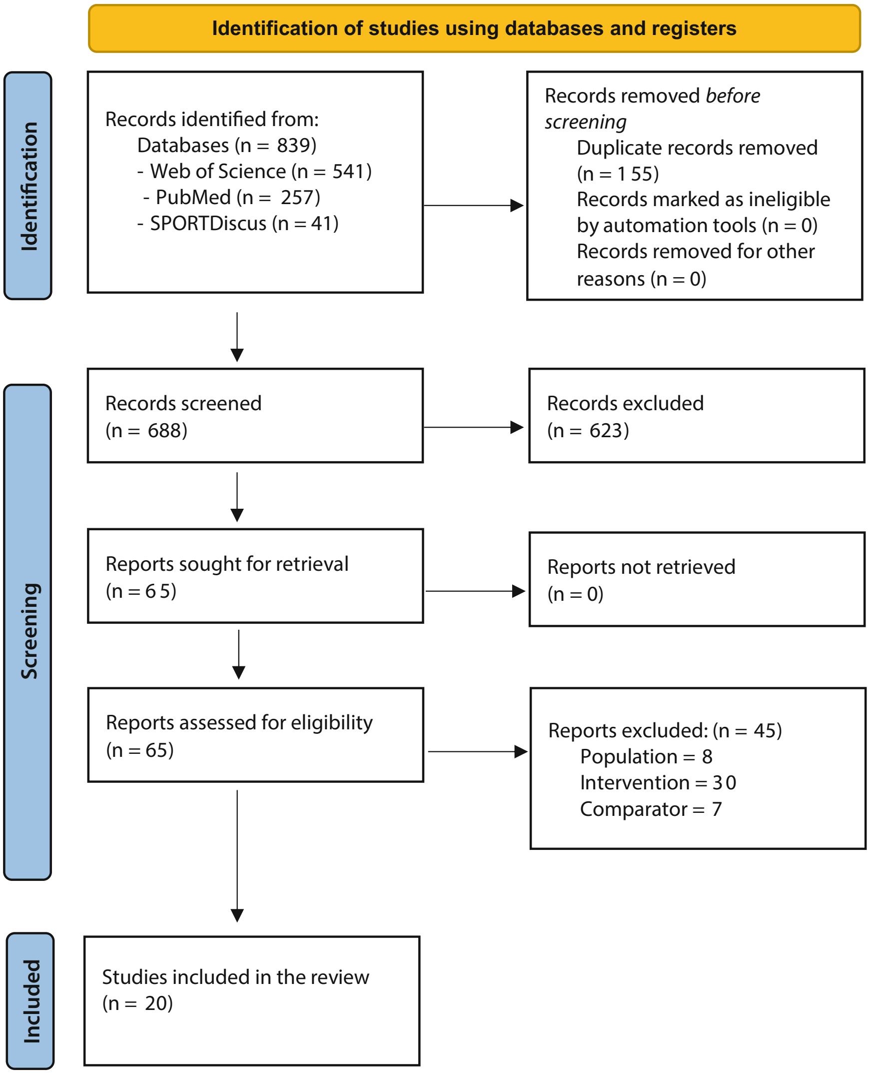

Fig. 1 ▲ Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flow diagram

studies included, we removed them and used 17 items. The AXIS tool does not present a numerical scale for a final score, but a degree of subjective assessment is suggested. We applied a cut-off point, requiring studies to score at least 12 out of 17 possible points to be included in the review. Studies scoring below this threshold were excluded from the analysis. Thus, we attributed one point to each item with a yes response.

Results

Study selection

Searching of databases identified 839 original studies (i.e. Web of Science: 541; PubMed: 257; SPORTDiscus: 41). These studies were then exported to the reference manager software (EndNote 20.0.1, Clarivate Analytics, Philadelphia, PA, USA). Duplicates (155 references) were subsequently removed either automatically or manually. The remaining 688 articles were screened for their relevance based on titles and abstracts, resulting in the removal of further 623 studies. Following the screening procedure, 65 articles were selected for in-depth reading and analysis. After reading full texts, further 45 studies were excluded because they did not meet the eligibility criteria described in ◘ **Table 1** with numbers 1, 2 and 3. Thus, 20 studies met all the inclusion criteria and were included in the review. All steps are described in ◘ **Fig. 1**.

Study characteristics

◘ **Table 2** describes the characteristics of the 20 studies included in this systematic review. All studies analysed GPS. There were 5 studies that analysed validity (Alphin, Sisson, Hudgins, Noonan, & Bunn, 2020; Nagahara et al., 2017; Reinhardt, Schwesig, Lauenroth, Schulze, & Kurz, 2019; Roe et al., 2017; Waldron, Worsfold, Twist, & Lamb, 2011b), one study that analysed reliability (Johnston et al., 2012), and 14 studies that analysed both validity and reliability (Akyildiz, Alvurdu, Ceylan, & Clemente, 2022; Beato, Coratella, Stiff, & Dello, 2018a; Beato et al., 2018b; Chahal, Lim, Pan, & Kong, 2022; Clavel et al., 2022; Coutts & Duffield, 2010; Gray, Jenkins, Andrews, Taaffe, & Glover, 2010; Johnston, Watsford, Pine, Spurrs, & Sporri, 2013; Johnston, Watsford, Kelly, Pine, & Spurrs, 2014; Lacome et al., 2019; Mooney, Hunter, O'brien, Berry, & Young, 2011; Muñoz-Lopez, Granero-Gil, Pino-Ortega, & De Hoyo, 2017; Vantieghem-Nicolas, Morin, Cotte, Sangnier, & Rossi, 2023; Waldron, Worsfold, Twist, & Lamb, 2011a). Only one study analysed female athletes (Alphin et al., 2020), and two studies included both female and male athletes (Beato et al., 2018a; Chahal et al., 2022), while the remaining studies only analysed male athletes.

Methodological quality

The results of the AXIS tool are presented in the Table 1 of the supplementary file. The overall quality score of the studies presented a mean of 13 of 17 points. Six studies presented a score of 15 (Akyildiz et al., 2022; Alphin et al., 2020; Chahal et al., 2022; Clavel et al., 2022; Johnston et al., 2014; Vantieghem-Nicolas et al., 2023), two studies presented a score of 14 (Johnston et al., 2012; Reinhardt et al., 2019), five studies presented a score of 13 (Beato et al., 2018b; Lacome et al., 2019; Mooney et al., 2011; Muñoz-Lopez et al., 2017; Nagahara et al., 2017), and the remaining five studies presented a score of 12 (Coutts & Duffield, 2010; Gray et al., 2010; Johnston et al., 2013; Waldron et al., 2011a; Waldron et al., 2011b). Because that score of 12 was the lower value of

Table 2 Study characteristics

Study	GPS model and brand	GPS characteristics	Comparator characteristics	*N*/Sport	Sex	Age (years)	Experimental protocol	Sprinting and/or peak speed	Validity outcomes	Reliability outcomes
Akyildiz et al. (2022)	10-Hz Polar Team Pro GPS (Polar Electro, Kempele, Finland)	10-Hz frequency (positioned chest and back)	Stalker Acceleration Test System (ATS) II radar device 50 Hz (Model: Stalker ATS II Applied concept, Dallas, TX, USA)	*N* = 32 trained soccer players	M	21.2 ± 3.2	Athletes performed Team Sport Simulation Cycle	Peak speed: > 20 km/h^{-1}	MAPE RMSE R^2	CV ICC
Alphin et al. (2020)	VX Sport GPS tracker (Wellington, New Zealand)	10-Hz frequency	ETG system (Freelap, Pleasanton, CA, USA)	*N* = 24 Collegiate lacrosse players	F	19.7 ± 1.2	Athletes performed 2 protocols: a) athletes sprinted the 20 m fly-in, and subsequent 80 m, and b) athletes sprinted the 20 m fly and subsequent 30 m	Peak speed: protocol a) 25.57 ± 1.46 km/h^{-1}, and b) 26.69 ± 1.26 km/h^{-1}	MAPE CCC R^2	–
Beato et al. (2018a)	GNSS (STATSports Apex, Newry, Northern Ireland)	Apex units: (dimension 30 mm (wide) × 80 mm (high), weight 48 g, 100-Hz gyroscope, 100-Hz triaxial accelerometer, and 10-Hz magnetometer)	Radar gun 34.7 GHz, Stalker ATS 2 (Stalker Sports Radar, Plano, TX, USA)	*N* = 20, University students	M F	21 ± 2	Athletes performed 2 protocols: a) specific team sports circuit of 128.5 m; b) sprint 20 m distance	Peak speed: Apex 10 Hz: 26.51 ± 2.3 km/h^{-1} Apex 18 Hz: 26.55 ± 2.6 km/h^{-1}	BIAS Absolute error	ICC TEM
Beato et al. (2018b)	Viper units (STATSports, Newry, Northern Ireland)	10-Hz frequency; triaxial accelerometer	Radar gun 34.7 GHz Stalker ATS 2 (Stalker Sports Radar, Plano, TX, USA)	*N* = 20, Team Sports	M	21 ± 2	Athletes performed 3 protocols: 400 m athletics track; specific teams sport circuit and 20 m sprint	Peak speed = 26.3 ± 2.4 km/h^{-1}	BIAS Absolut error CI (90%) Hopkins' Spreadsheet Linear Regression	TEM CV
Coutts and Duffield (2010)	1 Hz SPI-10 1 Hz SPI Elite 1 Hz WiSPI (GPSports, Canberra, Australia)	1-Hz frequency	GPS 2 SPI-10, 2 SPI Elite, and 2-WiSPI (GPSports, Canberra, Australia)	*N* = 2, Team Sports	M	32 ± 2	Athletes performed 8 trials of simulated team sport circuit	Sprint > 20 km/h^{-1}	ANOVA with Scheffe	CV CI
Chahal et al. (2022)	10-Hz Catapult GNSS (S5 OptimEye, Catapult Innovations, Melbourne, Australia)	10-Hz frequency	2 video cameras at 60 Hz	*N* = 13, Active participants	M F	21.6 ± 1.6	Athletes performed a sprint 45.72 m distance	Peak speed = 26.1 ± 1.8 km/h^{-1}	One sample *t*-tests Wilcoxon signed-rank test	ICC SEM
Clavel et al. (2022)	10-Hz GPS (Vector S7, Catapult Innovations, Melbourne, Australia)	10-Hz frequency	Radar gun 46.875 Hz (Stalker Pro II Sports Radar Gun, Plano, TX)	*N* = 16, U18 Rugby	M	–	Athletes performed 2 sprints of 50 m with at least 5 min recovery between each trial	Peak speed = 31.7 ± 3.78 km/h^{-1}	Bland Altman TEE Pearson's *r*	ICC CV

Table 2 (Continued)

Study	GPS model and brand	GPS characteristics	Comparator characteristics	*N*/Sport	Sex	Age (years)	Experimental protocol	Sprinting and/or peak speed	Validity outcomes	Reliability outcomes
Gray et al. (2010)	1 Hz WiSPI elite (GPSports, Canberra, Australia)	1-Hz frequency	Total station EDM/theodolite (Set 5A, Sokkia Co. Ltd., Japan)	*N* = 1, Team Sports	M	25	Athletes performed 5 trials of 200 m linear and nonlinear courses	Sprint = 25.2–28.8 km/h^{-1}	Bland Altman BIAS LoA Pearson's *r*	CV
Johnston et al. (2014)	Catapult MinimaxX (Minimax S4, 10 Hz, Firmware 6.70, Catapult Innovation Melbourne, Australia)	ND	15-Hz SPI-ProX (firmware, V2.4.3, GPSports, Canberra, Australia)	*N* = 8, Team Sports	M	26.1 ± 4.1	Athletes performed 2 testing days in the team Sport Simulation Circuit	Peak speed (22.98 ± 2.08; 22.99 ± 2.14 km/h^{-1}, respectively) Sprint > 20 km/h^{-1}	Pearson's *r*	ICC TEM
Johnston et al. (2012)	Catapult MinimaxX (Team Sport 2.5,5hz, Firmware 6.54, Catapult Innovations, Melbourne, Australia)	5 Hz frequency; triaxial accelerometer	Radar gun 48 Hz Stalker ATS II (Stalker Sports Radar, Plano, TX, USA)	*N* = 9, Team Sports	M	28.9 ± 9.5	Athletes performed 10 50 m effort and 10 trials of the team sport simulation circuit	Sprint > 25 km/h^{-1}	–	ICC TEM
Johnston et al. (2013)	Catapult MinimaxX® units (Catapult Innovations, Melbourne, Australia)	10-Hz Catapult MinimaxX® S4 (Firmware 6.70) 5-Hz MinimaxX S3 (Firmware 6.70)	Timing lights (Swift Performance Equipment, Lismore, Australia)	*N* = 8, trained men	M	26.1 ± 4.1	Athletes complete either one or two trials in a team sport simulation circuit	Peak speed: MinimaxX Unit 5 Hz: 24.28 ± 1.54 km·h^{-1} MinimaxX Unit 10 Hz: 23.96 ± 1.62 km·h^{-1}	Pearson's *r*	ICC TEM
Lacome et al. (2019)	GPS unit (Sensoreverywhere V2 GPS units, Digital simulation, Paris, France)	16-Hz frequency	Radar device 48 Hz Stalker ATS II (Stalker Sports Radar, Plano, TX, USA)	*N* = 15 Elite Rugby sevens	M	26 ± 5	Athletes performed 5 sprints over 40 m interspersed with five minutes of passive recovery	Peak speed: 33.12 km h^{-1}	TEE LoA	SWC TEM CV ICC
Mooney et al. (2011)	GPS device (1-Hz SPI Elite; GPSports, Canberra, Australia)	1-Hz frequency	Radar device Stalker Pro (Applied Concepts, Inc., Plano, TX, USA)	Validity: *N* = 17, Reliability: *N* = 26, soccer	M	Validity: 23 ± 2 Reliability: 22 ± 4	Validity: Athletes performed 5 sprints over 80 m separated by 3–5 min Reliability: Athletes performed 5 sprints over 80 m separated by 3–4 min of passive recovery	Peak speed: 29.2 ± 2.1 km h^{-1}	Pearson's *r*	ICC CV
Muñoz-Lopez et al. (2017)	WIMU-GPS (Quiko, Realtrack Systems Almeria, Spain)	5-Hz frequency	Dual-beam electronic timing gate OptoJump System (Polifemo Radio Light, Microgate, Bolzano, Italy)	*N* = 2, Team Sports	M	28.5 ± 2.1	Athletes performed 2 Team Sport Simulation Circuits	Peak speed Circuit: 29.02 ± 6.69 10-m: 22.13 ± 7.21 30 m: 28.99 ± 9.40 km/h^{-1}	R^2 BIAS	ICC

Table 2 (Continued)

Study	GPS model and brand	GPS characteristics	Comparator characteristics	*N*/Sport	Sex	Age (years)	Experimental protocol	Sprinting and/or peak speed	Validity outcomes	Reliability outcomes
Nagahara et al. (2017)	GPS unit (GPEXE, Exelio srl, Udine, Italy) GPS units (SPI proX; Gpsports, Canberra, Australia)	20-Hz GPEXE 5-Hz Spi proX	Radar device 50-Hz Stalker ATS II (Stalker Sports Radar, Plano, TX) Laser system 100 Hz LDM 301 (Jenoptik, Jena, Germany)	*N* = 32, Soccer and Rugby	M	20.0 ± 2.2	Athletes performed 2 protocols: a) athletes performed six to nine > 30 m sprints b) athletes performed one to five > 30 m sprints	Peak speed: GPEXE: 32.25 ± 2.01 km h^{-1} Spi proX: 30.45 ± 2.84 km h^{-1}	Pearson's *r* TEM	–
Reinhardt et al. (2019)	Polar Team Pro sensor (PTPS, Polar Electro, Kempele, Finland)	PTPS from a 10-Hz GPS with a 200-Hz microelectromechanical system consisting of a tri-axial accelerometer, gyroscope, and magnetometer	Timing Gates	*N* = 34, Soccer	M	20 ± 4	Athletes performed 1 linear sprint over 20 m distance	Peak speed zones: > 20 km h^{-1}	Pearson's *r* RMSE	–
Roe et al. (2017)	Catapult Optimeye S5, Catapult Innovation, Melbourne, Australia	10-Hz frequency	Infrared timing gate system (Brower timing systems, IR ENIT, Draper, UT, USA) Radar device Stalker ATS II (Stalker Sports Radar, Plano, Dallas, TX, USA)	*N* = 9, Rugby	M	19 ± 0.8	Athletes performed 3 trials of 40 m distance	Peak speed (Catapult Openfield software) = 31.5 ± 1.9 Peak speed (Catapult Sprint software) = 31.3 ± 2.0	TEE Pearson's r	–
Vantiegh Nicolas et al. (2023)	50 Hz GPS (K-Sport)	50 Hz frequency	Radar device Stalker ATS II (Stalker Sports Radar, Plano, Dallas, TX, USA)	*N* = 20, Soccer players and physical education students	M F	20 ± 6	Athletes performed 30 m sprints with 3 min recovery between each sprint	Peak speed: > 22.56 km h^{-1}	Bland Altman TEE Pearson's *r*	CV ICC
Waldron et al. (2011a)	GPS units (GPSports, SPI-Pro, Canberra, Australia)	5 Hz frequency (size = 90 × 45 × 5 mm; mass = 86 g; 6 g tri-axial accelerometer sampling at 100-Hz)	Infrared timing gates (Brower Timing Systems, Draper, UT, USA)	*N* = 19, Rugby	M	14.7 ± 0.5	Participants performed 3 maximal sprint efforts at each sprint interval (10 m, 20 m, and 30 m), separated by 3 min of passive recovery	Peak speed: 24.98 ± 1.97 km h^{-1}	Pearson's *r* LoA R^2	CV
Waldron et al. (2011b)	GPS device (5-Hz; GPSports, Canberra, Australia)	5-Hz frequency (size = 90 × 45 × 5 mm; mass = 86 g; 6 g tri-axial accelerometer sampling at 100-Hz)	Infrared timing gates system (Brower Timing Systems, Draper, UT, USA)	*N* = 60 Soccer and Rugby	M	14.2 ± 0.7	Athletes performed 1 linear maximal sprint of 30 m distance	Peak speed: 20.8 ± 1.35 km·h^{-1}	LoA Pearson's *r*	–

M male, *F* female, *GPS* global positioning system, *MAPE* mean absolute percent error, *CCC* Lin's concordance correlation coefficient, R^2 Bland–Altman correlation coefficient, *ICC* intraclass correlation, *TEM* technical error of measurement, *CV* coefficient of variation, *CI* confidence interval, *TE* technical error, *TEE* typical error of estimate, *SWC* smallest worthwhile change, *LoA* limits of agreement, *RMSE* root-mean square error, *EDM* electronic distances meters all assessments, we considered that the quality of the studies was good.

Results of individual studies: concurrent validity of GPS for measuring intense running and peak speed

The synthesis of the results regarding the concurrent validity of GPS for the estimation of sprinting or peak speed performance can be found in ▪ **Table 3**. Among the studies, five did not present validity for sprinting and peak speed performance (Akyildiz et al., 2022; Chahal et al., 2022; Johnston et al., 2014; Lacome et al., 2019; Waldron et al., 2011a). One study proved to be valid in linear movements and nonvalid in nonlinear movements (Gray et al., 2010). The remaining studies presented validity for sprinting and peak speed performance (Alphin et al., 2020; Beato et al., 2018a; Beato et al., 2018b; Chahal et al., 2022; Johnston et al., 2013; Mooney et al., 2011; Muñoz-Lopez et al., 2017; Nagahara et al., 2017; Reinhardt et al., 2019; Roe et al., 2017; Vantieghem-Nicolas et al., 2023; Waldron et al., 2011b). Information about evidence (valid or not) comes from the conclusions of the articles included in ▪ **Table 3**.

Results of individual studies: reliability of GPS for measuring intense running and peak speed

The synthesis of results about the reliability of GPS for the estimation of sprinting or peak speed performance can be found in ▪ **Table 4**. Among the studies, five did not present reliability for sprinting and peak speed performance (Akyildiz et al., 2022; Chahal et al., 2022; Johnston et al., 2012; Mooney et al., 2011; Waldron et al., 2011b). One study proved to be reliable for peak speed but not for sprint (Coutts & Duffield, 2010). The remaining studies presented reliability (Beato et al., 2018a; Clavel et al., 2022; Gray et al., 2010; Johnston et al., 2013; Johnston et al., 2014; Lacome et al., 2019; Muñoz-Lopez et al., 2017; Vantieghem-Nicolas et al., 2023; Waldron et al., 2011a). Only one study did not report reliability values (Waldron et al., 2011b). Information about evidence (reliable or not) comes from the conclusions of the articles included in ▪ **Table 4**.

▪ **Table 5** presents the main information about validity and reliability of the different GPS.

Discussion

The aim of this systematic review was to identify and summarize studies that have examined the concurrent validity and reliability of microelectromechanical devices for measuring intense running and peak speed performance. Regarding validity, 15 GPS were considered valid while one was also considered valid in linear movements but nonvalid in nonlinear movements. Moreover, 11 GPS were considered reliable, while one was also reliable for peak speed but nonreliable for sprint.

The use of GPS technologies allows the quick quantification of different measures during matches or training sessions, such as total distance, different intensity running thresholds, accelerations, decelerations, player load, metabolic power, and others. Considering the relevance of ensuring a summary of evidence about the concurrent validity and reliability of different models and brands for monitoring intense running and peak speed performance, this systematic review aimed to identify and summarise studies that have examined the concurrent validity and reliability of microelectromechanical devices (GPS) for measuring intense running and peak speed performance. The equipment traditionally used as a criterion for the assessment of the validity of GPS in the measurement of sprint performance and peak speed are reference methods that measure either the athletes' displacement (e.g. infrared timing gates) or velocity (e.g. radar and laser systems) as a function of time (Haugen & Buchheit, 2016), which provides reliable measurements of sprint performance over short (10 m) intervals (Cronin & Templeton, 2008; Duthie, Pyne, Ross, Livingstone, & Hooper, 2006). To avoid and isolate the bias that human biological variability could create in the analysis of the validation and accuracy of the equipment, the studies simultaneously use standard equipment and the equipment under validation to assess performance.

To discuss the evidence about the validity and reliability of GPS technology regarding intense running and peak speed performance in outdoor and indoor environments, this section will be organised according to the articles that tested the validity (Section "Concurrent validity of GPS for measuring sprinting performance") and reliability (Section "Reliability of GPS for measuring sprinting performance") of the GPS. Information about the validity, accuracy and reliability of the GPS is extremely important for better data collection and consequently, better interpretation of the results.

Concurrent validity of GPS for measuring sprinting performance

GPS with different sampling frequencies were compared with: electronic timing gates (ETG) in 5 studies, some radar devices in 7 studies, a motion capture system in 2 studies, an infrared timing system in 1 study, radar devices and electronic distance meters (EDM) equipment in 1 study, radar devices and ETG in one, electronic theodolites and EDM equipment in 1 study, and GPS at different sampling frequency of 1 Hz in 1 study and at 15 Hz in 1 study.

Among the included studies, participants performed different types of movements and distances repeated several times, such as maximal acceleration and decelerations, sprint, sports-specific movements, over a linear and nonlinear course with distances between 20 and 50 m and up to 200 m and simulated specific team sports running circuit up to 128.5 m, with and without a standing start. Five studies have reported a lack of validity of GPS equipment in nonlinear movements (Akyildiz et al., 2022; Gray et al., 2010; Johnston et al., 2014; Lacome et al., 2019; Waldron et al., 2011b).

Different conditions were used. Trials were carried out on flat hard ground, synthetic surface, or grass field. Four studies used synthetic/artificial turf soccer pitches (Akyildiz et al., 2022; Muñoz-Lopez et al., 2017; Reinhardt et al., 2019; Vantieghem-Nicolas et al., 2023), one a 400 m athletic track (Beato et al., 2018b),

Table 3 Concurrent validity of GPS for estimating intense running and peak speed performance

Study	GPS brand and model	Correlation coefficient	Evidence (Valid or not)
Akyildiz et al. (2022)	10-Hz Polar Team Pro GPS (Polar Electro, Kempele, Finland)	Chest MAPE (%): 9.4 RMSE: 2.87 R^2: 0.08 Back MAPE (%): 9.1 RMSE: 2.71 R^2: 0.09	Not valid
Alphin et al. (2020)	10-Hz VX Sport GPS tracker (Wellington, New Zealand)	80-m test: c = 0.891 (0.776, 0.948) and $p < 0.001$ 30-m test: pc = 0.808 (0.660, 0.896) and $p = 0.032$	Valid
Beato et al. (2018a)	GNSS 10 Hz Apex (STATSports, Northern Ireland)	$p = 0.32$ ES = 0.08 (–0.05, 0.22)	Valid
Beato et al. (2018a)	GNSS 18 Hz Apex (STATSports, Newry, Northern Ireland)	$p = 0.064$ ES = 0.08 (0.01, 0.15)	Valid
Beato et al. (2018b)	10-Hz Viper (STATSports, Newry, Northern Ireland)	Peak speed Absolute error = 0.40 ± 0.45 BIAS (%) = 1.80 ± 1.93 R = 0.98	Valid
Chahal et al. (2022)	10-Hz Catapult GNSS (S5 OptimEye, Catapult Innovations, Melbourne, Australia)	Nonextractable data	Not valid in distance and speed measurements
Clavel et al. (2022)	10-Hz GPS (Vector S7, Catapult Innovations, Melbourne, Australia)	Peak speed BIAS (%) = 0.28 (–0.63 to 0.07) TEE (%) = 1.7 (1.4 to 2.0) $r = 0.96$	Valid
Gray et al. (2010)	1-Hz WiSPI elite (GPSports, Canberra, Australia)	Nonextractable data	Valid in linear movements Nonvalid in nonlinear movements
Johnston et al. (2014)	10 Hz MinimaxX® S4 (Firmware 6.70, Catapult innovation, Melbourne, Australia) 15-Hz SPI-ProX (GPSports, firmware, V2.4.3, Canberra, Australia)	Peak speed $r = 0.89$ $r = 0.91$	Nonvalid Higher validity in 10-Hz GPS than in 15-Hz GPS
Johnston et al. (2013)	5-Hz MinimaxX S3 (Firmware 6.70, Catapult, Melbourne, Australia)	Peak speed: MinimaxX Unit 5 Hz: $r = 0.91$	Valid
Johnston et al. (2013)	10-Hz MinimaxX® S4 (Firmware 6.70, Catapult, Melbourne, Australia)	Peak speed: MinimaxX Unit 10 Hz: $r = 0.89$	Valid
Lacome et al. (2019)	16-Hz Sensoreverywhere V2 GPS (Digital simulation, Paris, France)	LoA = 1.07 TEE (%) = 2.03	Not valid
Mooney et al. (2011)	1-Hz SPI Elite (GPSports, Canberra, Australia)	$r = 0.93$	Valid
Muñoz-Lopez et al. (2017)	WIMU-GPS (Quiko, Realtrack Systems Almeria, Spain)	Team Sport Simulation Circuit A = 0.0 ± 1.68 (–3.29; 3.29, 95%LOA) 10-m sprint = 0.0 ± 0.53 (–1.04; 1.04, 95%LOA) 30-m sprint = 0.0 ± 0.76 (–1.49; 1.49, 95%LOA)	Valid
Nagahara et al. (2017)	20-Hz GPEXE (Exelio srl, Udine, Italy)	$r = 0.354$ $p = 0.005$	Valid
Nagahara et al. (2017)	5-Hz SPI proX (GPSports, Canberra, Australia)	$r = 0.794$ $p < 0.001$	Valid
Reinhardt et al. (2019)	10-Hz Polar Team Pro sensor (Polar Electro, Kempele, Finland)	$r = 0.74$	Valid
Roe et al. (2017)	Catapult Optimeye S5 (Catapult innovation, Melbourne, Australia)	Radar gun and GPS (Catapult Openfield Software) = 0.95 Radar gun and GPS (Catapult Sprint Software) = 0.96	Valid

Table 3 (Continued)

Study	GPS brand and model	Correlation coefficient	Evidence (Valid or not)
Vantieghem-Nicolas et al. (2023)	50 Hz GPS (K-Sport)	Peak speed GPS 1 BIAS (%) 0.11 TEE (%) = 1.9 $r = 0.99$ GPS 2 BIAS (%) −0.49 TEE (%) = 1.6 $r = 0.99$	Valid
Waldron et al. (2011a)	5-Hz SPI-Pro (GPSports, Canberra, Australia)	Peak speed 20 m sprint, LoA = 2.19 30 m sprint, LoA = 2.01	Not valid
Waldron et al. (2011b)	5-Hz SPI-Pro (GPSports, Canberra, Australia)	$r = 0.85$ $p < 0.005$	Valid

ES effect size, R^2 Bland–Altman correlation coefficient, *TEM* technical error of measurement, *LoA* limits of agreement, *GPS* global positioning system, *MAP* mean absolute percentage, *RMSE* root mean square error, *TEE* typical error of estimate

and 14 flat grass fields (Alphin et al., 2020; Beato et al., 2018a; Chahal et al., 2022; Clavel et al., 2022; Coutts & Duffield, 2010; Gray et al., 2010; Johnston et al., 2013; Johnston et al., 2014; Lacome et al., 2019; Mooney et al., 2011; Nagahara et al., 2017; Roe et al., 2017; Waldron et al., 2011a; Waldron et al., 2011b). None of the studies reported the influence of the floor surface on the recorded measurements.

Moreover, the studies included in this systematic review presented different methods to analyse validity. For instance, 18 studies had validity in the model used to test the validity of the findings. However, the GPS equipment 5 Hz GPSports (SPI-Pro) when opposed to the timing gates system (Waldron et al., 2011b) did not have validity, as did the 16 Hz GPS Sensoreverywhere V2 when opposed to a radar device (Lacome et al., 2019). The device 1 Hz Wi SPI Elite (GPSports) only presented validity in linear movements when opposed to the Total Station EDM/theodolite (Gray et al., 2010). In addition, the same study reinforced that path linearity and movement intensity appear to affect GPS distance accuracy in sprinting on a 200 m nonlinear course by linear movements and their intensity (Gray et al., 2010). The 1 Hz Wi SPI Elite (GPSports) model also showed a strong association and concurrent validation in linear paths with radar device (Mooney et al., 2011).

Contrary to the recommendations that a higher frequency sample acquisition increases the validity of the measures, it was revealed that the 10 Hz MinimaxX S4 Catapult device was not a device to measure peak speed (Johnston et al., 2014). This result was also supported when examining a 5-Hz SPI-Pro GPSports unit (Waldron et al., 2011b). However, these findings contrasted with the literature by showing a < 10% error ($p > 0.05$) for the validity of 1 and 5 Hz GPS units for measuring peak speed (Coutts & Duffield, 2010; Johnston et al., 2012; Mooney et al., 2011; Nagahara et al., 2017). The model 10 Hz Optimeye S5 Catapult to assess validity against a gold standard radar gun during the 40 m maximum sprint velocity provided a valid measure (Roe et al., 2017). Differences between investigations may be associated with test protocols or differences in sampling rate. Accordingly, these differences may be a consequence of the use of timing lights to measure the average peak speed score. In addition, the authors further argued that the location of time lights at 10 m intervals could have influenced the results. For that reason, it was suggested to use 5 m intervals for time lights to better analyse the speed profile of the participants (Johnston et al., 2014).

Higher acquisition rates appear to favour the validity of the measures. In this sense, the peak speed measured by the 10 and 18 Hz Apex STATSports units reported a 1–2% error compared with the criterion distances during the 20 m trials. Both Apex devices could be used with validity to measure these variables during matches or training sessions (Beato et al., 2018a). Other authors reported that a higher sampling frequency had concurrent validity for maximal sprint derived from 20 Hz GPS measurements (versus references devices, radar, or laser) than 5 Hz GPS units (Nagahara et al., 2017). Moreover, Muñoz-Lopez et al. (2017) stated that the 5 Hz GPS system (WIMU) is valid for measuring intense running (> 20 km·h⁻¹).

The 10 Hz VX Sport GPS model used to analyse validity showed a lower mean bias and mean absolute percent error of the GPS for the 80 m test than the 30 m test (Alphin et al., 2020). In an equivalence test, the GPS proved to be similar for both short and long distances, with both results being presented in an interval of 5% (Alphin et al., 2020). In addition, small errors of less than 5%, classified as good, were found for peak speed measured by the 10 Hz Viper Units; STATSports (Beato et al., 2018b). The 10 Hz GPS Polar Team Pro System also did not differ from the criterion equipment (timing gates) and the GPS for the 10 and 20 m trials (Reinhardt et al., 2019).

From the systems tested (e.g. VX Sport GPS tracker; Viper units STATSports; Apex unit STATSports; SPI-10, SPI Elite and Wi SPI GPSports; UWB Kinexon;

Table 4 Reliability of GPS for estimating intense running and peak speed performance

Study	GPS brand and model	Intraclass correlation coefficient [ICC] %TEM	Coefficient of variation [CV] (%)	Standard error of measurement [SEM]	Evidence (Reliable or not)
Akyildiz et al. (2022)	10-Hz Polar Team Pro GPS (Polar Electro, Kempele, Finland)	Chest ICC = 0.43 Back ICC = 0.49	Chest CV = 9.77 Back CV = 9.08	–	Not reliable
Beato et al. (2018a)	10 Hz GNSS Apex STATSports (Northern Ireland)	ICC = 0.96 (0.92, 0.98)	–	–	Reliable
Beato et al. (2018a)	18-Hz GNSS Apex, STATSports (STATSports™, Newry, Northern Ireland)	ICC = 0.98 (0.96,0.99)	–	–	Reliable
Beato et al. (2018b)	10-Hz Viper, STATSports (Newry, Northern Ireland)	–	Typical error CV = 0.7 (0.5–0.9)	–	Reliable
Coutts and Duffield (2010)	1-Hz SPI-10, 1-Hz SPI Elite 1-Hz WiSPI GPSports (Canberra, Australia)	–	SPI-10 Sprint = 30.4 (22.8–46.4) Peak speed = 5.8 (5.2–6.6) SPI Elite Sprint = 15.4 (11.7–22.9) Peak speed = 2.3 (2.1–6.6) WiSPI Sprint = 11.5 (11.5–25.4) Peak speed = 4.9 (4.3–5.7)	–	Reliable for peak speed Not reliable for sprint
Chahal et al. (2022)	10-Hz Catapult GNSS (S5 OptimEye, Catapult Innovations, Melbourne, Australia)	Distance ICC = 0.13 (–0.02, 0.55) Peak speed ICC = 0.32 (0.10, 0.73)	–	Distance SEM: 8.8 m Speed SEM: 1.3 m/s	Not reliable
Clavel et al. (2022)	10-Hz GPS (Vector S7, Catapult Innovations, Melbourne, Australia)	Peak speed ICC = 0.99 (0.98 to 1.00)	Peak speed = 0.5 (0.4 to 0.7)	–	Reliable
Gray et al. (2010)	1-Hz WiSPI elite (GPSports, Canberra, Australia)	–	Linear sprint intrareceiver = 2.71 Linear sprint interreceiver = 3.38 Nonlinear sprint intrareceiver = 4.8 Nonlinear sprint interreceiver = 6.04	–	Reliable
Jonhston et al. (2014)	10-Hz MinimaxX S4 (Catapult Innovation, Firmware 6.70, Melbourne, Australia) 15-Hz SPI-ProX (firmware, V2.4.3, GPSports, GPSports, Canberra, Australia)	Team Sports Simulation Circuit Peak speed ICC = 0.97 (%TEM = 1.6) Sprint > 20 km/h^{-1} = 0.89 (%TEM = 11.5)	–	–	Reliable
Johnston et al. (2012)	5-Hz MinimaxX Team Sport 2.5 (Catapult, Firmware 6.54, Catapult Innovations, Melbourne, Australia)	ICC Team Sport Simulation Circuit = 0.38 50 m Effort = 0.21 %TEM Team Sport Simulation Circuit = 112.0 50 m Effort = 59.3	–	–	Not reliable
Johnston et al. (2013)	5-Hz MinimaxX S3 (Firmware 6.70, Catapult Innovations, Melbourne, Australia)	ICC = 0.94	–	–	Reliable
Johnston et al. (2013)	10-Hz MinimaxX S4, Catapult (Firmware 6.70, Catapult Innovations, Melbourne, Australia)	ICC = 0.97	–	–	Reliable
Lacome et al. (2019)	16-Hz Sensoreverywhere V2 (Digital simulation, Paris, France)	ICC = 0.99	4.4%	–	Reliable

Table 4 (Continued)

Study	GPS brand and model	Intraclass correlation coefficient [ICC] %TEM	Coefficient of variation [CV] (%)	Standard error of measurement [SEM]	Evidence (Reliable or not)
Mooney et al. (2011)	1-Hz SPI Elite; (GPSports, Canberra, Australia)	ICC = 0.57	4.1%	–	Not reliable
Muñoz-Lopez et al. (2017)	5-Hz WIMU (Quiko, Realtrack Systems Almeria, Spain)	Team Sport Simulation Circuit B = 0.976 Motorized sprint (36.17 Km/h^{-1}) = 0.991	–	–	Reliable
Vantieghe Nicolas et al. (2023)	50 Hz GPS (K-Sport)	ICC = 0.99	1.6%	–	Reliable
Waldron et al. (2011a)	5-Hz SPI-Pro, (GPSports, Canberra, Australia)	–	Peak speed 20 m sprint = 2.02% 30 m sprint = 1.92%	–	Reliable

R^2 Bland–Altman correlation coefficient, *ICC* intraclass correlation, *TEM* technical error of measurement, *CV* coefficient of variation, *CI* confidence interval, *TE* technical error, *TEE* typical error of estimate

5 Hz MinimaxX S3, 10 Hz MinimaxX S4, 10 Hz Optimeye S5, Catapult; 1 Hz SPI Elite, 15 Hz SPI-ProX, 1 Hz Wi SPI GPSports; 5 Hz GPS WIMU; 20 Hz GPS GPEXE; Polar Team Pro sensor, 50 Hz GPS K-Sport), all revealed a mean error below 5% in the measurement sprinting performance (1 Hz Wi SPI Elite GPSports valid only in linear movements). It was evident that most studies present good and acceptable accuracy of GPS to estimate the sprinting performance achieved by players, although the decrease in accuracy could occur in nonlinear movements and at high intensities. However, the variety of criteria equipment used for validity comparisons can lead to differences between GPS, and these differences may be due to different sampling rate methods and data processing in the software. Considering the results of this systematic review, coaches, sports scientists, and practitioners should consider the validity of the GPS that they use or intend to use to monitor training sessions and competitions. These validation results can guide coaching staff concerning how to monitor your athletes and avoid using different devices interchangeably or exchange of portable units between athletes.

Reliability of GPS for measuring sprinting performance

To ensure consistency and allow comparisons over time and in a repeated way, testing the reliability of measurements collected through GPS devices is critical (Rico-Gonzalez, Arcos, Clemente, & Rojas-valverde, 2020). The reliability of the measures was tested to determine the within-subject variation, changes in the mean, and retest correlation (Hopkins, 2000). In the literature, the most common tests applied in reliability analysis are the typical error of measurement (TEM), CV and ICC (Bruton, Conway, & Holgate, 2000). According to the suggestions of Scott et al. (Scott et al., 2016), reliability can be interpreted as good for variability lower than 5%, moderate between 5 and 10%, and poor for 10% or above.

In this systematic review, 15 studies investigated reliability and 17 different GPS models. The following equipment was used in the studies: 10 Hz Polar Team Pro GPS (Akyildiz et al., 2022), 10 and 18 Hz Apex STATSports (Beato et al., 2018a), 10 Hz Viper STATSports (Beato et al., 2018b), SPI-10, SPI Elite, and 1 Hz Wi SPI GPSports (Coutts & Duffield, 2010), 1 Hz Wi SPI Elite, GPSports (Gray et al., 2010), 10 Hz MinimaxX S4 and 15 Hz SPI-ProX GPSports (Johnston et al., 2014), 10 Hz OptimEye S5 Catapult (Chahal et al., 2022), 10 Hz Vector S7 Catapult (Clavel et al., 2022), GPS5-Hz MinimaxX Team Sport 2.5 Catapult (Johnston et al., 2012), 5 Hz MinimaxX S3 and 10 Hz MinimaxX S4 Catapult (Johnston et al., 2013), 16 Hz V2 unit Sensoreverywhere (Lacome et al., 2019), 1 Hz SPI Elite GPSports (Mooney et al., 2011), 5 Hz GPS WIMU (Muñoz-Lopez et al., 2017), 50 Hz GPS K-Sport (Vantieghem-Nicolas et al., 2023) and 5 Hz SPI-Pro GPSports (Waldron et al., 2011a).

Among the studies, five did not present reliability for sprinting and peak speed performance (Akyildiz et al., 2022; Chahal et al., 2022; Johnston et al., 2012; Mooney et al., 2011; Waldron et al., 2011b). One study proved to be reliable for peak speed but not for sprint for all GPS models, 1 Hz SPI-10, 1 Hz SPI Elite GPSports, and 1 Hz Wi SPI GPSports (Coutts & Duffield, 2010). The study of Mooney et al. (2011) that used 1 Hz SPI Elite GPSports was not reliable. Although with a higher sampling rate, data from the 5 Hz SPI-Pro GPSports used in the study by Waldron et al. (2011b) were also not reliable. However, the reliability was strongest for 10 m and 20 m sprint speed. The authors reported that peak

Table 5 Summary of the validity and reliability of different GPS models

Studies	GPS brand and model	Validity	Reliability
Akyildiz et al. (2022)	10 Hz Polar Team Pro GPS (Polar Electro, Kempele, Finland)	Not valid	Not reliable
Alphin et al. (2020)	VX Sport GPS tracker (Wellington, New Zealand)	Valid	–
Beato et al. (2018a)	GNSS 10 Hz Apex, STATSports (Newry, Northern Ireland) GNSS 18 Hz Apex, STATSports (Newry, Northern Ireland)	Valid	Reliable
Beato et al. (2018b)	10 Hz Viper, STATSports (Newry, Northern Ireland)	Valid	Reliable
Chahal et al. (2022)	10 Hz Catapult GNSS (S5 OptimEye, Catapult Innovations, Melbourne, Australia)	Not valid	Not reliable
Clavel et al. (2022)	10 Hz GPS (Vector S7, Catapult Innovations, Melbourne, Australia)	Valid	Reliable
Coutts and Duffield (2010)	1 Hz SPI-10, GPS ports 1 Hz SPI Elite, GPS ports 1 Hz WiSPI, GPS ports (Canberra, Australia)	–	Reliable for peak speed Nonreliable for sprint
Gray et al. (2010)	1 Hz WiSPI elite, GPSports (Canberra, Australia)	Valid in linear movements Nonvalid in nonlinear movements	Reliable
Johnston et al. (2014)	10 Hz MinimaxX® S4 (Firmware 6.70, Catapult innovation, Melbourne, Australia) 15 Hz SPI-ProX GPSports (Firmware, V2.4.3, GPSports)	Valid	Reliable
Johnston et al. (2013)	5 Hz Catapult MinimaxX® S3 (Firmware 6.70)	Valid	Reliable
Johnston et al. (2013)	10 Hz Catapult MinimaxX® S4 (Firmware 6.70)	Valid	Reliable
Johnston et al. (2012)	5 Hz Minimax, X Catapult (Team Sport 2.5, Firmware 6.54, Catapult Innovations, Melbourne, Australia)	–	Not reliable
Lacome et al. (2019)	16 Hz (Sensoreverywhere V2 GPS units, Digital simulation, Paris, France)	Not valid	Reliable
Mooney et al. (2011)	1 Hz (SPI Elite; GPSports, Canberra, Australia)	Valid	Not reliable
Muñoz-Lopez et al. (2017)	5 Hz WIMU-GPS (Quiko, Realtrack Systems Almeria, Spain)	Valid	Reliable
Nagahara et al. (2017)	20 Hz (GPEXE, Exelio srl, Udine, Italy)	Valid	–
Nagahara et al. (2017)	5 Hz (SPI proX, GPSports, Canberra, Australia)	Valid	–
Reinhardt et al. (2019)	10 Hz Polar Team Pro sensor (PTPS, Polar Electro, Kempele, Finland)	Valid	–
Roe et al. (2017)	Catapult Optimeye S5 (Catapult innovation, Melbourne, Australia)	Valid	–
Vantieghem-Nicolas et al. (2023)	50 Hz GPS (K-Sport)	Valid	Reliable
Waldron et al. (2011a)	5 Hz (SPI-Pro, GPSports, Canberra, Australia)	Not valid	Reliable
Waldron et al. (2011b)	5 Hz (GPSports, Canberra, Australia)	Valid	–

speed over 30 m proved to be the most reliable measure. Some authors (Waldron et al., 2011b) stated that apparently, through GPS measurements, the athletes' true peak seep was never attained during the analysis, probably due to the very short distance of 30 m used in the experimental protocol. However, the authors stated that a total error of 0.8 $\text{km}\cdot\text{h}^{-1}$ provides a useful variable for detecting minor changes in performance.

Johnston et al. found that despite testing the interunit reliability of GPS units with high sampling rates, the 10 Hz MinimaxX S4 (Catapult) and the 15 Hz SPI-ProX (GPSports), it was clear that the 10 Hz GPS units, when compared with the 15 Hz GPS units, presented higher levels of interunit reliability for most of the analysed movements (including peak speed) (Johnston et al., 2014).

Another study did not show reliability in its measurements (Johnston et al., 2012). The authors studied the interreliability results for GPS as a measure of distance covered under two different exercise conditions. Although it was clear from the test condition of "50 m Effort" results that GPS gives a valid measure of peak speed, in contrast, the reliability of GPS as a measure of peak speed was less clear based on the analysis of the %TEM and ICC scores. The interreliability results for GPS as a measure of distance covered during sprinting in the test condition of "Team Sport Simulation Circuit" presented indicators of poor reliability. At the "50 m Effort" the ICC and the %TEM were considered to be of poor reliability. However, the interreliability results for GPS as a measure of average peak speed (unit 1: 21.79 ± 2.63 $\text{km}\cdot\text{h}^{-1}$; unit 2: 21.82 ± 2.03 $\text{km}\cdot\text{h}^{-1}$) present a moderate level of error (7.5%) and large ICC score (0.52). The authors speculated that the reported GPS error may have been caused by the path followed by each athlete in the execution of the "Team Sport Simulation Circuit" and by errors derived from the acquisition of GPS data, such as missing data, a loss of satellite lock or the varying number of satellites the GPS unit locked into during the testing.

According to previous research (Clemente, Akyildiz, & Pino-ortega,

2021) in studies that reported low reliability, the test conditions (movements and distances) in which the equipment was tested, the sample of subjects tested and biological differences should also be considered.

The remaining studies presented reliability (Beato et al., 2018a; Clavel et al., 2022; Gray et al., 2010; Johnston et al., 2013; Johnston et al., 2014; Lacome et al., 2019; Muñoz-Lopez et al., 2017; Vantieghem-Nicolas et al., 2023; Waldron et al., 2011a). According to a previous study (Coutts & Duffield, 2010), these results may indicate that new GPS models with higher acquisition sampling rates will generally appear to have greater reliability than older 1 Hz GPS models. The improved accuracy and reliability in the newer models may be attributed to custom algorithms that use data from an accelerometer with a higher acquisition sampling rate that corrects the shortcomings of 1 Hz GPS models. Additionally, the differences found in the results collected with different GPS devices indicate that they should not be used interchangeably when measuring high intensity running. For each of the low sampling acquisition rate models studied, the intramodel reliability for peak speed measures was low and the CV increased for the high-speed zones. The large CV found on all GPS devices analysed suggests that the sampling rate of 1 Hz may not be able to detect relevant changes in running distances at speeds $>20\,\mathrm{km}\cdot\mathrm{h}^{-1}$ (Coutts & Duffield, 2010; Mooney et al., 2011). Short sprints and movements such as acceleration performed at high speed and of very short duration occur in team sports; therefore, some data may not be recorded by GPS devices with a 1 Hz sampling rate (Coutts & Duffield, 2010). This fact may explain the poor level of reliability found in the measurement of movements performed at high intensity; thus, it is suggested that studies should examine the efficacy of using increased sampling rates to measure time–motion in team sports. This aspect was also mentioned previously (Johnston et al., 2012) for both 1 Hz units and 5 Hz units, which presented a poor degree of interreliability when measuring demands movement performed $>25\,\mathrm{km}\cdot\mathrm{h}^{-1}$. However, the results of these studies were not consensual. Other authors (Gray et al., 2010) described intrareceiver measurements with 1 Hz GPS (Wi SPI Elite GPSports) in linear sprints and nonlinear sprints as reliable. However, the same authors (Gray et al., 2010) also stated that despite the reliability of the GPS data having proved to be good in all trials, there was a decrease in reliability in movements performed at high intensity, especially sprinting.

Overall, GPS devices that are recorded at a sampling rate of 1 Hz may not provide accurate data for movements performed at high speed and on nonlinear paths (Coutts & Duffield, 2010; Gray et al., 2010). The nonlinear trajectory and intensity of the movement can significantly influence the reliability of distance estimation. Measurement of sprinting performance using GPS with a lower sampling acquisition rate demonstrates reduced reliability in nonlinear movement patterns as movement intensity increases. Thus, during periods of high-intensity nonlinear movement in team sports, multiple changes in direction during high-speed runs may reduce GPS reliability. The distance measured by GPS with a sampling rate of 1 Hz may be underestimated and may not meet an acceptable level of accuracy for some types of usage (Gray et al., 2010). It is difficult to analyse the discrepancies in the studies' results that used GPS units with the same sampling rate because of differences in the methodological procedures between the studies. The same goes for different frequencies to determine whether, for example, 5 or 1 Hz units give a more valid measure of sprinting performance.

In summary, GPS devices with low sampling rates may not have acceptable accuracy and reliability for most sprinting performance measures relevant to team and field sports that often demand brief, intermittent sprinting over nonlinear paths. Therefore, the coaching staff should be advised to take these aspects into account when interpreting information collected by this type of device.

Study limitations, future research and practical implications

The current study increases knowledge on the validity and reliability of GPS for determining intense running and peak speed performance in team sports. However, caution should be taken when using GPS because some limitations in both practical and technological aspects are known. Some changes in accuracy (measurement error) when tracking may be related to the distance of the signal to multiple satellites and the quality of satellite signals as they may be obstructed by the atmosphere and local environmental objects (e.g. stadiums and tall buildings) (Larsson, 2003; Scott et al., 2016). Barrier-free open spaces allow for better reception and the strongest signal. The number of satellites interacting with the GPS receiver appears to play an important role in determining the accuracy of position estimates (Misra & Enge, 2006). Furthermore, the positioning of satellites interacting with the receiver is also vital in determining the accuracy of measurements recorded by the receiver (Witte & Wilson, 2004) and improving the measurement known as the dilution of precision, which is determined by the quantification of the satellite's distribution across the horizon (Witte & Wilson, 2004). Regardless of sampling rate, coaches and practitioners should be aware of the limitations of earlier 1 and 5 Hz GPS units when interpreting distance during high-intensity running and sprinting.

First, the different methodological approaches, screening constraints and protocols applied in the reviewed studies make it difficult to compare results. Second, the related conditions of exercise testing, the movements and the distances in which the equipment was tested, and the criterion reference device are different from study to study. Third, the data that is transferred to software applications by the algorithms used by the GPS could also influence the interpretations of the results. It should also be considered the different samples of subjects tested and biological differences. Finally, conditions of pseudo replication by the participants may impact the results of the analysed studies. As a future research direction, conducting a meta-analysis could provide a more comprehensive and statistically significant interpretation of the different validity and reliability indicators reported in various studies, offering a unified perspective on the performance of GPS systems.

Some examples of how GPS can be used in the sport context are through tracking the player's sprints and total distance covered, which allows the coaching staff to determine the quantification of the imposed training load and whether that player is fit for their next match or could benefit from recovery. However, GPS is not only used to track a player's health and fitness. The value of the data collected through these electronic performance and tracking system devices goes beyond that. Test criteria were developed following medical and mechanical research, and there are currently test protocols reflecting possible injury scenarios that should be avoided.

For sports scientists and practitioners, this study suggests there are various aspects to consider when measuring intense running and peak speed via GPS technology. However, future studies are needed to analyse and compare whether higher sampling frequencies improve the validity and reliability of such measures. Regarding practical applications and validity and reliability, **Table 5** presents a summary of the valid and reliable GPS.

Conclusions

This systematic review summarises evidence of the validity and reliability of GPS for measuring intense running and peak speed performance. A total of 16 studies in this systematic review investigated validity. The GPS models 16 Hz Sensoreverywhere V2 (Digital simulation), 1 Hz WiSPI Elite (GPSports; nonvalid in nonlinear movements), 5 Hz SPI-Pro (GPSports), 10-Hz MinimaxX S4 (Catapult), 15 Hz SPI-ProX (GPSports), 10-Hz Team Pro GPS (Polar), 10 Hz OptimEye S5 (Catapult) have been reported as not achieving validity in some studies. The following devices were reported to not be reliable: 10 Hz Apex STATSports, 1 Hz Wi SPI Elite GPSports, 10 Hz MinimaxX S4 Catapult; 15 Hz SPI-ProX GPSports, 16 Hz V2 Sensoreverywhere, 5 Hz GPS WIMU, 10 Hz Polar Team Pro GPS, 10 Hz OptimEye S5 Catapult and 5 Hz SPI-Pro GPSports.

Although there is no consensus among studies, the measurement of intense running in GPS with lower sampling rate acquisition demonstrated reduced validity and reliability in nonlinear movement patterns and also as movement intensity increases.

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Declarations

Conflict of interest. H. Nobari, A.D. Martins, J.P. Brito, E. Mainer-Pardos, P. Valdés-Badilla and R. Oliveira declare that they have no competing interests.

For this article no studies with human participants or animals were performed by any of the authors. All studies mentioned were in accordance with the ethical standards indicated in each case.

References

Akyildiz, Z., Alvurdu, S., Ceylan, H. I., & Clemente, F. M. (2022). Validity and reliability of 10 Hz GPS sensor for measuring distance and maximal speed in soccer: Possible differences of unit positioning. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *0*(0), 17543371221098888. https://doi.org/10.1177/17543371221098888.

Alphin, K. L., Sisson, O. M., Hudgins, B. L., Noonan, C. D., & Bunn, J. A. (2020). Accuracy assessment of a gps device for maximum sprint speed. *International Journal of Exercise Science*, *13*(4), 273–280.

Andrzejewski, M., Chmura, J., Pluta, B., Strzelczyk, R., & Kasprzak, A. (2013). Analysis of sprinting activities of professional soccer players. *Journal of Strength and Conditioning Research*, *27*(8), 2134–2140. https://doi.org/10.1519/JSC.0b013e318279423e.

Barbero-Álvarez, J. C., Coutts, A., Granda, J., Barbero-Álvarez, V., & Castagna, C. (2010). The validity and reliability of a global positioning satellite system device to assess speed and repeated sprint ability (RSA) in athletes. *Journal of Science and Medicine in Sport*, *13*(2), 232–235. https://doi.org/10.1016/j.jsams.2009.02.005.

Beato, M., Coratella, G., Stiff, A., & Dello, I. A. (2018a). The validity and between-unit variability of GNSS units (STATSports apex 10 and 18 Hz) for measuring distance and peak speed in team sports. *Frontiers in Physiology*, *9*, 1–8. https://doi.org/10.3389/fphys.2018.01288.

Beato, M., Devereux, G., & Stiff, A. (2018b). Validity and reliability of global positioning system units (STATsports viper) for measuring distance and peak speed in sports. *Journal of Strength and Conditioning Research*, *32*(10), 2831–2837. https://doi.org/10.1519/JSC.0000000000002778.

Bruton, A., Conway, J.H., & Holgate, S.T. (2000). Reliability: What is it Measured?', how is it. *Physiotherapy*, *86*(2), 94–99. https://doi.org/10.1016/S0031-9406(05)61211-4.

Chahal, A. K., Lim, J. Z., Pan, J.-W., & Kong, P. W. (2022). Inter-unit consistency and validity of 10-Hz GNSS units in straight-line sprint running. *Sensors*. https://doi.org/10.3390/s22051888.

Clavel, P., Leduc, C., Morin, J.-B., Owen, C., Samozino, P., Peeters, A., Buchheit, M., & Lacome, M. (2022). Concurrent validity and reliability of sprinting force-velocity profile assessed with GPS devices in elite athletes. *International Journal of Sports Physiology and Performance*, *17*(10), 1527–1531. https://doi.org/10.1123/ijspp.2021-0339.

Clemente, F. M., Akyildiz, Z., & Pino-ortega, J. (2021). Validity and reliability of the inertial measurement unit for barbell velocity assessments : a systematic review. *Sensors*, *21*(7), 1–19. https://doi.org/10.3390/s21072511.

Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of Science and Medicine in Sport*, *13*(1), 133–135. https://doi.org/10.1016/j.jsams.2008.09.015.

Crang, Z. L., Duthie, G., Cole, M. H., Weakley, J., Hewitt, A., & Johnston, R. D. (2020). The validity and reliability of wearable microtechnology for intermittent team sports: a systematic review. *Sports Medicine*. https://doi.org/10.1007/s40279-020-01399-1.

Cronin, J. B., & Templeton, R. L. (2008). Timining light height affects sprint times. *Journal of Strength and Conditioning Research*, *22*(1), 318–320. https://doi.org/10.1519/JSC.0b013e31815fa3d3.

Denegar, C. R., & Ball, D. W. (1993). Assessing reliability and precision of measurement: an introduction to Intraclass correlation and standard error of measurement. *Journal of Sport Rehabilitation*, *2*(1), 35–42. https://doi.org/10.1123/jsr.2.1.35.

Downes, M. J., Brennan, M. L., Williams, H. C., & Dean, R. S. (2016). Development of a critical appraisal tool to assess the quality of cross-sectional studies (AXIS). *BMJ Open*, *6*(12), 1–7. https://doi.org/10.1136/bmjopen-2016-011458.

Duthie, G. M., Pyne, D. B., Ross, A. A., Livingstone, S. G., & Hooper, S. L. (2006). The reliability of ten-meter sprint time using different starting techniques. *Journal of Strength and Conditioning Research*, *20*(2), 246–251. https://doi.org/10.1519/R-17084.1.

Gray, A. J., Jenkins, D., Andrews, M. H., Taaffe, D. R., & Glover, M. L. (2010). Validity and reliability of GPS for measuring distance travelled in field-based team sports. *Journal of Sports Sciences*, *28*(12), 1319–1325. https://doi.org/10.1080/02640414.2010.504783.

Gualtieri, A., Rampinini, E., Dello Iacono, A., & Beato, M. (2023). High-speed running and sprinting in professional adult soccer: Current thresholds definition, match demands and training strategies. A systematic review. *Frontiers in Sports and Active Living*, *5*, 1–16. https://doi.org/10.3389/fspor.2023.1116293.

Haugen, T., & Buchheit, M. (2016). Sprint running performance monitoring: methodological and practical considerations. *Sports Medicine*, *46*(5), 641–656. https://doi.org/10.1007/s40279-015-0446-0.

Haugen, T., Tønnessen, E., Hisdal, J., & Seiler, S. (2014). The role and development of sprinting speed in soccer. [Faculty of health and sport science, University of Agder]. *International journal of sports physiology and performance*. https://doi.org/10.1123/ijspp.2013-0121.

Haugen, T., Seiler, S., Sandbakk, Ø., & Tønnessen, E. (2019). The training and development of elite sprint performance: an integration of scientific and best practice literature. *Sports Medicine—Open*, *5*(1), 44. https://doi.org/10.1186/s40798-019-0221-0.

Healy, R., Kenny, I. C., & Harrison, A. J. (2022). Profiling elite male 100-m sprint performance: the role of maximum velocity and relative acceleration. *Journal of Sport and Health Science*, *11*(1), 75–84. https://doi.org/10.1016/j.jshs.2019.10.002.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, *30*(1), 1–15. https://doi.org/10.2165/00007256-200030010-00001.

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), e192708. https://doi.org/10.1371/journal.pone.0192708.

Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., Murphy, A. J., & Pruyn, E. C. (2012). The validaty and reliability of 5-Hz global positioning system units to measure team sports demands. *Journal of Strength and Conditioning Research*, *26*(3), 758–765.

Johnston, R. J., Watsford, M. L., Pine, M. J., Spurrs, R. W., & Sporri, D. (2013). Assessment of 5 Hz and 10 Hz GPS units for measuring athlete movement demands. *International Journal of Performance Analysis in Sport*, *13*(1), 262–274. https://doi.org/10.1080/24748668.2013.11868646.

Jonhston, R. J., Watsford, M. L., Kelly, S. J., Pine, M. J., & Spurrs, R. W. (2014). Validity and Interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *Journal of Strength and Conditioning Research*, *28*(6), 1649–1655. https://doi.org/10.1519/JSC.0000000000000323.

Lacome, M., Peeters, A., Mathieu, B., Marrier, B., Carling, C., & Piscione, J. (2019). Can we use GPS for assessing sprinting performance in rugby sevens? A concurrent validity and between-device reliability study. *Biology of Sport*, *36*(1), 25–29. https://doi.org/10.5114/biolsport.2018.78903.

Larsson, P. (2003). Global positioning system and sport-specific testing. *Sports Medicine*, *33*(15), 1093–1101. https://doi.org/10.2165/00007256-200333150-00002.

Majumdar, A. S., & Robergs, R. A. (2011). The science of speed: determinants of performance in the 100 m sprint. *International Journal of Sports Science & Coaching*, *6*(3), 479–493. https://doi.org/10.1260/1747-9541.6.3.479.

Malone, S., Owen, A., Mendes, B., Hughes, B., Collins, K., & Gabbett, T. J. (2018). High-speed running and sprinting as an injury risk factor in soccer: can well-developed physical qualities reduce the risk? *Journal of Science and Medicine in Sport*, *21*(3), 257–262. https://doi.org/10.1016/j.jsams.2017.05.016.

Massard, T., Eggers, T., & Lovell, R. (2018). Peak speed determination in football: is sprint testing necessary? *Science and Medicine in Football*, *2*(2), 123–126. https://doi.org/10.1080/24733938.2017.1398409.

Methley, A. M., Campbell, S., Chew-Graham, C., McNally, R., & Cheraghi-Sohi, S. (2014). PICO, PICOS and SPIDER: A comparison study of specificity and sensitivity in three search tools for qualitative systematic reviews. *BMC Health Services Research*. https://doi.org/10.1186/s12913-014-0579-0.

Miguel, M., Oliveira, R., Loureiro, N., García-Rubio, J., & Ibáñez, S. J. (2021). Load measures in training/match monitoring in soccer: a systematic review. *International Journal of Environmental Research and Public Health*, *18*(5), 1–26. https://doi.org/10.3390/ijerph18052721.

Misra, P., & Enge, P. (2006). *Global positioning system: signals, measurements, and performance* (2nd edn.). L. Ganga-Jamuna Press.

Mooney, M. G., Hunter, J. R., O'brien, B. J., Berry, J. T., & Young, W. B. (2011). Reliability and validity of a novel intermittent peak running speed test for Australian football. *Journal of Strength and Conditioning Research*, *25*(4), 973–979. https://doi.org/10.1519/JSC.0b013e3181d09dde.

Muñoz-Lopez, A., Granero-Gil, P., Pino-Ortega, J., & De Hoyo, M. (2017). The validity and reliability of a 5-hz GPS device for quantifying athletes' sprints and movement demands specific to team sports. *Journal of Human Sport and Exercise*, *12*(1), 156–166. https://doi.org/10.14198/jhse.2017.121.13.

Nagahara, R., Botter, A., Rejc, E., Koido, M., Shimizu, T., Samozino, P., & Morin, J.-B. (2017). Concurrent validity of GPS for deriving mechanical properties of sprint acceleration. *International Journal*, *14*(2), 156–162. https://doi.org/10.1123/ijspp.2015-0566.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*. https://doi.org/10.1136/bmj.n71.

Pino-Ortega, J., Oliva-Lozano, J. M., Gantois, P., Nakamura, F. Y., & Rico-González, M. (2021). Comparison of the validity and reliability of local positioning systems against other tracking technologies in team sport: a systematic review. In *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*. https://doi.org/10.1177/1754337120988236.

Rampinini, E., Alberti, G., Fiorenza, M., Riggio, M., Sassi, R., Borges, T., & Coutts, A. (2014). Accuracy of GPS devices for measuring high-intensity running in field-based team sports. *International Journal of Sports Medicine*, *36*(01), 49–53. https://doi.org/10.1055/s-0034-1385866.

Reinhardt, L., Schwesig, R., Lauenroth, A., Schulze, S., & Kurz, E. (2019). Enhanced sprint performance analysis in soccer: new insights from a GPS-based tracking system. *PLoS ONE*, *14*(5), 1–11. https://doi.org/10.1371/journal.pone.0217782.

Rico-Gonzalez, M., Arcos, A. L., Clemente, F. M., & Rojas-valverde, D. (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.

Rico-González, M., Pino-Ortega, J., Clemente, F., & Arcos, L. A. (2021). Guidelines for performing systematic reviews in sports science. *Biology of Sport*, *39*(2), 463–471. https://doi.org/10.5114/biolsport.2022.106386.

Roe, G., Darrall-Jones, J., Black, C., Shaw, W., Till, K., & Jones, B. (2017). Validity of 10 HZ GPS and timing gates for assessing maximum velocity in professional rugby union players. *International Journal of Sports Physiology and Performance*, *14*(2), 156–162. https://doi.org/10.1123/ijspp.2016-0256.

Romero-Franco, N., Jiménez-Reyes, P., Castaño-Zambudio, A., Capelo-Ramírez, F., Rodríguez-Juan, J. J., González-Hernández, J., Toscano-Bendala, F. J., Cuadrado-Peñafiel, V., & Balsalobre-Fernández, C. (2017). Sprint performance and mechanical outputs computed with an iPhone app: comparison with existing reference methods. *European Journal of Sport Science*, *17*(4), 386–392. https://doi.org/10.1080/17461391.2016.1249031.

Ryan, R., Synnot, A., Prictor, M., & Hill, S. (2021). Data extraction template for included studies. Cochrane consumers and communication group. http://cccrg.cochrane.org/author-resources

Scott, M. T. U., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport. *Journal of Strength and Conditioning Research*, *30*(5), 1470–1490. https://doi.org/10.1519/JSC.0000000000001221.

Vantieghem-Nicolas, L., Morin, J.-B., Cotte, T., Sangnier, S., & Rossi, J. (2023). Concurrent validity and reliability of the sprint force–velocity profile assessed with K-AI wearable tech. *Sensors*. https://doi.org/10.3390/s23198189.

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011a). Concurrent validity and test–retest reliability of a global positioning system (gps) and timing gates to assess sprint performance variables. *Journal of Sports Sciences*, *29*(15), 1613–1619. https://doi.org/10.1080/02640414.2011.608703.

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011b). Predicting 30 m timing gate speed from a 5 Hz Global Positioning System (GPS) device. *International Journal of Performance Analysis in Sport*, *11*(3), 575–582. https://doi.org/10.1080/24748668.2011.11868575.

Witte, T. H., & Wilson, A. M. (2004). Accuracy of non-differential GPS for the determination of speed over ground. *Journal of Biomechanics*, *37*(12), 1891–1898. https://doi.org/10.1016/j.jbiomech.2004.02.031.