Validation methods for global and local positioning-based athlete monitoring systems in team sports: a scoping review

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ABSTRACT
Background/Objective Global navigation satellite systems (GNSS) and local positioning systems (LPS) are to date common tools to measure external training load in athletes. The aim of this scoping review was to map out and critically appraise the methods used to validate different GNSS and LPS used in team sports.

Method A total of 48 studies met the eligibility criteria and were included in the review. The reference systems applied in the validations, and the parameters investigated were extracted from the studies.

Results The results show a substantial range of reference systems used to validate GNSS and LPS and a substantial number of investigated parameters. The majority of the validation studies have employed relatively simple field-based research designs, with use of measure tape/known distance as reference measure for distance. Timing gates and radar guns were frequently used as reference system for average and peak speed. Fewer studies have used reference system that allow for validation of instantaneous dynamic position, such as infrared camera-based motion capture systems.

Conclusions Because most validation studies use simple and cost-effective reference systems which do not allow to quantify the exact path athletes travel and hence misjudge the true path length and speed, caution should be taken when interpreting the results of validation studies, especially when comparing results between studies. Studies validating instantaneous dynamic position-based measures is warranted, since they may have a wider application and enable comparisons both between studies and over time.

INTRODUCTION
Objective analyses of physical training load in team sports can provide better understanding of the specific physical demands of a sport, the physical development of players over time, health and performance, and can help to improve training practices. Different methods for time-motion analysis, such as hand notation and video analysis, have been used to objectively assess training load for many decades. However, the time-consuming nature of such analysis has restricted its use. The development of wearable athlete monitoring systems has made objective athlete monitoring more available in team sports. Most wearable athlete monitoring systems consist of a global navigation satellite system (GNSS) for outdoor use or a local positioning system (LPS) for indoor use. GNSS and LPS systems provide meaningful position-based measures such as speed or path length for team sports. The use of GNSS-based and LPS-based athlete monitoring systems is now commonplace in team sports, and the number of research publications related to the application of these technologies in team sports is high and increasing exponentially (figure 1). Wearable athlete monitoring systems often also include inertial sensors, such as accelerometers and gyroscopes. These are typically used to measure acceleration and parameters based on acceleration. This article does not address inertial sensors but focuses on GNSS/LPS technology.

The large number of GNSS and LPS system applications in sport teams and research emphasise the importance of the question of whether these systems are sufficiently validated and can accurately measure what they are intended to measure. Good internal and external validity of data collection systems...
able tracking devices applied in sports should be small, to measure. If the internal validity of a system is reflects the ability to accurately measure what the system The internal validity of a system is equally important. It validity compared to investigations in laboratory settings. competition and hence substantially improve external monitoring systems are applied in team sport is that they allow collection of data during real-life training and thus substantially improve external performance and/or increased health risks. One main reason why wearable athlete monitoring systems are applied in team sport is that they allow collection of data during real-life training and competition and hence substantially improve external validity compared to investigations in laboratory settings. The internal validity of a system is equally important. It reflects the ability to accurately measure what the system intends to measure. If the internal validity of a system is not adequate, training load can be overestimated or underestimated, and the application of such measurement systems may cause harm to athletes by the prescription of inadequate training, leading to decreased performance and/or increased health risks.

Both GNSS and LPS are prone to measurement error, and there are many factors that can influence position validity. Calculation of the GNSS or LPS position of a wearable athlete monitoring system (receiver) is based on position and time information from satellites circulating around the earth (for GNSS) or local nodes mounted around the field of play (for LPS). Satellites and nodes emit an electromagnetic signal that is received by the receiver on the athlete. From these signals, there are several techniques that can be used to calculate instantaneous position, such as time-of-flight, time-difference-of-arrival, angle-of-arrival and received signal strength. GNSS use time-of-flight, while LPS vary between different systems in which technique they use. The main device-related factors that influence the validity of this kind of position measurement include antenna and board type, number of satellites/nodes used for position calculation, signal type used, processing method, measurement frequency and parameter calculation process. Since wearable tracking devices applied in sports should be small, light and user-friendly, the manufacturers of such devices optimise the trade-off between system performance, form factor, handling simplicity and cost. Due to these manufacturing compromises and the continuous system improvements in hardware and firmware, data processing and parameters, the validity of such systems needs to be investigated prior to use. To date, several validity studies have been published for GNSS, and to a lesser extent for newer LPS in team sports. The GNSS studies show a large range of standards (hereafter called reference systems) applied to validate wearable athlete monitoring systems and the parameters investigated.

In recognition of the importance validity has in match and training analysis in team sports, and the apparent range of validation methods applied in GNSS/LPS studies, this scoping review aims to present and critically appraise the methods used to validate the various GPS and LPS used in team sports.

METHOD
Review protocol
The protocol for this review is available at the Open Science Framework (URL: https://osf.io/3wn82/), where both the protocol and the full search strategy can be found (URL: https://osf.io/rmcgf/). This review was conducted and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews.

Eligibility criteria
Articles were eligible for inclusion in this review if they (1) included investigation of validity/accuracy for GNSS or LPS and (2) were aiming to investigate this in relation to team sports. Articles were excluded if they were (1) published in a non-English language or (2) only available in conference abstract or conference proceedings format. Reviews or other studies with no primary data were not included in this scoping review.

Search strategy
A systematic electronic database search was conducted in SPORTDiscus and PubMed for all published manuscripts prior to the search date (15.09.19). The search strategy included the following terms (and variations of these terms): ‘Global Positioning System’ OR ‘Global Navigation Satellite System’ OR ‘Local Positioning System’ AND ‘Validity’ OR ‘Accuracy’ AND ‘Team Sports’. The full search strategy can be found at the Open Science Framework (URL: https://osf.io/rmcgf/). No filters or limitations were imposed during the search.

Study selection
Search results were exported to a reference manager library (Endnote, X9.2), where duplicates were removed. The citations were then uploaded to the systematic review software DistillerSR (Evidence Partners, Ottawa, Canada). Titles and abstracts of the citations were screened for eligibility independently by two reviewers.
Full texts of potentially eligible articles were retrieved before a final assessment was completed independently by the same two reviewers. Any discrepancies between reviewer eligibility assessments were resolved through discussion with a third reviewer. All three reviewers were familiar with the topic of the review.

Data extraction
GNSS/LPS specifications (brand, model and sampling frequency), sporting tasks assessed, reference system used for the validation, and parameters investigated were extracted from the included studies. Tasks were classified into four different categories: linear (straight line) tasks, non-linear tasks, team sport circuits and game-like situations (eg, small-side games). The type of reference system used to assess validity was extracted as stated in the studies. The parameters for time, averaged static position, instantaneous dynamic position, distance travelled, average speed, peak speed, instantaneous speed, average acceleration, peak acceleration and instantaneous acceleration were extracted. Other parameters, such as metabolic power or time to cover distance, were categorised as ‘other’. Data extraction was performed by two independent reviewers.

RESULTS
The database search identified 454 relevant records. Duplicates (n=76) were removed, so 378 titles and abstracts were reviewed. A total of 48 studies met the eligibility criteria and were included in the review. An overview of the search and selection process is presented in figure 2.

The studies investigated from one to five parameters each. Distance was the most frequently investigated parameter (34 articles), followed by average and peak speed. Fewer studies investigated dynamic position, or instantaneous speed and acceleration (figure 3).

Five different reference systems were used to investigate the validity of distance, where tape measure/known distance constituted the most frequently used reference systems. For validation of speed the reference systems applied were timing gates, radar gun and infrared camera-based motion capture systems. For the validation of acceleration only infrared camera systems were used. A summary of the results is given in table 1, while a full documentation of the different reference systems used and parameters assessed is shown in table 2 (LPS) and table 3 (GNSS).

A variety of different tasks are used to investigate the validity and accuracy of GNSS/LPS. Linear tasks were the most frequently used (tables 2–3) and were included in most studies. Different circuits and courses imitating team sports movements were also frequently used. Game-like situations were only used in three of the 48 included studies (tables 2–3).

DISCUSSION
This study provides an overview of the published, peer reviewed studies investigating the validity of GNSS and LPS in team sports. Since the first validation study on GNSS in team sports was published in 2006, the number of validation studies has steadily increased in this field. It seems that the increasing number of validation studies is required, since the number of manufacturers and types of GNSS/LPS-devices, and with these the variety of hardware and firmware, sampling rates and data-processing methods, have increased. In total, the validity of at least 23 GNSS and six LPS models—from 17 different manufacturers—for team sports applications have been investigated in the literature.

The results show a substantial range of reference systems employed to validate GNSS and LPS, and a substantial number of parameters that were investigated. Most of the validation studies have employed relatively simple field-based research designs, using a tape measure/known distance as the reference system for distance. Timing gates and radar guns were frequently used as reference systems for average and peak speed. Fewer studies have used reference systems that allow for validation of instantaneous dynamic position, such as infrared camera-based motion capture systems.
Distance travelled and peak and average speed were the
most frequently investigated parameters. The high num-
ber of studies investigating these parameters is justified by
their frequent use in time-motion analyses in team
sports.

Only a few studies have investigated the
validity of instantaneous dynamic position, which may
be due to the unavailability of appropriate reference sys-
tems, such as infrared camera-based motion capture sys-
tems. However, some studies did not provide
instantaneous dynamic position, even though the refer-
ence system applied could have provided this
information. We believe that insight into the valid-
ity of instantaneous dynamic position could be beneficial
for several reasons. First, other parameters (such as dis-
tance) are integrations or derivatives of instantaneous
dynamic position and hence, deviations in position mea-
surement are propagated to these parameters and poten-
tially amplified by data processing, such as filtering and
parameter calculation methodology. Such data proces-
sing steps will likely deviate between devices and manu-
facturers. Thus, appropriate validations of a system’s
instantaneous dynamic position would allow comparison
of the system’s ability to measure the basic parameter
(position) and allow pinpointing of a) the error caused
by the basic parameter (position) measurement and b)
the manufacturer’s data processing. Second, parameters
such as distance or speed can be affected by firmware
update-related changes in the manufacturer’s data pro-
cessing (typically parameter calculation and filtering).
Hence, altered firmware may cause differences in the
propagation parameters such as distance and speed com-
pared with earlier firmware versions, even though the
measurement of the basic parameter (position) may
remain unchanged. It is likely that system improvements
more often affect data processing (parameter calculation
and filtering) than the basic measurement (instantaneous
dynamic position). Therefore, third, GINS/LS data are also used for tactical analyses, such as mean position over time
and dynamic distances between players, which are
based on position. Therefore, it is important that studies
also investigate the validity of instantaneous
position. However, some studies did not provide
instantaneous dynamic position, which may be due to the unavailability of appropriate reference sys-
tems such as infrared camera-based motion capture sys-
tems. Therefore, we suggest that the validity of instantaneous
dynamic position should be included in validation stu-
dies, as it may have a wider application and could in the
long run be both time and cost saving due to its more
long-term stability across firmware versions.

Some studies lacking an appropriate reference system
for instantaneous dynamic position have investigated
time-averaged static positions. Two studies have
measured positions as reference points, while one
study applied the average position of the receiver as a reference. These two validation methods of the
receiver are inherently different and may elicit vastly
different results. The average position should be used
for studies with a varying number of participants.

Table 1: Overview of different reference systems used to validate the most common performance and training load parameters

| Parameter                  | Time averaged static position | Instantaneous dynamic position | Distance travelled | Average speed | Peak speed | Instantaneous speed | Average acceleration | Peak acceleration | Instantaneous acceleration |
|----------------------------|-------------------------------|--------------------------------|--------------------|--------------|-----------|--------------------|--------------------|----------------------|--------------------------|
| Theodolite                 | 2                             | 2                              |                    |              |           |                    |                    |                      |                          |
| Tape measure/known distance| 1                             | 19                             |                    |              |           |                    |                    |                      |                          |
| Trundle wheel              | 7                             |                                |                    |              |           |                    |                    |                      |                          |
| Radar gun/laser gun        | 1                             | 1                              |                    | 6            | 1         |                    |                    |                      |                          |
| Timing gates               | 8                             | 4                              | 1                  | 3            | 2         | 1                  |                    |                      |                          |
| Infrared camera-based motion capture system | 3 | 5                              | 7                  | 6            | 2         | 3                  | 2                  | 1                    |                          |
| Other                      | 1                             | 1                              | 1                  | 1            |           |                    |                    |                      |                          |

Note: Only a few studies have investigated the validity of instantaneous dynamic position, which may be due to the unavailability of appropriate reference systems. We believe that insight into the validity of instantaneous dynamic position could be beneficial for several reasons.
| System(s) model (Manufacturer) | System information frequency, technology | Tasks | Reference system | Parameter |
|--------------------------------|------------------------------------------|-------|-----------------|-----------|
| Bastida-Castilla et al 2018‡  | WIMUPRO (Realtrack systems) 20 Hz, LPS | Linear tasks | Timing gates | Distance travelled |
|                                |                                          | Non-linear tasks | Trundle wheel | Average speed |
| Bastida-Castilla et al 2019‡  | WIMUPRO (Realtrack systems) 20 Hz, LPS | Linear tasks | Calibration procedures of | Instantaneous dynamic position |
|                                |                                          | Non-linear tasks | LPS | |
| Figueira et al 2018‡          | NBN23 (Quuppa) 10 Hz, LPS              | Non-linear tasks | Known distance | Distance travelled (relative) |
| Frencken et al 2010§          | Inmotio (Inmotio Object tracking) 45 Hz, LPS | Linear tasks | Average position | Time averaged static position |
|                                |                                          | Non-linear tasks | Tape measure | Distance |
|                                |                                          |                   | Timing gates | Average speed |
| Hoppe et al (2018)§‡          | Kinexon One (Kinexon Precision Technologies) 20 Hz, LPS | Team sport circuit | Tape measure | Distance travelled |
|                                |                                          |                   | Trundle wheel | Other |
| Leser et al. 2014§            | Ubisense (Ubisense) 4.17 Hz, LPS        | Game-like situations | Trundle wheel | Distance travelled |
| Link et al. 2019§             | Inmotio (Inmotio Object tracking) 100 Hz, LPS | Linear tasks | Tachymeter | Other |
|                                | Kinexon (Kinexon Precision Technologies) 15 Hz, LPS | Non-linear tasks | Timing gates | |
| Linke et al 2018§             | Inmotio (Inmotio Object tracking) 45 Hz, LPS | Linear tasks | Infrared camera-based motion capture system | Instantaneous dynamic position |
|                                |                                          | Non-linear tasks | Speed | Instantaneous speed |
| Luteberget et al 2018§         | ClearSky T6 (Catapult Sports) 20 Hz, LPS | Linear tasks | Infrared camera-based motion capture system | Instantaneous dynamic position |
|                                |                                          | Non-linear tasks | Distance travelled | Average speed |
|                                |                                          | Game-like situations | | Instantaneous speed |
| Ogris et al 2012§             | LPM04.59 (Abatec) 45 Hz, LPS            | Linear tasks | Infrared camera-based motion capture system | Instantaneous dynamic position |
|                                |                                          | Non-linear tasks | Average speed | Speed |
| Rhodes et al 2014§            | Ubisense (Ubisense) 4 Hz, LPS† 8 Hz, LPS† 16 Hz, LPS† | Linear tasks | Theodolite | Time averaged static position |
|                                |                                          | Non-linear tasks | Timing gates | Distance |
|                                |                                          | Game-like situations | | Average speed |
| Sathyyan et al 2012§           | WASP system (Undisclosed) 10 Hz, LPS    | Linear tasks | Theodolite | Time averaged static position |
|                                |                                          | Non-linear tasks | Tape measure | Dynamic position (relative) |
|                                |                                          |                   | |

Continued
measurement obtained using the same device as the one to be validated provides only random error and cannot measure the systematic deviance from the true location. Thus, if the true static position is unknown, the relative position difference should be stated as a precision measure, not an accuracy or validity measure.

Several validation studies have used premeasured distances as reference systems for distance and average speed. This is a simple and cost-effective way to investigate the validity of tracking systems. However, the method is not an ideal reference system, as it is not possible to quantify the exact path travelled by the athlete as long as the athlete’s true path is not tracked instantaneously. During human locomotor tasks the individual and thus the device will seldom follow a straight line between two points. This could affect the outcome of validation studies, as is pointed out by some authors. Thus, smaller or larger deviations in the athlete’s position may go undetected and can lead to an underestimation or overestimation of the accuracy of the investigated system. To avoid this problem, the use of reference systems that measure the true instantaneous trajectory of the athlete’s device, such as infrared camera-based motion capture systems, video-based tracking, or, previously validated high-end GNSS devices, is warranted. Such reference systems also make it possible to investigate more complex tasks, such as game-like situations, which are inherently the most specific conditions to test the systems in.

Timing gates are also easy to apply and are often used as the reference system for mean speed, and in some cases peak speed and instantaneous speed. However, timing gates only determine mean speed in the sections between gates. Mean speed provides only limited insight in team sport applications, since it does not contribute much to the understanding of team sports, where speed constantly fluctuates as a function of the acceleration and deceleration of the athlete. Team sport analysis systems often sort speed data into ranges (speed zones) and express these as a function of time or distance as a comprehensive metric for the ‘distribution of intensity’ of the athletes’ physical load. Even though instantaneous speed measurements are commonly used to categorise speed as a function of time or distance, most validation studies only investigate the validity of mean speed over time. This is a serious shortcoming, since mean speed over time may not allow conclusions to be reached on the described distribution of intensity, which is based on instantaneous speed.

Some studies include the validity of peak speed; however, only a few studies have looked at the instantaneous speed over the range of a whole task. Radar guns were used in several studies to assess peak and instantaneous speed. The validity of radar guns during non-straight-line running is currently unknown, and they are thus used only in straight-line sprints in the current literature. Hence, a radar gun is not a suitable reference system for team sports motion, since most team

| Parameter | Distance travelled | Average speed | Peak speed | Average acceleration | Peak acceleration |
|-----------|-------------------|---------------|------------|---------------------|------------------|
| Infrared camera-based motion capture system | Instantaneous position | | | | |
| Laser gun | | | | | |
| Linear tasks | | | | | |
| Non-linear tasks | | | | | |
| Linear tasks | | | | | |
| Non-linear tasks | | | | | |

| Reference system | Infrared camera-based motion capture system |
|------------------|---------------------------------------------|
| Distance travelled | Average speed | Peak speed | Average acceleration | Peak acceleration |
| Linear tasks | Non-linear tasks | Linear tasks | Non-linear tasks | Linear tasks | Non-linear tasks |

Table 2

### System(s) model (Manufacturer)
- Serpiello et al 2018
- Siegle et al 2013
- Stevens et al 2014

### System information frequency, technology
- 10 Hz, LPS
- 45 Hz, LPS
- Undisclosed

### Tasks
- Linear tasks
- Non-linear tasks

### Parameter
- Distance travelled
- Average speed
- Peak speed
- Average acceleration
- Peak acceleration

† Some unit used with different sampling frequency.
‡ Studies investigating both GNSS/GPS and LPS.
| References | System(s) model (Manufacturer) | System information frequency, technology | Tasks | Reference system | Parameter |
|------------|--------------------------------|------------------------------------------|-------|------------------|-----------|
| Akenhead et al 2014 | MinimaxX S4 (Catapult Sports) | 10 Hz, GPS | Linear tasks | Laser gun | Instantaneous speed |
| Barbero-Álvarez et al 2010 | SPI Elite (GPSports Systems) | 1 Hz, GPS | Linear tasks | Timing gates | Peak speed |
| Barr et al 2019 | SPI HPU (GPSports Systems) | 5 Hz*, GPS | Linear tasks | Timing gates | Instantaneous speed |
| Bastida-Castilla et al 2018 | WIMUPRO (Realtrack systems) | 10 Hz, GPS | Linear tasks | Timing gates | Distance travelled |
| Bastida-Castilla et al 2018 | WIMUPRO (Realtrack systems) | 10 Hz, GPS | Linear tasks | Calibration procedures of LPS | Instantaneous dynamic position |
| Bataller-Cervera et al 2019 | Viper (STATSports) | 10 Hz, GPS | Linear tasks | Timing gates | Average speed |
| Beato et al 2018 | Apex 10 Hz (STATSports) | 10 Hz, GNSS | Linear tasks | Tape measure | Distance travelled |
| Beato et al 2018 | Apex 18 Hz (STATSports) | 18 Hz, GPS | Team sport circuit | Radar gun | Peak speed |
| Beato et al 2016 | Undisclosed (STATSports) | 10 Hz, GPS | Linear tasks | Tape measure | Distance travelled |
| Castellano et al 2011 | MinimaxX v4.0 (Catapult Sports) | 10 Hz, GPS | Linear tasks | Tape measure | Distance travelled |
| Coutts‡ Duffield 2010 | SPI-10 (GPSports Systems) | 1 Hz, GPS | Team sport circuit | Tape measure | Distance travelled |
| Delaney et al 2019 | EVO (GPSports Systems) | 10 Hz, GNSS | Linear tasks | Infrared camera-based motion capture system | Average speed |
| Duffield et al 2010 | MinimaxX (Catapult Sports) | 5 Hz, GPS | Linear tasks | Infrared camera-based motion capture system | Distance travelled |
| Edgecomb‡ Norton 2006 | SPI-10 (GPSports Systems) | Undisclosed, GPS | Team sport circuit | Trundle wheel | Distance travelled |
| Gray et al 2010 | WI SPI elite (GPSports Systems) | 1 Hz, GPS | Linear tasks | Theodolite | Distance travelled |
| Hoppe et al 2018 | GPEXEPRO (Exelio srl) | 18 Hz, GPS | Team sport circuit | Tape measure | Distance travelled |

Continued
Table 3 Continued

| References      | System(s) model (Manufacturer) | System information frequency, technology | Tasks                     | Reference system | Parameter          |
|-----------------|---------------------------------|------------------------------------------|---------------------------|-----------------|--------------------|
| Jennings et al 2010 | MinimaxX Team 2.5 (Catapult Sports) | 1 Hz, GPS† 5 Hz, GPS† | Linear tasks Non-linear tasks Team sport circuit | Tape measure     | Distance travelled |
| Johnston et al 2014 | MinimaxX S4 (Catapult Sports) SPI-ProX (GPSports Systems) | 10 Hz, GPS 10 Hz*, GPS | Team sport circuit | Tape measure Timing gates | Distance travelled Peak speed |
| Johnston et al 2013 | MinimaxX S3 (Catapult Sports) MinimaxX S4 (Catapult Sports) | 5 Hz, GPS 10 Hz, GPS | Team sport circuit | Tape measure Timing gates | Distance travelled Peak speed |
| Johnston et al 2012 | MinimaxX Team 2.5 (Catapult Sports) | 5 Hz, GPS | Linear tasks Team sport circuit | Tape measure Timing gates Radar gun | Distance travelled Peak speed |
| Köklü et al 2015 | SPI ProX (GPSports Systems) | 5 Hz*, GPS | Linear tasks Non-linear tasks | Tape measure Timing gates | Distance travelled Average speed |
| Lacome et al 2019 | Sensoreverywhere V2 GPS (Digital simulation) | 16 Hz, GPS | Linear tasks | Radar gun | Peak speed          |
| Linke et al 2018 | SPI Pro X (GPSport Systems) | 5 Hz*, GPS | Linear tasks Non-linear tasks Game-like situations | Infrared camera-based motion capture system | Instantaneous dynamic position Instantaneous speed Instantaneous acceleration |
| MacLeod et al 2009 | SPI Elite (GPSports Systems) | 1 Hz, GPS | Team sport circuit | Trundle wheel Timing gates | Distance travelled Average speed |
| Muñoz-Lopez et al 2017 | WIMU (Realtrack Systems) | 5 Hz, GPS | Linear tasks Team sport circuit | Tape measure | Distance travelled |
| Nagahara et al 2017 | GPEXE (Exelio srl) SPI-Pro X (GPSport Systems) | 20 Hz, GPS 5 Hz*, GPS | Linear tasks | Radar gun Laser gun | Peak speed |
| Nikolaidis et al 2018 | Johan GPS (JOHAN sports) | 10 Hz, GPS | Linear tasks Non-linear tasks | Known distance | Distance travelled |
| Padulo et al 2019 | Spin GNSS (Spintialia) | 50 Hz, GNSS | Linear tasks Non-linear tasks | Tape measure | Distance travelled Average speed |
| Petersen et al 2009 | SPI-10 (GPSports Systems) SPI-Pro (GPSports Systems) MinimaxX (Catapult sports) | 1 Hz, GPS 5 Hz, GPS 5 Hz, GPS | Linear tasks Non-linear tasks | Known distance | Distance travelled |
| Portas et al 2010 | MinimaxX v2.5 (Catapult sports) | 1 Hz, GPS† 5 Hz, GPS† | Linear tasks Non-linear tasks Team sport circuit | Trundle wheel | Distance travelled |
| Rampinini et al 2015 | SPI-Pro (GPSports Systems) MinimaxX S4 (Catapult sports) | 5 Hz, GPS 10 Hz, GPS | Linear tasks | Radar gun | Distance travelled Other |
sports involve mostly non-straight line motion. Reference systems such as infrared camera-based motion capture systems, video-based tracking, or previously validated high-end GNSS devices are warranted.

**CONCLUSION**

The most frequently investigated parameter in GNSS and LPS validity studies was distance travelled, followed by average and peak speed. Tape measure/known distance was the most frequent reference system applied. Few studies have investigated instantaneous parameters, such as instantaneous dynamic position or instantaneous speed. We discovered a large range of reference systems and methods employed to validate wearable athlete monitoring systems; thus, the appropriateness of the employed reference systems may vary, and caution should be applied when interpreting the results of validation studies, especially when comparing results between studies. More studies investigating instantaneous dynamic position may have a wider application and enable comparisons both between studies and over time.

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