



## Review

# Quantification of the validity and reliability of sprint performance metrics computed using inertial sensors: A systematic review

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## ARTICLE INFO

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## ABSTRACT

**Background:** Wearable inertial sensors enable sprinting to be biomechanically evaluated in a simple and time efficient manner outside of a laboratory setting.

**Research Question:** Are wearable inertial sensors a valid and reliable method for collecting and measuring sprint performance variables compared to referenced systems?

**Methods:** PubMed, SPORTDiscus, and Web of Science were searched using the Boolean phrases: ((run\* OR sprinting OR sprint\*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid\* OR reliabil\*)). Articles with injury-free subjects of any age, sex or activity level were included.

**Results:** Fifteen studies met the inclusion criteria and were retained for analysis. In summary, higher Intra-class correlation [ICC] or Pearson correlation coefficients ( $r$ ) were observed for contact time ( $ICC \geq 0.80$ ,  $r \geq 0.99$ ), trunk angular displacement ( $r \geq 0.99$ ), vertical and horizontal force ( $ICC \geq 0.88$ ), and theoretical measures of force, velocity and power ( $r \geq 0.81$ ). Low coefficient of variation (CV) were found in peak velocity ( $\leq 1\%$ ), average velocity ( $\leq 3\%$ ), and contact time ( $\leq 3\%$ ). Average and peak velocity, and resultant forces, were found to have a wide range of  $r$  (0.32–0.92) and CVs (0.78–20.2%). The lowest  $r$  (-0.24 to 0.49) and highest CVs (15–22.4%) were noted for average acceleration, crania-caudal force, instantaneous forces, medio-lateral ground reaction forces, and rate of decrease in ratio of forces.

**Significance:** Due to a wide range of methodological differences, a clear understanding of the validity and reliability of different inertial sensors for the analysis of sprinting has yet to be established. Future research into the sensor's placement, attachment method and sampling frequency are among several factors that need further investigation.

## 1. Introduction

Many sports, including athletics and team sports, require athletes to perform maximal effort sprinting. Sprinting is a complex form of motion utilising all the major structures in the human body. The popularity of this activity and its importance in sport has encouraged a considerable body of research in this area. This understanding has been enhanced by advances in technology including wearable sensors, faster frame rate cameras, force plates, and improved motion analysis systems. Accurately capturing and analysing kinematic data (steps, joint angles, velocities, and accelerations) and kinetic data (forces and power output) is of great importance to practitioners, as the information is able to provide insights into movement performance and irregularities [1,2]. Ideally an athlete's sprint performance should be measured within their natural sporting context ensuring that any findings are ecologically valid and meaningful. This is highlighted in research that

has found differences in kinematics and kinetics between non-motorised, and motorised, treadmill running and sprinting, compared to over ground running and sprinting [3–5].

During sprinting, leg muscles support the body against gravity and accelerate or decelerate the body in a forward direction [6]. External forces act on the body, including ground reaction forces (GRF) and inertial forces from moving body segments, which need to be balanced by internal forces developed from muscles, tendons, ligaments and joint capsules [7]. Measurement of these external forces and temporal parameters can be acquired through laboratory equipment such as force plate technology and optical motion analysis systems, but only within definable and limited spatial boundaries [8]. Force platforms allow measurement of the three orthogonal components of the GRF vector during a single running step. Optical motion analysis systems use sets of cameras, passive or active markers, and software to calculate joint kinematics and spatio-temporal parameters and are considered the gold

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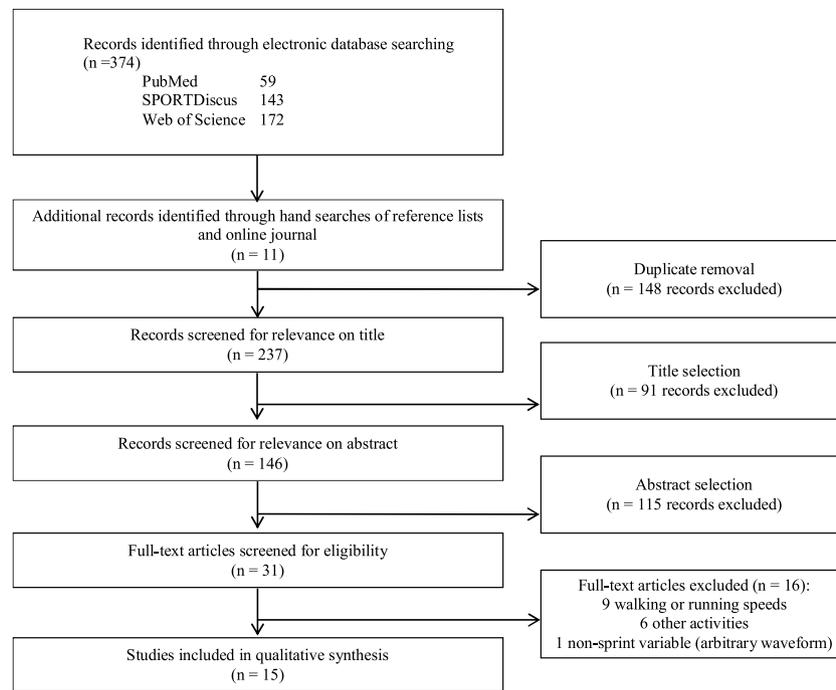


Figure 1. Flow chart of article selection process.

standard for human motion analysis [9]. However, these systems require dedicated space, expensive equipment, and can require lengthy test setup and data processing times. Furthermore, subjects are restricted to a confined area in the laboratory, and therefore, the system can only capture a small amount of continuous data [10]. Although high-speed cameras, timing gates and laser or radar guns can be used to provide a field-based testing environment, they lack some of the kinematic and kinetic measurement parameters found with the use of other devices. Moreover, they have limited capture volume and thus may reduce specificity to the desired activity. Field-based testing, however, can be used to characterise the general mechanical ability to produce horizontal external force of the subject during sprint-running, as reflected in the linear force–velocity ( $F$ - $v$ ) relationship obtained from direct mechanical-based procedures that use the centre of mass displacement estimate [11,12]. Subsequently, the mechanical capabilities of the lower limbs can be characterised by the variables: theoretical maximum velocity ( $V_o$ ), theoretical maximum force ( $F_o$ ), peak power production ( $P_o$ ), slope of linear force-velocity relationship ( $S_{fv}$ ), and rate of decrease in ratio of forces ( $D_{rf}$ ) [13]. However, these mechanical-based procedures calculate horizontal forces from time and distance derived variables and are also likely not to detect inter-step variability as the models give the average tendency of change in GRF components with time of both limbs [14].

One measurement tool not restricted to the aforementioned boundaries are wearable inertial sensors, such as an accelerometer or inertial measurement unit (IMU), which not only contains an accelerometer, but also a gyroscope, and often a magnetometer. These sensors have been used to analyse kinematic movement parameters such as jumping, walking and running in both laboratory and field based settings [15,16]. Advances in microelectromechanical systems have enabled these portable, low cost, and low power body mounted sensors to be attached to various areas of the body enabling motion analysis for biomechanical research [9]. Accelerometers measure human movement in terms of acceleration in up to three orthogonal planes: vertical, antero-posterior, and medio-lateral [17]. Modern IMU's collect data from tri-axial accelerometers (linear acceleration measurements) and tri-axial gyroscopes (angular velocity measurements) without external references [18], thus providing a more practical approach to data

collection.

Measurements of kinematics and kinetics during sprinting have been investigated using high-speed cameras, timing gates, force plates and motion analysis systems, however, given the more practical applications of the aforementioned sensors; measurements from these inertial sensors may be of more use to practitioners. Norris et al. [1], in a review of wearable sensors during running, suggested that placement of sensors closest to the area of interest along with the use of bi/tri-axial accelerometers appeared to provide the most accurate results. However, notwithstanding this suggestion, the efficacy of inertial sensors for quantifying sprint performance is poorly understood. Therefore, the purpose of this article was to review the validity and reliability of inertial sensors to referenced systems during sprinting.

## 2. Methods

### 2.1. Literature search strategies

The review was conducted in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement guidelines [19]. A systematic search of the literature was undertaken for studies that used wearable IMUs and accelerometers during sprinting that assessed validity and reliability. Articles were found from international peer-reviewed journals or conference papers from inception to October 2018. The following Boolean phrases were used for the searches ((run\* OR sprinting OR sprint\*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid\* OR reliabil\*)). Additional studies were also found by reviewing the reference lists from the retrieved studies.

### 2.2. Inclusion and exclusion criteria

Studies with injury-free subjects of any age, gender or activity level were included. No restrictions were imposed on publication date or publication status. Studies were limited to the English language and only full-text articles were included from peer reviewed journals or conference papers. Studies were included that involved maximum effort sprinting, therefore, sub max sprints or running studies were excluded.

Moreover, studies were excluded that did not present the numerical result (i.e. results presented as figures/graphs).

### 2.3. Study selection

One reviewer searched the databases and selected studies. The other reviewers were available to assist with study eligibility. A search of electronic databases and a scan of article reference lists revealed 374 relevant studies, with an additional 11 studies found via hand searches of the article's reference list. After applying the inclusion and exclusion criteria, 15 studies were retained for further analysis (Fig. 1).

### 2.4. Methodological quality score

Methodological quality was assessed using the quality index of Downs and Black [20] modified version [21]. A value of 0 or 1 was assigned to the different subcategories of the following items: reporting, external validity, and internal validity. A modified scoring system based on Moens et al. [21] was used. A total score < 7/17 was low quality, 8–12/17 was moderate, and scores  $\geq$  13/17 were high quality.

### 2.5. Data analysis

Validity and reliability acceptance thresholds are commonly set for intra-class correlation coefficient (ICC) and correlation coefficients ( $r$ )  $\geq$  0.70 [22,23] and coefficient of variation (CV)  $\leq$  10% [24]. However, a recent article by Prescott [25] highlighted the limitations of such an approach. Namely ICCs rarely have a place in which different measurement methods are compared, where inter- and intra-rater variability is assessed or in more general situations where components of variability in measurement are being assessed. Cognisant of these limitations, this article simply states the values published in the respective articles and leaves it to the reader to make their own interpretations as to the statistical and practical utility of the findings.

## 3. Results

### 3.1. Definition of terms

The variables discussed in this review are defined and clarified as sprint times and sprint velocities; temporal measures; sensor displacement and angular velocity; and forces. The details of the terms within each variable are provided in Table 1.

### 3.2. Study characteristics

The study characteristics of the 15 articles are summarised in Table 2. All the studies included validity measures, five of the studies assessed intra-day reliability, while no studies assessed inter-day reliability. Descriptions of populations sampled in the studies included: healthy active subjects, recreational athletes, sprint athletes, national track and field athletes, and rugby players. The number of subjects ranged from three to twenty-eight, with nine of the studies containing less than ten subjects. Over ground sprinting distances ranged from 10 m to 100 m, with two studies analysing the initial take-off steps within a laboratory setting. Sprint analysis ranged from initial take-off steps, from either block or standing starts, to steps during maximum velocity phase, to all steps throughout a 60 m sprint and velocity throughout a 100 m sprint. Eleven of the studies placed the sensor on the back (ranging in position from in-between scapulae to sacrum), with two studies using the shank, and the remaining two studies using a foot or ankle placement. Methods of sensor attachments included memory foam with an elastic belt, housed within a lycra vest, double sided tape and elastic straps, while four studies did not specify their attachment method. Quality assessment scores of the sixteen studies included ranged from 8 to 11, with an average score of 9.9/17,

indicating a moderate methodological quality for the studies reviewed (Table 2).

### 3.3. Wearable sensor specifications and reference systems used

Details of the wearable sensor systems utilised and their respective specifications can be found in Table 3. Nine of the studies used an IMU, five studies used only a tri-axial accelerometer, and one study used a dual-axial accelerometer for data collection. Accelerometer and gyroscope capability ranged from  $\pm$  6 g to  $\pm$  24 g and  $\pm$  500 deg/s to  $\pm$  2000 deg/s, respectively. Sample rates ranged from 100 Hz to 1000 Hz. Many different post-processing techniques were applied, including noise reduction and sensor fusion algorithms. Moving averages (3 to 40 point) and low pass Butterworth filters (10 to 100 Hz) were the most common noise reduction algorithms applied. Sprint performance parameters calculated include sprint times and velocities, temporal measures, sensor displacement and angular velocity, and forces. Contact times were determined using minimum and maximum peaks in the acceleration signal, with some studies utilising a 'critical threshold'. Average accelerations were determined using moving averages, peak velocities were calculated by integration of the horizontal acceleration signal; while Setuain et al. [14] integrated external reference systems to determine linear velocities. Double integration of the acceleration signal calculated angular displacements, with the most common filters used being Kalman and Madgwick. GRF were derived using Newton's Law/inverse dynamics method, coupled with quaternion-based rotation matrices and the instantaneous centre of mass acceleration. Six different reference systems were used for validity comparison. Six studies used force plate technology, four studies used timing lights, three studies used high-speed video camera, one study used motion capture, one study used infrared photocells, and one study used a laser gun.

### 3.4. Validity and reliability measures

The summarised results of the validity and reliability of wearable sensors during sprinting can be found in Table 4. A wide variety of outcome variables were used in the assessment of validity and reliability: sprint times, peak and average velocity, step variables, segment angular displacement and velocities, GRF and maximum power. Moreover, a range of statistical measures were used which included: Bland-Altman level of agreement (LoA), CV, ICC,  $r$ , root mean square error (RMSE), mean difference and mean error.

Higher levels of validity were found in contact time (ICC  $\geq$  0.80,  $r \geq$  0.99, LoA bias-8 to 25 ms), stride time (LoA bias 25 ms), trunk angular displacement ( $r \geq$  0.99), resultant force ( $r \geq$  0.76), vertical and horizontal force ( $r = \geq$  0.88), and  $V_o$ ,  $F_o$ ,  $P_o$ , and  $S_{fv}$  ( $r \geq$  0.81). Mixed validity findings occurred in peak and average velocity ( $r =$  0.32-0.95) and resultant force ( $r =$  0.35-0.76). Lower levels of validity were found in crania-caudal force ( $r =$  0.12-0.39), instantaneous forces ( $r =$  -0.24 to 0.64), medio-lateral GRF ( $r =$  0.35), and rate of decrease in ratio of forces ( $r =$  0.33). Regarding reliability, low levels of CV were found in peak velocity (CV  $\leq$  1%, LoA bias  $0.00 \pm 0.8$  km/h), average velocity (CV  $\leq$  3%, ICC  $\geq$  0.91), contact time (CV  $\leq$  4%, ICC  $\geq$  0.91), trunk angular displacement ( $r \geq$  0.99), and theoretical measures of  $V_o$ ,  $F_o$ , and  $P_o$ , (ICC  $\geq$  0.88). However, lower levels of reliability results were in  $D_{rf}$  ( $r =$  0.66).

## 4. Discussion

The purpose of this article was to review the validity and reliability of inertial sensors to referenced systems during sprinting. From the studies reviewed, it was observed that a wide range of sprint performance variables, as well as validity and reliability measures were used, when comparing different sensor placements with different criterion reference systems. The reader needs to be cognisant that due to these methodological differences, it is difficult to interpret anything with

**Table 1**  
Definition of terms.

Term	Definition of variable
Sprint times and sprint velocities	
Average acceleration (m/s <sup>2</sup> )	The change in velocity from a given distance by the time taken to travel the distance.
Average velocity (m/s)	The displacement over a given distance by the time taken to travel the distance.
Peak velocity (m/s)	Maximal average velocity between foot contacts [26]. Average velocity from maximum velocity to sprint end [27].
V <sub>o</sub> (m/s)	Theoretical velocity for zero horizontal force. As per previous methodology [11].
Temporal measures	
Contact time (ms)	Determined from landing and take-off ground contact of one foot. See individual paper methodologies for details [28,29,30,31].
Stride time (s)	First contact of one foot to the next contact of the same foot.
Sensor displacement and angular velocity	
Medio-lateral axis displacement	The time spent either side of the vertical axis [38].
Trunk displacement angle pick-up phase (°)	Angular orientation of the trunk (from IMU and stereophotogrammetric reference frame) during the phase ranging from block clearing to the upright position See paper methodology for details [32].
Trunk displacement angle whole phase (°)	Angular orientation of the trunk from “set” position block clearing upright position. See paper methodology for details [32].
Shank angular velocity (°/s)	Integration of angular acceleration to provide angular velocity. See paper methodology for details [33]
Forces	
D <sub>ref</sub> (%/m/s)	Rate of decrease in ratio of forces. As per previous methodology [11].
Horizontal force (N)	Horizontal / anterior-posterior force exerted by the ground on a body in contact with it. Described as F <sub>h</sub> as per methodology [14]. Described as F <sub>x</sub> as per methodology [34].
F <sub>v</sub> (N)	Vertical force exerted by the ground on a body in contact with it.
F <sub>res</sub> (N)	Resultant force from the average value of F <sub>h</sub> and F <sub>v</sub> [14,34]
F <sub>y</sub> (N)	Medio-lateral force exerted by the ground on a body in contact with it.
F <sub>o</sub> (N)	Theoretical maximal horizontal force the runner can apply at zero velocity. As per previous methodology [11].
P <sub>o</sub> (W)	Theoretical maximum power developed by the runner. As per previous methodology [11].
Resultant force (N)	Resultant of the tri-axial data from acceleration values (m/s <sup>2</sup> ) that were converted to force values [35].
S <sub>fv</sub> (N/m/s)	Slope of linear force-velocity relationship. As per previous methodology [11].

certainty, the factors responsible for this uncertainty warrant consideration. Nonetheless, the following sections attempt to lend some insight into the value and utility of these sensors in quantifying sprint performance under the following section titles: sprint times and sprint velocities; temporal measures; sensor displacement and angular velocity; and forces.

#### 4.1. Measures of sprint times and sprint velocities

##### 4.1.1. Validity

Higher levels of validity were found in 20 m sprint times (ICC  $\geq$  0.99,  $r \geq$  0.99, LoA bias  $6 \pm 1.8$  ms) and V<sub>o</sub> ( $r >$  0.80) [14,37]. Validity findings ranged in peak and average velocity ( $r = 0.32$ -0.95) [17,27]. Additional measures of validity not reported in Table 3 were mean differences:  $1.5 \pm 2.4\%$  in peak velocity,  $0.1 \pm 10.1\%$  in 0–10 m velocity,  $9.1 \pm 2.9\%$  in 10–20 m velocity, and  $< 5.3 \pm 4\%$  in all other 10 m velocity phases up to 100 m [27], and mean absolute error of 0.63 m/s (7.84%) in peak velocity [26].

Researchers used sensor placements of in-between scapula [17,36,37], sacrum [26,27] or lumbar [14]. There appears no consistent trend as to which placement was found more valid than another. The reasons for these variations have been attributed to the attachment methods (straps, tape, vest pocket), which may have influenced the accuracy of the findings through increased external noise due to the sensor being vibrated, or hit against the body during rapid sprint movements, especially during the start of a sprint. The sampling frequencies from the sensors used in these studies, ranged from 100 Hz to 1000 Hz. Though validity measures were found with lower sampling frequencies (~100 Hz), it would seem sampling frequency of  $\geq$  500 Hz enabled a greater level of validity. This is highlighted by Bastida Castillo et al. [37] who used two different IMU sampling rates (100 Hz and 1000 Hz) on different days. Though levels of agreement in sprint times were found with both sampling rates, the higher frequency slightly underestimated times (mean difference = -0.001 to -0.002 s), while the lower sample frequency slightly overestimated, with a larger range (mean difference = 0.000 to 0.009 s). Of note, this study used wireless transmissions from light gates to trigger the inertial sensor timing subsystem. This enables timing of specific distance check points to be incorporated into IMU data. The results reported by this study validate

the timing subsystems of each technology, but do not solve any challenges presented by sprint assessment. Therefore, caution is required when interpreting the validity of 20 m sprint times from wearable sensors based on this study.

Four research groups [17,26,36,37] used timing gates as the reference systems, another group used laser [27], and one group of researchers used a force plate [14]. Though measures against the laser and force plate were found to be valid, mixed validity results were found compared to the timing gate systems. For example, peak velocity was found to be valid (mean difference 1.5%,  $r = 0.92$ ) against laser [27], whereas a systematic difference (mean difference 7.8%) was found in peak velocity measures compared to timing gates [26]. Differences in sampling rates between reference systems and sensors, and methods of handling of the raw data may have contributed to the disparity in results. Moreover, discrepancies in findings between the studies may relate to the different sensors (IMU and accelerometer) used. Of note, different sprint variables and validity measures were used between studies, therefore, limiting the scope of these comparisons.

It would seem that the validity of velocity improved after the initial start and early acceleration phase of the sprint. This is highlighted by Parrington et al. (2016) who reported lower levels of correlation ( $r = 0.32$ ) during the initial 10 m, though beyond this distance higher levels of correlation agreement ( $r >$  0.85) were found for all distance markers up to 100 m. The authors also reported that the first split (0–10 m) had the highest variance (SD  $\pm$  10.1%), whilst the second split (10–20 m) had the highest per cent difference between the devices (9.1%). Moreover, Alexander et al. [17] found there was a smaller correlation ( $r = -0.32$  to -0.47) during 0–10 m compared to 10–20 m ( $r = -0.52$  to -0.53), suggesting that validity improves as the sprint distance increases. Similarly, Gurchiek et al. [26] found no systematic differences between the IMU and photocell estimates of average velocity for the final two 10 m splits (20–30 m and 30–40 m), whereas, the average velocity for the first two 10 m splits was significantly different. These differences in the start and early acceleration phase may be attributed to the variability associated with this type of motion (rapid change in body position), and the algorithm used to curve fit this phase not being fully representative of individual sprint performance. Moreover, a limitation of the study by Alexander et al. [17] relates to compensation of axis orientation due to accelerometer having its own

**Table 2**  
Study characteristics of the 15 articles included in the review.

Study	Sensor placement and attachment method	Sample (age, mass, height, 100 m best time)	Sprint description	Intraday reliability	Validity	Methodology quality
Purcell et al. [30]	Shank	6 healthy subjects (25.2 y)	3 x over ground sprint (distance and start position unknown) Analysis from steps: 1,3,5,9, and all steps	N	Y	10
Channells et al. [33]	Shank	6 athletes	Over ground sprint (distance and start position unknown) Analysis from 3 seconds rest between trials	N	Y	8
Waldron et al. [36]	In-between scapulae Attachment within a pouch in lycra vest	19 male rugby league players (14.7 ± 0.45, 1.76 ± 0.65 m, 72.8 ± 10.7 kg)	2 x 30 m over ground sprint. (standing start) 3 min rest between trials	Y	Y	11
Bergamini et al. [29]	L1 Attached via memory foam and elastic belt	6 amateur athletes (2 females, 4 males)	3 x 60 m over ground sprint indoor track (block start) 10 min rest between trials Analysis 2 strides from 40 m mark	N	Y	9
Bergamini et al. [29]	L1 Attached via memory foam and elastic belt	5 national track and field athletes (2 females, 3 males, 10.17-11.52 s)	3 x 60 m over ground sprint indoor track (block start) 10 min rest between trials Analysis 2 strides from 40 m mark	N	Y	9
Bergamini et al. [32]	L2 Attached via memory foam and elastic belt	5 male sprint athletes (23.8 ± 0.8 y; 72.4 ± 3.8 kg; 1.79 ± 0.07 m, 11.21 - 11.50 s)	4 x 12 m over ground indoor laboratory (block start) Analysis block start phase and the first three steps	Y	Y	9
Wundersitz et al. [35]	T2 Attachment within a pouch in lycra vest	12 males and 5 females team sport athletes (21 ± 2 y; 1.82 ± 0.08 m; 78.2 ± 11.6 kg)	4 x 10 m over ground sprint (start position not specified) 1 min rest between trials Step at 5 m analysed	N	Y	11
Alexander et al. [17]	In-between scapulae Attachment within a pouch in lycra vest	5 male university athletes (20.6 ± 0.5 y; 81.0 ± 10.6 kg)	3 x 40 m over ground sprint (standing start) 5 min rest between trials	N	Y	10
Ammann et al. [28]	Foot Attachment via elastic strap to the laces	7 males. 5 females (25.3 ± 3.2, 1.74 ± 0.08 m, 64.8 ± 10.2 kg)	3 x 40 m over ground sprint (start position not specified) 5 min rest between trials	Y	Y	11
Parrington et al. [27]	Sacrum Attachment via double sided tape	5 sub elite male sprinters	8 x 100 m over ground sprint (start position not specified) Self-selected rest between trials	N	Y	10
Schmidt et al. [31]	Ankle (lateral border) Attachment via elastic strap	12 track and field athletes (10 males, 2 females)	3-5 x 60 m over ground sprint (start position not specified) 10 min rest between trials Analysis 15 m during maximum velocity	N	Y	10
Bastida Castillo et al. [37]	In-between scapulae Attachment within a pouch in lycra vest	3 athletes	6 x 20 m over ground sprint (start position not specified)	N	Y	9
Gurchiek et al. [34]	Sacrum Attachment via double sided tape and elastic strap	15 subjects (12 males, 3 females, 23.2 ± 2.1 y; 1.78 ± 0.09 m; 75.5 ± 12.5 kg)	6 x sprint take-off indoor laboratory (standing split stance) Initial two-foot push and first contact step	N	Y	11
Kenneally-Dabrowski et al. [38]	In-between scapulae Attachment within a pouch in lycra vest	13 male rugby union players (23.8 ± 2.4 y; 1.86 ± 0.08 m; 102.3 ± 12.2 kg)	3 x 40 m over ground sprint (start position not specified) Analysis of steps between 25 m and 32.2 m	N	Y	11
Setuain et al. [14]	L4-L5	16 recreational runners 8 females (26.1 ± 4.4 y; 1.66 ± 0.07 m; 59.8 ± 8.0 kg). 8 males (31.5 ± 6.3 y; 1.77 ± 0.07 m; 78.3 ± 13.0 kg)	4 x 20 m over ground sprint (start position not specified) 90 sec rest between trials Analysis all steps after the initial 2 steps	Y	Y	10
Gurchiek et al. [26]	Sacrum Attachment via double sided tape and elastic strap	28 collegiate level sprinters and general students (16 males, 12 females, 20.9 ± 2.3 y; 1.73 ± 0.09 m; 71.1 ± 11.7 kg)	3 x 40 m over ground sprint (crouched 4-point start position) 3 min rest between trials	Y	Y	11

**Table 3**  
Wearable sensor systems specifications and reference systems.

Study	Sensor type	Sensor hardware specification	Reference system	Synchronisation method	Variables	Post Processing
Purcell et al. [30]	Tri-axial accelerometer (Analog Devices ADXL321)	Tri-axial accelerometer ( ± 18 g) Sampled at 250 Hz	One force platform (Kistler piezoelectric force plate) Sampled at 1000 Hz	Synchronisation pulse	Contact time	Minimum in the x axis acceleration for initial contact. Minimum and max in x and z axis accelerations for toe-off, with the mean used define the end of contact time.
Channells et al. [33]	Dual-axial accelerometer (Analog devices ADXL321)	Dual-axial accelerometer ( ± 18 g) Sampled at 250 Hz	One high-speed camera	Synchronised but no details	Shank angular velocity	Low pass 100 Hz RC filter Integration and double integration of the tangential data provided the angular velocity No details provided
Waldron et al. [36]	Tri-axial accelerometer (GPSports, SPI-Pro, Canberra, Australia)	Tri-axial accelerometer ( ± 6 g) Sampled at 100 Hz	Timing gates (Brower Timing Systems, Draper, UT) at 60 cm height	No details provided	Peak velocity at 10 m, 20 m, 30 m	
Bergamini et al. [29]	IMU (FreeSense, Sensorize, Italy)	Tri-axial accelerometer ( ± 6 g) and a tri-axial gyroscope ( ± 500 deg/s) Sampled at 200 Hz	6 adjacent in ground force platforms (Z20740AA, Kistler, Switzerland; total surface: 6.6 × 0.6 m) Sampled at 200 Hz	Synchronisation strike on force plate	Contact time Stride time	Noise reduction with wavelet based smoothing. Min and max of acceleration signal to determine ground contact phases. Identified key features in raw data Gyroscope-based algorithms
Bergamini et al. [29]	IMU (FreeSense, Sensorize, Italy)	Tri-axial accelerometer ( ± 6 g) and a tri-axial gyroscope ( ± 500 deg/s) Sampled at 200 Hz	One high-speed camera (Casio Exilim EX-F1, Japan.), 5 m away from the lane. Sampled at 300 Hz (70 Hz Butterworth filter)	No synchronisation performed	Contact time Stride time	Noise reduction with wavelet based smoothing Algorithms derived from the above force data.
Bergamini et al. [32]	IMU (FreeSense, Sensorize, Italy)	Tri-axial accelerometer ( ± 6 g) and a tri-axial gyroscope ( ± 500 deg/s) Sampled at 100 Hz	9-camera stereophotogrammetric system (Vicon MX3, Oxford, UK) Sampled at 200 Hz	Synchronisation via sudden standing trunk flexion-extension.	Trunk displacement angle	Noise reduction with low-pass filter (40-point moving average) Adaptive Kalman filter Filter ratios altered for different sprint phases (i.e. sprint start), and Ad Hoc trials to determine constants Quanternion-based Initial offset was needed for every subject Butterworth filter 4 <sup>th</sup> order dual pass at 10, 15, 20, 25 Hz
Wundersitz et al. [35]	Tri-axial acceleration sensor (Bosch, BMA150, Stuttgart, Germany)	Tri-axial acceleration sensor ( ± 8 g) Sampled at 100 Hz	In-ground force plate (BP600900, Advanced Mechanical Technology Inc., Watertown, USA) Sampled at 100 Hz (10 Hz data smoothed)	Synchronisation via video software to identify ground contact	Crania-caudal force Resultant force	
Alexander et al. [17]	Tri-axial accelerometer (GPSports, SPLHPU, Canberra, Australia)	Tri-axial accelerometer ( ± 16 g) Sampled at 100 Hz	Dual-beam timing gates (Swift, Brisbane, Australia)	Synchronisation through time stamps of sensor and camera	Average acceleration at 0-10 m and 10-20 m	3. 10 point moving average Start was identified as the instant from the minimum anterior-posterior acceleration trace that increased above zero. The sprint time, measured by the timing gates, was added to the starting point to signify the end of the trial. Min and max of acceleration signal to determine ground contact phases
Ammann et al. [28]	IMU (InvenSense, Inc., San Jose, CA, USA)	Tri-axial accelerometer ( ± 16 g), a tri-axial gyroscope, and a tri-axial magnetometer Sampled at 1000 Hz	One high-speed camera (HSC Marathon Ultra) Sampled at 1000 Hz	No details provided	Contact time	
Parrington et al. [27]	IMU (iMeasureU Blue Thunder IMU, Auckland, New Zealand)	Tri-axial accelerometer ( ± 16 g), tri-axial gyroscope (2000 deg/s), and a tri-axial magnetometer ( ± 1200 deg/s) Sampled at 500 Hz	Laser gun (LAVEG Sport, Jenoptik, Germany) Sampled at 100 Hz	Synchronisation method was start and stop times in IMU software	Peak velocity at every 10 m from 0 to 100 m	Horizontal accelerations were isolated, integration to calculate velocity, and further integration used to calculate displacement. Madgwick Filter Rotation matrices (to get acceleration), with double integration to get (continued on next page)

Table 3 (continued)

Study	Sensor type	Sensor hardware specification	Reference system	Synchronisation method	Variables	Post Processing
Schmidt et al. [31]	IMU	Tri-axial accelerometer ( ± 16 g range) and tri-axial gyroscope (16 bit and ± 1000 deg/s range) Sampled at 1000 Hz	OptojumpNext photoceell system (Microgate, Bolzano, Italy.) Sampled at 1000 Hz	No details provided	Contact time	displacement. Broken into piecewise functions for sprint phases No filtering of raw data Peak detection method with critical threshold (usually 5 g) and min and max of acceleration signal to determine ground contact Reset of analog and digital signal after each step to avoid drift IMU software used an atomic clock and made automatic selection from mark to mark.
Bastida Castillo et al. [37]	IMU (WIMU PRO, RealTrack System, Almeria, Spain)	Tri-axial accelerometer ( ± 16 g range), tri-axial gyroscope ( ± 2000 deg/s range), and a tri-axial magnetometer Sampled at 100 and 1000 Hz	Timing gates (ChronoJump, Spain)	No details provided	20 m time	
Gurchiek et al. [34]	IMU (Yost Data Logger 3-Space Sensor, YEI Technology, Portsmouth, OH, USA)	Tri-axial accelerometer ( ± 24 g) and a tri-axial gyroscope ( ± 2000 degree/s) Sampled at 450 Hz	Force plate (AMTI, Watertown, MA) Sampled at 1000 Hz	Synchronisation using cross-correlation of data obtained from two countermovement jumps prior to the movement trials No details provided	Step-average force and Instantaneous force for $F_s, F_y, F_v, F_{res}$	Low pass filter: 30 Hz Quanternion-based Rotation matrices to obtain IMU estimate of force in the force plate frame. Min and max of acceleration signal to determine ground contact phases Butterworth low pass filter at 100 Hz. Noise reduction with 5 m splits, using least-squares fit was used to estimate bias in acceleration, and then velocity based on corrected acceleration signals (with bias). For variables of interest, integration of the horizontal acceleration signal to get horizontal velocity and then integrate that velocity to get distance covered. Instantaneous horizontal and vertical GRF opponents were calculated using instantaneous centre of mass acceleration Sensor Orientation: an on-board algorithm was used to produce orientation data - the output is all acceleration signal expressed in a track-fixed reference frame (earth reference frame). Low pass filter at 1 Hz Kalman filter
Kennally-Dabrowski et al. [38]	Tri-axial accelerometer (GPSports, Canberra, Australia)	Tri-axial accelerometer ( ± 16 g) Sampled at 100 Hz	8 contiguous force plates (Kistler, Amherst, MA, USA) Sampled at 1000 Hz	No details provided	Medio-lateral displacement Stride time	
Setuain et al. [14]	IMU (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, Netherlands)	Tri-axial accelerometer, a tri-axial gyroscope, and a tri-axial magnetometer Sampled at 120 Hz	10 m force platform system (Raute Precision, Lahti, Finland) Sampled at 1000 Hz	Synchronisation of time via two pulse signals	$F_h, F_v, F_o, V_o, S_v, D_{if}$	
Gurchiek et al. [26]	IMU (Yost Data Logger 3-Space Sensors, YEI Technology, Portsmouth, OH, USA)	Tri-axial accelerometer ( ± 24 g range), tri-axial gyroscope ( ± 2000 deg/s range), and a tri-axial magnetometer Sampled at 450 Hz	Timing gates (Brower Timing Systems, Draper, UT)	Synchronisation of frames with the initial forward movement of the IMU and of hand touch coming off the touch sensor	Peak velocity Velocity at every 10 m from 0 to 40 m	

$D_{if}$  - rate of decrease in ratio of forces;  $F_h$  - horizontal force;  $F_o$  - horizontal force at zero velocity;  $F_{res}$  - resultant force;  $F_v$  - vertical force;  $F_x$  - anterior-posterior force;  $F_y$  - medio-lateral force;  $F_z$  - ground reaction force; IMU - inertial measurement unit;  $P_o$  - maximum power;  $S_N$  - Slope of linear force-velocity relationship;  $V_o$  - velocity for zero horizontal force.

**Table 4**  
Validity and reliability results from the wearable sensors.

Study	Validity/reliability	Variables	Sensor mean	Reference system mean	Absolute reliability CV (%)	LoA bias	RMSE	ICC (95% CI)	r (95 % CI)	
Purcell et al. [30]	Concurrent validity (accelerometer vs. force plate)	Contact time (ms)	14.5 ± 1.9	16.5 ± 1.2	9.81	2.05 ± 3.62				
		Step 1							0.951	
		Step 3							0.967	
		Step 5							0.991	
		All steps							0.997	
Channells et al. [33]	Concurrent validity (accelerometer vs. high-speed camera)	Shank angular velocity (°/s)					89.7-143.2 (5.0-9.1%)			
		10 m velocity (km/h)	18.3 ± 1.7	20.5 ± 1.2	8.54	2.19 ± 3.34				
		20 m velocity (km/h)	20.7 ± 1.4	22.7 ± 1.2	6.61	2.01 ± 2.18				
		30 m velocity (km/h)			2.06	0.05 ± 1.05				
		10 m velocity (km/h)			1.92	-0.05 ± 1.17				
Waldron et al. [36]	Concurrent validity (accelerometer vs. timing gates)	30 m velocity (km/h)	125 ± 15		2.02	-0.09 ± 0.84				
		Peak velocity (km/h)			0.78	0.00 ± 0.80				
		Contact time (ms)				25				
		Stride time (ms)	495 ± 40			25				
		Contact time (ms)	105 ± 15							
Bergamini et al. [29]	Concurrent validity (IMU vs. high-speed camera)	Stride time (ms)	455 ± 15			25				
		Trunk displacement angle whole phase (°)							0.994 ± 0.013	
		Trunk displacement angle pick-up phase (°)								0.995 ± 0.015
		Trunk displacement angle whole phase (°)								0.998 ± 0.002
		Trunk displacement angle pick-up phase (°)								0.998 ± 0.001
Wundersitz et al. [35]	Concurrent validity (accelerometer vs. force plate)	Crania-caudal force (N)	1582 ± 408	1731 ± 245	15-16.2				0.12-0.39	
		Resultant force (N)	2194 ± 317	1755 ± 253	11.7-16.4				0.35-0.76	
		0-10 m average acceleration (m/s <sup>2</sup> )								
		Raw output			22.49	1.11 (-1.67, 3.90)				-0.447
		3 point moved average			21.41	1.26 (-1.45, 3.97)				-0.403
Alexander et al. [17]	Concurrent validity (accelerometer vs. timing gates)	10 point moved average			20.17	1.53 (-1.13, 4.13)				
		10-20 m average velocity (m/s)			20.22	2.87 (-1.87, 7.61)				
		Raw output								2.88 (-1.88, 7.63)
		3 point moved average			20.23	2.91 (-1.81, 7.64)				-0.516
		10 point moved average			20.01					-0.526
Ammann et al. [28]	Concurrent validity (IMU vs. high-speed camera)	Contact time (ms)	118.3 ± 11.6	117.5 ± 9.0				0.808		
		Intraday reliability (IMU)			2.9-3.8					(0.653-0.894) 0.911-0.960

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Table 4 (continued)

Study	Validity/reliability	Variables	Sensor mean	Reference system mean	Absolute reliability CV (%)	LoA bias	RMSE	ICC	Relative reliability r
Parrington et al. [27]	Concurrent validity (IMU vs. laser)	Peak velocity (m/s) 0-10 m velocity (m/s) 10-20 m velocity (m/s) 20-30 m velocity (m/s) 30-40 m velocity (m/s) 40-50 m velocity (m/s) 50-60 m velocity (m/s) 60-70 m velocity (m/s) 70-80 m velocity (m/s) 80-90 m velocity (m/s) 90-100 m velocity (m/s)							0.92 0.32 0.85 0.89 0.90 0.92 0.93 0.95 0.95 0.93 0.86
Schmidt et al. [31]	Concurrent validity (IMU vs. optojump)	Contact time (ms)	124.6 ± 10.6			-2.5 (-11.8, 6.8)			
Bastida Castillo et al. [37]	Concurrent validity (IMU vs. timing gates)	20 m time (s)		5.04 ± 0.20			1.00	1.00	1.00
		100 Hz IMU	5.04 ± 0.20						
		1000 Hz IMU	5.14 ± 0.25	5.14 ± 0.25		0.06 (-2.9, 4.1)	1.00	1.00	1.00
Gurchiek et al. [34]	Concurrent validity (IMU vs. force plate)	Step-average force							
		F <sub>x</sub> (N)				2.52 (77.5, 77.5)	37.70		0.89
		F <sub>y</sub> (N)				-15.9 (-144.2, 112.3)	66.30		0.35
		F <sub>v</sub> (N)				-34.1 (-171.8, 103.7)			0.88
		F <sub>res</sub> (N)				-29.7 (-163.8, 104.4)	54.19		
		F <sub>res</sub> (N)					70.22		0.90
		Instantaneous force							
		F <sub>x</sub> (N)					400.1 ± 219.6		0.64 ± 0.15
		F <sub>y</sub> (N)					406.7 ± 260.8		-0.24 ± 0.31
		F <sub>v</sub> (N)					368.2 ± 210.7		0.50 ± 0.30
		F <sub>res</sub> (N)					466.3 ± 282.0		0.49 ± 0.29
Kenneally-Dabrowski et al. [38]	Concurrent validity (accelerometer vs. force plate)	Medio-lateral axis displacement Stride time (s)				0.189 (-0.286, 0.663)			0.088
						-0.26 (-0.09, 0.039)			
Setuain et al. [14]	Concurrent validity (IMU vs. force plate)	F <sub>h</sub> (N)	119 ± 92	116 ± 105		(-100.8, 93.0)			-0.177 0.87 (0.87, 0.87)
		F <sub>v</sub> (N)	661 ± 135	670 ± 145		(-126.5, 144.2)			0.88 (0.88, 0.88)
		F <sub>o</sub> (N)	383 ± 110	391 ± 103		(-42.7, 57.9)			0.97 (0.96, 0.98)
		V <sub>o</sub> (m/s)	8.61 ± 0.85	8.42 ± 0.69		(-1.28, 0.80)			0.76 (0.71, 0.81)
		P <sub>o</sub> (W)	873 ± 246	779 ± 241		(-234.2, 89.9)			0.90 (0.88, 0.91)
		S <sub>o</sub> (N/m/s)	-44.6 ± 12.7	-46.2 ± 10.7		(-9.64, 6.40)			0.93 (0.91, 0.94)
		D <sub>o</sub> (%/m/s)	-6.32 ± 1.08	-5.76 ± 0.68		(-1.38, 2.50)			0.33 (0.26, 0.41)
	Intraday reliability (IMU)	F <sub>o</sub> (N)				(-97.46, 61.84)			0.93 (0.79, 0.98)
		V <sub>o</sub> (m/s)				(-0.58, 0.51)			0.88 (0.65, 0.96)

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Table 4 (continued)

Study	Validity/reliability	Variables	Sensor mean	Reference system mean	Absolute reliability CV (%)	LoA bias	RMSE	ICC	Relative reliability r	
Gurchiek et al. [26]	Concurrent validity (IMU vs. timing gates)	P <sub>o</sub> (W)	8.50	8.30 ± 1.09		(-175.2, 105.0)			0.95 (0.83, 0.98)	
		S <sub>w</sub> (N/m/s)	± 1.24			(-9.34, 13.01)			0.89 (0.70, 0.97)	
		D <sub>rt</sub> (%/m/s)				(-2.03, 2.36)			0.66 (0.20, 0.88)	
	Intraday reliability (IMU)	Peak velocity (m/s)								
		0-10 m velocity (m/s)	7.49 ± 0.86	7.73 ± 0.89						
		10-20 m velocity (m/s)	8.11 ± 1.09	8.16 ± 1.02						
		20-30 m velocity (m/s)	8.42 ± 1.24	8.29 ± 1.08						
		30-40 m velocity (m/s)	8.50 ± 1.24	8.30 ± 1.09						
		Peak velocity (m/s)								
		0-10 m velocity (m/s)					-0.12 (-0.59, 0.34)			
		10-20 m velocity (m/s)					-0.25(-1.18, 0.68)			
		20-30 m velocity (m/s)					-0.05 (-1.30, 1.20)			
30-40 m velocity (m/s)					0.13 (-1.32, 1.59)					

CV – coefficient of variance; CI – confidence interval; D<sub>rt</sub> – rate of decrease in ratio of forces; F<sub>h</sub> – horizontal force; F<sub>p</sub> – resultant force; F<sub>v</sub> – vertical force; F<sub>x</sub> – anterior-posterior force; F<sub>y</sub> – medio-lateral force; ICC – intraclass correlation coefficient; LoA – level of agreement; P<sub>p</sub> – maximum power; r – Pearson's correlation coefficient; RMSE – root mean square error; S<sub>w</sub> – Slope of linear force-velocity relationship; V<sub>o</sub> – velocity for zero horizontal force.

axis frame of reference affecting the validity comparison.

4.1.2. Reliability

Reliability levels were reported for peak velocity (CV ≤ 1%, LoA bias 0.00 ± 0.8 km/h), average velocity (CV ≤ 3%, and V<sub>o</sub> (ICC ≥ 0.88, LoA 95% range -0.58 to 0.51 m/s) [14,36]. Waldron et al. [36] reported peak velocity (CV = 0.78%, 95% LoA bias 0.00 ± 0.08 km/h) and velocity at all distance marks 10–30 m (CV = < 3%, LoA bias -0.09 ± 1.17 km/h) reliable. Setuain et al. (2017) also measured sprint performance over a short distance (20 m), and reported coefficients (ICC ≥ 0.88, LoA 95% range -0.58 to 0.51 m/s) with respect to the reliability of V<sub>o</sub>. Gurchiek et al. (2018) reported greater reliability in 0–10 m (LoA bias -0.12 m/s) and 30–40 m (LoA bias 0.13 m/s) average velocity compared to 10–20 m (LoA bias -0.25 m/s)). Possible reasons for differences may relate to individual changes in velocity throughout 10–20 m as subjects start from 0 m/s and may attain similar max velocity.

4.1.3. Summary In summary, higher levels of validity were found in 20 m sprint times and V<sub>o</sub>, with mixed levels of validity found for peak and average velocity. However, peak velocity, average velocity, and V<sub>o</sub> were all reported to be reliable. It would seem that variables are less accurate during the start of the sprint and early acceleration phase (< 20 m), most likely due to the rapid changes in body and limb positions causing a greater amount of external noise and complications with sensor orientation. Moreover, the validity and reliability of the sprint measures seem to be affected by the sampling frequency and reference system used.

4.2. Temporal measures

4.2.1. Validity

Levels of validity were reported for contact time (r ≥ 0.99, ICC ≥ 0.8, LoA bias -8 to 25 ms and stride time (LoA bias 25 ms) [8,28–30]. Additional measures of validity not reported in Table 3 were mean difference of 4.3 ms (3.4%), and systematic error of -2.5 ± 4.8 ms in contact time [8], and mean difference of 0.1 ± 6.7% and systematic bias of 0.4 ms in contact time [28].

Three researcher groups used sensor placements of the lower leg [8,28,30], with one group using the lumbar [29], and one group using in-between the scapulae [38]. It would seem that the highest validity was associated with lower leg and lumbar placements, whereas the in-between scapulae placement was found to be problematic. The reasons for these variations may be attributed to the sensor is further away from the impact point (the foot), and attachment issues within the vest affecting shock attenuation which may reduce accelerations recorded, resulting in lower validity levels. The sampling frequencies used in these studies ranged from 50 Hz to 1000 Hz, with improved validity found with ≥ 200 Hz.

Three groups [29,30,38] used force plates as the reference systems, with two groups using a high-speed camera [28,29] and one group using a Optojump photocell system [8]. Though measures against the photocell system and high-speed camera were found to have higher validity, mixed results were found for the force plate comparisons. Discrepancies in findings between the studies in step detection validity may relate to the different phases of the sprint being measured (< 10 m, 25–32 m, and 40 m). However, these differences may also relate to the previously mentioned sensor positions with Kenneally-Dabrowski et al. (2017) using an in-between scapula placement and reporting a non-significant relationship (r = -0.177).

4.2.2. Reliability

Reliability levels were reported for contact time (CV ≤ 4%, ICC ≥ 0.91) from one group [28]. The authors noted that small differences in velocity, that occur naturally between individuals and trials, reflect in the variability of the measures. As such, the authors proposed that sensors may be used to measure contact times, whereby measured

changes reflect true changes [28].

#### 4.2.3. Summary

In summary, it appears that: 1) the more lower-limb distal the sensor is located (i.e. the closer the sensor was to the foot), and 2) the higher the sample rate, the more accurate the detection of temporal step variables. Contact times were found to have higher validity and reliability, whilst validity was also found in measures of stride time.

### 4.3. Sensor displacement and angular velocity

#### 4.3.1. Validity

Levels of validity were found in trunk angular displacement ( $r \geq 0.99$ ) and shank angular velocity (RMSE < 10%) [32,33]. Additional measures of validity not reported in the Table 3 were mean differences in trunk angular displacement at the following identification points: on your marks phase  $1 \pm 1^\circ$ , set phase  $1 \pm 1^\circ$ , transition phase  $4 \pm 4^\circ$ , pick-up phase  $9 \pm 6^\circ$  [32].

Sensor placements varied from in-between scapula [38], lumbar [29], and shank [33]. It would seem that the strongest validity has been associated with lumbar sensor placement, whereas the in-between scapulae placement was found problematic. Sensors placed closer to the area of interest appear to result in a higher level of validity i.e. lumbar placement for trunk displacement, and shank placement for shank velocity. The sampling frequencies used ranged from 100 Hz to 250 Hz, with higher levels of validity found when  $\geq 200$  Hz were used. However, as different variables were measured, the comparisons in placement and sampling frequency is limited and conclusions should be made with caution.

Two groups used high speed cameras [32,33], and one group used force plates [38] as reference systems. Analysis from a block start and initial three steps, revealed high levels of validity ( $r = 0.994$ , RMSE = 4%), and low levels of disparity (<  $10^\circ$ ) in trunk angular displacement with a lower back sensor placement [32]. The authors also reported small RMSE errors ( $1 \pm 1^\circ$ ) during on your marks and set phases of a sprint, though the errors were larger for the set ( $4 \pm 4^\circ$ ) and transition comparisons ( $9 \pm 6^\circ$ ). Channells et al. [33] used a tri-axial accelerometer, attached to the shank, and found that the sensor can accurately measure angular velocity with RMSE < 10%. Though measures against the high-speed cameras were found to have high levels of validity, Kenneally-Dabrowski et al. [38] reported minimal association was found between sensor (in-between scapulae placement) and force plate data in medio-lateral axis step displacement (correlation 0.088) during the maximum velocity phase. As previously mentioned, given the small amount of literature as well as the variety of assessments, it is uncertain how the reference systems that were used may have affected the validity.

#### 4.3.2. Reliability

Only Bergamini et al. [32] reported reliability ( $r = 0.998$ , RMSE = 5%) in trunk angular displacement with a lower back sensor placement that was recorded during the initial start and three steps [32].

#### 4.3.3. Summary

In summary, it would seem that sensors sampled at  $\geq 200$  Hz, and placed closer to the area of measurement, result in higher validity when quantifying displacement measures. Body segment displacement and velocity appears to result in greater validity, as compared to step axis displacement. However, as only two studies quantified displacement, across different sites, with minimal validity and reliability measures, clearly more research is required.

### 4.4. Forces

#### 4.4.1. Validity

Levels of validity were found for resultant peak force ( $r \geq 0.76$ ), vertical and horizontal force ( $r \geq 0.88$ ), and  $F_o$ ,  $P_o$ , and  $S_{fv}$  ( $r \geq 0.94$ ) [14,34,35].

Researchers have used sensor placements in different positions on the back: T2 [35], lumbar [14], and sacrum [34]. It would seem that the highest validity was associated with sensor placement closer to the centre of mass (lumbar and sacrum), whereas the T2 placement resulted in mixed levels of validity, depending on the measurement of interest. Similar to temporal measures, the reasons for these variations may be attributed to differences in sensor placement and attachment i.e. the sensors further away from the impact point (the foot) and housed in lycra vest appear to result in lower validity. Moreover, Wundersitz et al. [35] noted that the sensor's location on the upper body may promote misalignment of the crania-caudal axis from the global vertical axis, and further consideration of device location and harness design to limit unwanted movement is required.

The sampling frequencies used in these studies to quantify the variables of interest ranged from 100 Hz to 450 Hz, with improved validity found with  $\geq 120$  Hz. Though lower levels of validity were found with sampling at 100 Hz, the placement of the sensor used by Wundersitz et al. [35] may have attributed these findings. All three groups used force plates as the reference systems for comparison. However, though Setuain et al. [14] and Gurchiek et al. [34] had force plates sampling at 1000 Hz, Wundersitz et al. [35] had force plate sample rate of 100 Hz. Therefore, the lower sampling rate with both the sensor and force plate, coupled with the sensors placement, may have contributed to the lack of validity found from this group. Moreover, the highest level of validity ( $r = 0.76$ ) from this group was found in resultant forces when data smoothing at 10 Hz positively affected the resultant accelerometer data.

Of note, similar to previous variables, it seems that the phase of the sprint measured can impact on the validity of force measures. From the initial push from both feet and first step from a standing start, GRF and resultant forces were compared across measurement modalities in two ways: instantaneous sensor forces compared to reference sampled GRF and step-average GRF by Gurchiek et al. [34]. Levels of validity were higher for all step-average GRF values ( $r > 0.89$ ) except for the medio-lateral component ( $F_y$ ) of GRF ( $r = -0.35$ ). Levels were lower for instantaneous values of GRF ( $r > 0.49$ ), with medio-lateral GRF ( $-0.24 \pm 0.31$ ) found to have the greatest variance [34]. From the 5 m mark, Wundersitz et al. [35] reported mixed agreement levels between systems in crania-caudal forces ( $r = 0.12-0.39$ ) and in resultant forces ( $r = 0.35-0.76$ ). In contrast to initial step measures in the other two studies, analysed steps during a 20 m sprint (the initial two take-off steps were not analysed) found the vertical and horizontal GRF values measured with both systems were correlated ( $r = 0.88$  for both GRF vectors).

#### 4.4.2. Reliability

Reliability was reported for  $F_o$ ,  $P_o$ , and  $S_{fv}$  (ICC  $\geq 0.88$ ) [14]. iz- Though the  $D_{rf}$  was found to result in lower levels of reliability (ICC = 0.66). Setuain et al. [14] noted that the convergence of forces at the centre of mass resulted in greater variability in the  $D_{rf}$  obtained from the IMU, thus lower levels of reliability. Furthermore, the aforementioned forces depended on the sprinter's technique and/or ability to apply horizontal GRF during the sprint at increasing velocities, therefore, the error in rate of decrease in ratio of forces may be associated with individual differences in sprint mechanics. This highlights the importance of sensor placement, particularly as the centre of mass is moved abruptly during the start of a sprint, with more research needed to understand the effect of placement and its impact on data collection.

#### 4.4.3. Summary

In summary, resultant peak force, vertical and horizontal force, and  $F_o$ ,  $P_o$ , and  $S_{fv}$  were found to have higher levels of validity. The  $D_{rf}$  had lower validity and reliability, while the medio-lateral component of force was also found to have low validity. Similar to previous measurement variables, it appears that measures of force are less accurately collected during the start and early acceleration phase of the sprint, possibly due to the changing body position and changing force profile. Greater accuracy was found with higher sampling frequencies ( $\geq 100$  Hz) and sensor placement closer to the centre of mass, though different measures were collected between studies, warranting caution in interpreting these findings.

#### 4.5. Limitations

A limitation of this review relates to multiple differences in methodologies between studies. Essentially there is a large number of variables that are likely to impact data collection and thus each variable has not been isolated and assessed for its contribution. Thus, variations in methodologies impact multiple variables, making critical analysis on any one variable problematic. Specifically, differences in the placement, sampling frequencies and specification of the wearable sensor devices makes definitive conclusions problematic. Moreover, a range of reference systems were used, which differed in set-up and data capture capabilities. Differences in measure of sprint performance also varied between studies. A range of different statistical measures were used, though no inter-day reliability measures have been completed. Moreover, the use of correlations instead of ICCs in several studies and no measures of absolute consistency/typical error highlights a statistical limitation in the research reviewed. Therefore, caution is warranted when interpreting the findings and this article simply states the values published in the respective articles and leaves the reader to make their own interpretations of the findings.

#### 4.6. Practical applications and future considerations

Though a clear understanding of the validity and reliability of inertial sensors has yet to be found, some general recommendations can be made. Inertial sensors can be used to measure the following variables with some confidence: contact times, resultant peak force, vertical and horizontal force, and  $F_o$ ,  $P_o$ , and  $S_{fv}$ . Sensors attached closer to the centre of mass appear more appropriate for measuring sprint performance (i.e. sprint times and velocity) and collecting force data. Sensors attached distally (i.e. closer to the foot), provide a more accurate detection of temporal step measurement variables. With the abrupt changes in body position during the initial start take-off, the in-between scapulae position (vest pouch) may be subjected to more movement for this phase of the sprint and thus less valid and reliable, though more research is needed into both positions. Sensor attachment which allows freedom of movement and minimises skin movement artefact are other important aspects requiring consideration. Straps and adhesive tapes were mainly used to attach the sensors to the segments of interest in the studies in this review. These methods are flexible and convenient to use, however, errors caused by skin movement may be considerable. Sensors placed in-between the scapulae may result in extra external noise when housed in a vest due to the sensor movement and possible impacts onto the body, and therefore maybe better placed on the skin for greater accuracy. Another important note related to sensor attachment was to ensure the axes of the wearable sensors align with the anatomical axes of the segments. After sensor attachment, static and dynamic calibration procedures need to be performed to obtain segment calibration. Moreover, the accuracy of the orientation estimation can be affected by calibration stages of the individual sensors (i.e. accelerometer, gyroscope, and magnetometer), biases, diverse noise types, and sensor fusion algorithm issues. Using higher sampling rates ( $> 200$  Hz) improves agreement levels when measuring sprint performance, temporal,

displacement and force measures. Practitioners should consider higher end sampling rates (500–1000 Hz) to improve precision and accuracy during data collection. This is improving with increasing capabilities of technology. Synchronisation of sensors and references systems should be performed with an electronic trigger, rather than observational technique, which could lead to differences between measurement methods. Information on filtering frequencies was minimal, therefore, future research is needed on data logging and data processing methodologies.

Future research is required to completely assess validity and reliability measurements from wearable sensors during sprint-running. Specifically, the validity and reliability of short distance sprint split times ( $< 20$  m), and the inter-day reliability of additional variables of interest. As average and peak velocity was found to show mixed validity from different methodologies, further research is required to ascertain whether wearable sensors can accurately measure these variables. As mixed results have been found in measures of every 10 m during a sprint, future studies may wish to investigate the analysis of multiple step contacts, rather than a single step contacts and arbitrary distance windows for the assessment of kinetic and kinematic data. Step analysis can be split into various groupings such as groups of every 4 steps [39,40], or initial 2 steps for the start and steps 3–10 for initial acceleration [41]. Moreover, future research is required to fully understand the intra and inter-day reliability of all variables of interest from wearable sensors.

## 5. Conclusion

Wearable inertial sensors enable the collection of kinematic and kinetic data during sprinting in a simple and time efficient manner outside of a laboratory setting. A wide range of validity and reliability measures were used and compared to different referenced systems with the accuracy of measurements seemingly affected by methodological differences. In summary, caution is warranted for findings related to the start and initial acceleration phase of sprint-running, as reduced validity and reliability was found during variables measured  $< 20$  m. This is most likely due to the movement of the lower back in relation to the centre of mass as the sprinting posture becomes more upright. Sensors attached to a more distal placement (i.e. closer to the foot), provide a more accurate detection of temporal step measurement variables, though sensors attached on the lower back appear suitable for measuring sprint performance (i.e. sprint times and velocity) and force data. Using a higher the sample rate ( $> 200$  Hz) improves accuracy levels in sprint times and velocity, temporal, displacement and force measures. The attachment method used to fix a sensor to the body requires consideration in sprinting studies as the high-speed movements of the trunk and limbs means that an appropriate attachment method could minimise skin and clothing artefact movements. Moreover, the attachment method and calibration method can impact on potential errors caused by improper alignment to anatomical axes. Though the validity and reliability of wearable inertial sensors appears promising, due to the small number of studies in this area, and differences in methodologies, additional research is needed to verify the findings of this review.

The authors report no conflict of interests related to this article.

## Appendix A. Details of search strategy

### Pubmed

Search = ((run\* OR sprinting OR sprint\*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid\* OR reliabil\*))

59 retrieved

### SPORTDiscus (1988–2018)

Search = ((run\* OR sprinting OR sprint\*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid\* OR reliabil\*))

Source types = academic journals

143 retrieved

Web of science (1980–2018)

Search = ((run\* OR sprinting OR sprint\*) AND (IMU OR inertial sensor OR wearable sensor OR accelerometer OR gyroscope) AND (valid\* OR reliabil\*))

Categories = sport science

Document type = article, proceedings paper, review

172 retrieved

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