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Original research

The validity of raw custom-processed global navigation satellite systems data during straight-line sprinting across multiple days

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ABSTRACT

Objectives: (1) Determine the validity of instantaneous speed and acceleration and (2) the variation in validity over time (multiple sessions) for global navigation satellite systems (GNSS) devices.
Design: Repeated measures.
Methods: 10-Hz GNSS devices from Statsports (n = 2, Apex Pro) and Catapult (n = 2, Vector S7) were examined, whilst a speed laser manufactured by MuscleLab (n = 1, LaserSpeed) was the criterion measure, sampling at 2.56 kHz, with data exported at 1000 Hz. Ten participants completed 40 m sprinting and changes of pace on three separate days. Root mean square error (RMSE) was used to assess the magnitude and direction of the difference between GNSS and criterion measures (instantaneous speed, instantaneous acceleration). Linear mixed models were built to assess the difference in validity across days.
Results: RMSE ranged from 0.14 to 0.21 $m \cdot s^{-1}$ and 0.22 to 0.47 $m \cdot s^{-2}$ for speed and acceleration, respectively showing strong agreement. There were small variations in the agreement to criterion between days for both devices for speed (Catapult RMSE = 0.12 to 21 $m \cdot s^{-1}$; Statsports RMSE = 0.14 to 0.17 $m \cdot s^{-1}$) and for acceleration (Catapult RMSE = 0.26 to 0.47 $m \cdot s^{-2}$; Statsports RMSE = 0.22 to 0.43 $m \cdot s^{-2}$) across all movements. There was a negative linear relationship between speed and acceleration error as speed increased.
Conclusions: Wearable microtechnology devices from Catapult (Vector S7) and Statsports (Apex Pro) have suitable validity when measuring instantaneous speed and acceleration across multiple days. There may be small variations during different sessions and over the speed spectrum.

Practical implications

The following practical applications are in reference to raw data:

- Practitioners can be confident in the validity of the instantaneous speed, instantaneous acceleration, peak speed, peak acceleration, and peak deceleration measures provided by Catapult (Vector S7 10-Hz) and Statsports (Apex Pro 10-Hz) GNSS devices during straight-line sprinting and change of pace movements.
- Practitioners can also be confident that the validity of the instantaneous speed, and instantaneous acceleration measures provided by Catapult (Vector-S7 10-Hz) and Statsports (Apex Pro 10-Hz) will not largely fluctuate between sessions.
- These devices can be used in traditional outdoor speed testing (timing gates) to provide measures of speed which can be referenced in future training practices (e.g., percentage of maximum speed) or as a replacement in speed testing where a laser or radar would typically be used.
- There are still small differences between manufacturers' data, and they are not directly comparable.

1. Introduction

Wearable microtechnology housing global navigation satellite systems (GNSS) and inertial measurement units are commonly used in team sports to track player movement during training and match-play.[1] These devices can calculate various metrics (e.g., distance, speed, acceleration), which allow for the external loads of athletes to be monitored over time.

Global navigation satellite systems have long been used to calculate speed across a range of scenarios, including the movement of vehicles and the speed of a runner during a marathon.[2] There are two methods

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GNSS use to calculate instantaneous speed (i.e., speed at a point in time). First, speed can be derived from the GNSS chip by calculating changes in the position of the unit in relation to the satellites (i.e., positional differentiation). The frequency at which it calculates position, and therefore speed, is dependent on the sampling rate of the GNSS, which is typically 5 to 10 Hz in commercially available devices. One issue with this method is that it does not account for changes in elevation that will alter the distance travelled and therefore speed. As such, most commercially available devices use the second method calculating speed via 'Doppler Shift', which uses a complex algorithm to measure the change in radio frequencies when a receiver is in motion.[3]

It is common for speed measures to be used in a practical setting. For example, maximum speed is often measured using a GNSS during physical testing (e.g., 40 m sprint).[4] This information can then be used to guide future training practices, such as setting peak speed targets during rehabilitation training (e.g., 90 % of peak speed), which is also measured using GNSS. Similarly, data are often assessed in real-time during training, and decisions on whether players have achieved enough high-speed distance or sprint efforts may result in additional 'top-up' running to be performed.[5] Other measures of interest to practitioners (e.g., high-speed running distance, accelerations) are all derived from the speed recorded by the device. Thus, it is vital that end-users understand the validity of the outcomes recorded by these devices.

Previous research has investigated the ability of these devices to accurately measure speed during straight-line sprinting.[6] It has been found that devices from Catapult (MinimaxX S4, SPI-ProX 15-Hz) and Statsports (Viper 10-Hz) possess suitable validity (SEE = 0.1 to 0.2 $m \cdot s^{-1}$, CV = 3.1 to 8.3 %, Bias = 0.13 $m \cdot s^{-1}$),[7–9] but may be influenced by strong accelerations (SEE = 0.32 $m \cdot s^{-1}$) and decelerations (CV = 11.3 %).[7,8,10] Peak speed measures have also been shown to be valid (Bias = 1.8 to 2.4 %, SEE = 1.9 %, CV = 2.5 to 5.1 %) for more recent devices from Catapult (Optimeye S5 10-Hz, SPI-ProX 15-Hz) and Statsports (Apex 10-Hz, Viper 10-Hz).[7,11,12] However, as the technology develops and new devices are released, it is important to understand their accuracy in relation to criterion measures. Furthermore, some of these studies,[9,11,12] have only looked at discrete sections of the entire time series, such as peak speed or peak accelerations, which only consider a fraction of the data points within the entire time series. Similarly, whilst other studies have assessed speed over the entire time series,[7,8] it is unclear how the validity is derived from each individual data point, or if it the data has been aggregated to average speed. Given that for particular manufacturers (e.g. Statsports), metrics such as total distance are derived from speed over the entirety of the time series, simply assessing certain points of the time series does not reflect the accuracy of these devices for all the data they capture. Speed is also used to allocate accumulated distance into banded zones for threshold-based distance metrics (e.g. high-speed running distance), which are commonly used in practice, although they vary greatly within the literature and between sports. As such, further research is required to understand how the GNSS derived data behaves in relation to a criterion measure across the speed spectrum.

To the best of the authors' knowledge, the most recent devices from Catapult (Vector S7 10-Hz) and Statsports (Apex Pro 10-Hz) have not yet been examined in a peer-reviewed study. These are currently two of the most widely used devices across high performance sport. Though it is plausible to assume that validity of speed will be similar, or superior to previously released models, the hardware, chip sets and software data processing methods (e.g., filters) differ, which will likely influence their output. Previous research has also only looked at validity on single occasions (e.g., during a single session). Though informative, this does not provide insight into the validity over time. Team sport athletes train and compete at different times of the day and on different days of the week, where varying environmental conditions may influence factors such as satellite number and horizontal dilution of precision (HDOP) [a measure of the geometric arrangement of the satellite configuration, with lower values indicating better accuracy, ideally being less than one]. Collectively, these factors may impact a device's accuracy. It is therefore important to understand if there is any variation in the validity of these devices across multiple sessions. This concept is similar to within-device reliability (i.e., consistency of a device to produce the same output when exposed to repeated identical movements), which has yet to be suitably examined. Previous research has either had the device mounted to a calibrated rig,[13] or asked participants to repeat a set of movements.[14,15] Both methods have their issues. For example, having a person reproduce movements on a pre-marked course results in error that includes both human and technological error of the device, making it impossible to determine how much error the device is responsible for. A calibrated rig or monorail[7] is an improvement in reproducing identical movements with a high level of accuracy, but it does not produce the variety of movements over different distances that players are performing during training or competition, therefore lacking ecological validity. As such, it would be plausible to assume that if a device is valid, or at least the error is consistent across multiple days, it also possesses suitable within-device reliability. Therefore, the aims of this study were to determine the (1) validity of instantaneous speed and acceleration and the (2) variation in validity over time (multiple sessions) as well as the (3) validity of peak speed, peak acceleration and peak deceleration for the Catapult (Vector S7 10-Hz) and Statsports (Apex Pro 10-Hz) GNSS devices.

2. Methods

Ten participants (n = 9 males; 1 female) who were recreationally active or team sport players (mean ± *SD*; age, 26.9 ± 4.4 years; height, 178.0 ± 10.9 cm; body mass, 87.1 ± 16.3 kg) volunteered to participate in this study. All participants were made aware of the risks and benefits of the research prior to providing informed consent. The participants were encouraged to maintain habitual nutrition and hydration in the 24 h prior to testing and abstain from any vigorous physical activity for 48 h prior to testing. Participants wore their normal training clothes across all testing sessions. All procedures were approved by the Australian Catholic University Human Research Ethics Committee (2020-38H).

The 10-Hz GNSS devices examined in this study were manufactured by Statsports (n = 2, Firmware = APX + 4.03; Apex Pro, Statsports, Newry, Ireland) and Catapult (n = 2, Firmware = v6.10; Vector, Catapult Sports, Melbourne, Australia), whilst a speed laser manufactured by MuscleLab (n = 1, LaserSpeed, MuscleLab, Stathelle, Norway) was used as the criterion measure; sampling at 2.56 kHz, with data exported at 1000 Hz. This laser has recently been validated against a 3D-motion capture system (Vicon), showing strong agreement.[16] Only two GNSS devices from each manufacturer were used due to the excellent agreement previously shown between devices.[17]

Following a warmup involving dynamic stretches and running at progressive intensities over 40 m, the participants were required to complete straight-line sprints and straight-line changes of pace over 40 m. For the straight-line sprints, the participants were instructed to accelerate before reaching maximum speed within the 40-m course and then maintain this to the best of their ability until they reached the 40-m endpoint. For the changes of pace movement, participants were required to accelerate and decelerate at least once every 10 m. They were instructed to alternate between maximal acceleration and deceleration for each interval, whilst only ceasing movement completely at the end of the 40-m course. Allowing for variation in the two activities (i.e., distance taken to reach peak speed and the rate of acceleration and deceleration) would increase the ecological validity of the results, due to the stochastic nature of training and competition and improve the fit of the statistical models used due to variations in speed and acceleration between trials. For both activities, participants began from a standing start and were instructed as to when they could begin each sprint. There was a minimum of two minutes recovery between each repetition to help maintain velocities across trials. Three separate sessions (each seven days apart) were conducted over a three-week period to allow for the variation in validity to be examined. All sessions were performed in the morning (time; 09:00 to 10:00 h, temperature; 21.4 ± 1.3 °C, humidity; 51.3 ± 23.5 %). All sessions were completed on the same full-size, grassed rugby league field (68-m width, 100-m length).

Devices were switched on 10 min prior to the start of each session to give them time to connect to satellites. During the protocol, devices were individually worn within a tight-fitting manufacturer provided vest, in a vertical position that allowed adequate exposure of the GNSS antenna to the satellites. The devices were exposed to 6 to 8 repetitions of each activity type, per session. Thus, 78 straight-line sprints (Statsports = 40, Catapult = 38) and 74 straight-line changes of pace (Statsports = 36, Catapult = 38) were performed across all sessions. The laser manufacturer's proprietary software (MuscleLab) was programmed so that the trial would 'self-terminate' once the participant had reached 40 m. The laser was positioned on a tripod 5 m behind the starting point of the movement for each repetition. Using the laser's optic-reflective red dot sight, the same member of the research team tracked the participant, positioning the site between the scapulae. Lasers have been used consistently throughout the literature to assess the validity of the sampling frequency of GNSS devices.[7,8,12,18] The laser used in the current study is accurate at detecting changes in position which it uses to measure instantaneous velocity.[19]

The GNSS and laser data were downloaded after each session using the manufacturer's proprietary software (Apex Pro Series, Statsports; OpenField, Catapult Sports; MuscleLab, MuscleLab). Raw 10-Hz GNSS and 1000-Hz laser data were exported in comma-separated values (.csv) format for analysis. The raw laser and GNSS files were imported into RStudio (version 1.4.1103, Posit, Boston, Massachusetts, United States) for processing using the R statistical programming language (version 4.0.5, R Foundation for Statistical Computing, Vienna, Austria). It is important to note that the raw GNSS data may have already had a level of filtering applied by the manufacturer, however the nature of any such data treatment is not disclosed to the end-user. Laser data were down-sampled to 10 Hz by taking the first and then every hundredth data point in the time series (e.g. data point 1, 101, 201, 301). Then, a 4th order 1-Hz low-pass Butterworth filter was applied to instantaneous speed for both GNSS and laser data; this filter was selected as it has been widely used within the application of GNSS time series data in team sports.[20] As there was no common timestamp between the GNSS and laser files, they needed to be synchronised using the following steps.[21] First, a time column was created within each file which accrued in 0.1 s increments. Second, the data were bound together so that the GNSS data and the laser data from the same activity were within the same data frame. Third, the data were shifted to synchronise the separate time series data sets. This was done by moving each time series by one row 50 data points behind and 50 data points ahead and calculating the root mean square error (RMSE) between both time series for each shift of the data. This lead and lag of the data ensured that the data was correctly aligned by accounting for discrepancies in the recorded time by plus to minus 5 s. The shift that provided the smallest RMSE was then used to ultimately 'shift' the time series within each data frame to align the two data sets. The synchronised data were then plotted and visually inspected to ensure alignment had been achieved. At each data point, instantaneous acceleration ($m \cdot s^{-2}$) (i.e., change in pace) was then calculated, using the three-point central-method, whereby the initial speed is subtracted from the subsequent speed and divided by the difference in time (0.2 s).[20] The difference in speed and acceleration between the laser and GNSS speed was then calculated for each data point. It should be noted that the method used to derive acceleration is different to that used by the manufacturers' proprietary software, which are not typically disclosed to the end-user. By processing all raw data using the same methods, it will reduce the discrepancy between accelerations from Statsports and Catapult.[20] Thus, there is a need to develop an industry standard for calculating acceleration in team sports using GNSS. Peak speed, acceleration and deceleration were derived from the raw data by taking the highest values from the GNSS and laser for each trial.

2.1. Statistical analysis

The statistical analyses for instantaneous speed and acceleration across the entire time series were performed in RStudio using R programming language. To determine the magnitude of the difference between the laser and GNSS, the RMSE was calculated for each movement using the error (GNSS – Laser) from each individual 10-Hz datapoint across the entire synchronised time series.

$$RMSE = \sqrt{\frac{\sum^{N} (GNSS\ Speed - Laser\ Speed)^2}{N}}$$

Due to the dependency arising from repeated measures on the same individual from the same GNSS device, linear mixed models were fit using the *nlme* package to determine if there was a significant difference between validity (RMSE) across days. Unit ID was incorporated as a random effect, whilst manufacturer and day were used as fixed effects. Separate models were built for each activity type and fit with restricted estimated maximum likelihood.

The statistical analyses for the peak speed, acceleration and deceleration were performed using a customised spreadsheet.[22] The magnitude of the error and relationship between the laser and GNSS for these variables were assessed using mean error ± 95 % confidence limits (CL) and typical error of the estimate (TEE) ± 95 % CL.

Data were presented as mean ± SD and statistical significance was set at $p < 0.05$.

3. Results

The results in this study are derived purely from the raw data and, therefore, may not necessarily reflect the validity of data subjected to the filtering and calculation processes deriving the output practitioners will obtain from the proprietary software.

Table 1
Validity of Global Navigation Satellite Systems devices to assess instantaneous speed ($m \cdot s^{-1}$); data are presented as mean ± SD.

		Apex Pro (Statsports)					Vector S7 (Catapult)				
		Laser	GNSS	Satellite no.	HDOP	RMSE	Laser	GNSS	Satellite no.	HDOP	RMSE
Sprint	Day 1	5.9 ± 2.0	5.9 ± 1.9	22.6	0.4	0.17 ± 0.04	5.6 ± 2.1	5.5 ± 2.0	14.4	0.7	0.17 ± 0.03[a]
	Day 2	5.8 ± 1.7	5.8 ± 1.6	22.3	0.4	0.15 ± 0.04	6.1 ± 1.7	6.1 ± 1.6	18.6	0.6	0.15 ± 0.03
	Day 3	5.5 ± 1.5	5.4 ± 1.5	21.1	0.4	0.14 ± 0.04	5.5 ± 1.5	5.4 ± 1.4	17.2	0.5	0.12 ± 0.03
	Average	5.7 ± 1.7	5.7 ± 1.7	22.2	0.4	0.16 ± 0.02	5.7 ± 1.8	5.7 ± 1.7	16.7	0.6	0.15 ± 0.04
Change of Pace	Day 1	4.9 ± 1.6	4.8 ± 1.6	22.6	0.4	0.16 ± 0.03	4.6 ± 1.9	4.6 ± 1.8	14.9	0.6	0.21 ± 0.08[a]
	Day 2	4.3 ± 1.8	4.3 ± 1.7	22.6	0.4	0.14 ± 0.02	4.4 ± 2.0	4.3 ± 2.0	18.8	0.5	0.18 ± 0.04
	Day 3	4.3 ± 1.4	4.3 ± 1.4	20.4	0.4	0.14 ± 0.02	3.8 ± 1.6	3.8 ± 1.5	16.7	0.6	0.14 ± 0.03
	Average	4.5 ± 1.6	4.5 ± 1.6	21.8	0.4	0.15 ± 0.04	4.2 ± 1.9	4.2 ± 1.8	16.6	0.6	0.18 ± 0.06

[a] Indicates a significant difference of validity compared to Day 3; GNSS, Global Navigation Satellite System; HDOP, horizontal dilution of precision; RMSE, root mean square error.

Table 2
Validity of Global Navigation Satellite Systems devices to assess instantaneous acceleration (m·s^{-2}); data are presented as mean ± SD.

		Apex Pro (Statsports)					Vector S7 (Catapult)				
		Laser	GNSS	Satellite no.	HDOP	RMSE	Laser	GNSS	Satellite no.	HDOP	RMSE
Sprint	Day 1	0.7 ± 1.5	0.7 ± 1.5	22.6	0.4	0.43 ± 0.12	0.5 ± 1.5	0.5 ± 1.5	14.4	0.7	0.37 ± 0.11
	Day 2	0.6 ± 1.5	0.6 ± 1.5	22.3	0.4	0.41 ± 0.05	0.7 ± 1.4	0.7 ± 1.4	18.6	0.6	0.47 ± 0.10[a]
	Day 3	0.6 ± 1.3	0.6 ± 1.2	21.1	0.4	0.39 ± 0.05	0.6 ± 1.1	0.6 ± 1.2	17.2	0.5	0.34 ± 0.06
	Average	0.6 ± 1.4	0.6 ± 1.4	22.2	0.4	0.41 ± 0.08	0.6 ± 1.4	0.6 ± 1.4	16.7	0.6	0.39 ± 0.10
Change of pace	Day 1	0.5 ± 1.5	0.5 ± 1.4	22.6	0.4	0.31 ± 0.06	0.6 ± 1.7	0.5 ± 1.5	14.9	0.6	0.40 ± 0.13[a]
	Day 2	0.1 ± 1.9	0.1 ± 1.8	22.6	0.4	0.27 ± 0.08	0.6 ± 1.8	0.4 ± 1.7	18.8	0.5	0.37 ± 0.07[a]
	Day 3	0.5 ± 1.5	0.5 ± 1.4	20.4	0.4	0.22 ± 0.04	0.3 ± 1.6	0.3 ± 1.5	16.7	0.6	0.26 ± 0.08
	Average	0.4 ± 1.6	0.4 ± 1.5	21.8	0.4	0.27 ± 0.06	0.4 ± 1.7	0.4 ± 1.5	16.6	0.6	0.34 ± 0.11

[a] Indicates a significant difference of validity compared to Day 3; GNSS, Global Navigation Satellite System; HDOP, horizontal dilution of precision; RMSE, root mean square error.

Upon completion of data collection, some laser files (n = 18) had not successfully saved to the laser's proprietary software. Therefore, a total of 76 sprint (Statsports = 39, Catapult = 37) and 58 change of pace (Statsports = 26, Catapult = 32) files were analysed. There was an average of 25 sprint (Statsports = 13.0, Catapult = 12.3) and 19 change of pace (Statsports = 8.7, Catapult = 10.7) files from each day (sprint range = 13 to 23, change of pace range = 23 to 27). The total number of raw data points analysed for straight-line sprints and straight-line changes of pace, were 5428 and 5022, respectively. Across days, satellites ranged from 15 to 19 for Catapult and 21 to 23 for Statsports, whilst the HDOP was 0.5 to 0.6 for Catapult and 0.4 for Statsports. Although HDOP values were slightly low, satellite connectivity was high and therefore conditions were appropriate for data collection.[23]

The validity of the GNSS devices compared to criterion is presented in Tables 1 (Instantaneous Speed), 2 (Instantaneous Acceleration) and 3 (Peak Speed, Acceleration and Deceleration).

There were small differences in RMSE between days for all devices. For Statsports devices, RMSE ranged from 0.14 to 0.17 m·s^{-1} for speed ($p = 0.29$ to 1.00) and 0.22 to 0.43 m·s^{-2} for acceleration ($p = 0.13$ to 0.99) across all movements. For these Catapult, RMSE ranged from 0.12 to 0.21 m·s^{-1} for speed ($p = 0.001$ to 0.85) and 0.26 to 0.47 m·s^{-2} for acceleration ($p = 0.001$ to 0.85) across all movements ($p = 0.009$ to 0.99).

The error observed for instantaneous speed and acceleration are shown in Figs. 1 and 2, respectively.

4. Discussion

The aims of this study were to determine the (1) validity and (2) variation in validity over time (multiple sessions) for the Catapult (Vector S7 10-Hz) and Statsports (Apex Pro 10-Hz) GNSS devices. The main findings of this study show that all devices were valid across multiple sessions for measures of instantaneous speed and acceleration, highlighted by no significant differences to the criterion measure. However, there may be some small variation in this agreement across days. In addition, measures of peak speed, acceleration and deceleration also appear valid for both manufacturers.

The Catapult (Vector S7 10-Hz) and Statsports (Apex Pro 10-Hz) devices appear suitable to measure instantaneous speed during straight-line sprinting and change of pace movements. These results are similar to studies that used older Catapult devices (MinimaxX 10-Hz) during straight-line sprinting.[7,8] When visually inspecting the error, there does appear to be a consistent overestimation, albeit small, of instantaneous speeds below 5 m·s^{-1} (Fig. 1) for both devices. Previous research has shown that instantaneous speed accuracy is compromised during accelerations >4 m·s^{-2}.[7] This is similar to the findings of the present study, where acceleration is greatest at lower velocities, due to the activities performed in the study (e.g., beginning of a sprint). During these periods, the device must measure speed where the change in speed from datapoint to datapoint is at its greatest, and thus validity is impacted. Despite this, the error on these datapoints was still low and when averaged across the entire time series, the error was negligible, as such metrics such as average acceleration and total distance are unlikely to be impacted. These errors may have more of an impact on discrete variables such as banded acceleration counts which have previously been shown to have poorer reliability than variables that consider the entire time series.[17,24] Practitioners can be confident in the validity of the instantaneous speed derived from these devices.

With respect to instantaneous acceleration during both straight-line sprinting and change of pace movements, the two manufacturers' devices were shown to offer suitable validity. It is important to note however, that this was attributable to the devices' accuracy in measuring speed, from which acceleration is derived. There was a tendency for instantaneous acceleration to be overestimated at changes of pace over 3 m·s^{-2} (Fig. 2A, C) during a straight-line sprint. The reason for these errors occurring in the straight-line sprint and not the change of pace activity (Fig. 2B, D) may be due to the speed at which the participant accelerated as they knew they were required to reach peak speed rather than speeding up to slow down again in 10 m. Therefore, the changes in speed from point-to-point are much greater, which cause inflations in the acceleration error at slower speeds. This is aligned with the previous suggestions in this study, that speed measured at slower speeds, and thus likely periods of high acceleration, is slightly overestimated. Because instantaneous acceleration is derived from speed, its accuracy is influenced in the same way. Despite this, practitioners can be confident that the changes in pace obtained by these units are accurate measures of the activity that has been performed, particularly if they are assessing metrics of average acceleration over the entire time series, where mean error was close to zero for all devices and movements.

Table 3
Validity of Global Navigation Satellite Systems devices to assess peak speed (m·s^{-1}), peak acceleration (m·s^{-2}) and peak deceleration (m·s^{-2}); data are presented as mean ± SD.

		Apex Pro (Statsports)				Vector S7 (Catapult)			
		Laser	GNSS	Mean error (95 %CL)	TEE (95 % CL)	Laser	GNSS	Mean error (95 % CL)	TEE (95 % CL)
Sprint	Speed (m·s^{-1})	7.1 ± 1.0	7.4 ± 1.0	0.26 (0.19 to 0.34)	0.23 (0.19 to 0.29)	7.1 ± 1.0	7.0 ± 1.0	−0.08 (−0.11 to 0.05)	0.10 (0.08 to 0.13)
	Acceleration (m·s^{-2})	3.9 ± 0.6	3.5 ± 0.4	−0.39 (−0.50 to −0.28)	0.33 (0.27 to 0.43)	3.6 ± 0.5	3.4 ± 0.4	−0.25 (−0.34 to −0.16)	0.27 (0.22 to 0.35)
	Deceleration (m·s^{-2})	−1.2 ± 0.9	−1.5 ± 0.7	−0.35 (−0.45 to −0.25)	0.25 (0.21 to 0.33)	−1.0 ± 0.8	−1.4 ± 0.6	−0.35 (−0.45 to −0.24)	0.28 (0.23 to 0.37)
Change of pace	Speed (m·s^{-1})	6.1 ± 0.7	6.2 ± 0.8	0.07 (−0.05 to 0.18)	0.27 (0.21 to 0.38)	6.2 ± 0.8	6.1 ± 0.8	−0.26 (−0.45 to 0.07)	0.10 (0.08 to 0.14)
	Acceleration (m·s^{-2})	3.9 ± 0.4	3.6 ± 0.4	−0.29 (−0.37 to −0.21)	0.19 (0.15 to 0.27)	3.9 ± 0.6	3.5 ± 0.4	−0.37 (−0.50 to −0.23)	0.35 (0.28 to 0.46)
	Deceleration (m·s^{-2})	−1.5 ± 0.8	−1.6 ± 0.7	−0.07 (−0.19 to 0.05)	0.30 (0.23 to 0.41)	−1.8 ± 0.6	−1.9 ± 1.5	−0.09 (−0.25 to 0.08)	0.43 (0.34 to 0.57)

GNSS, Global Navigation Satellite System; CL, confidence limits; TEE, typical error of the estimate.

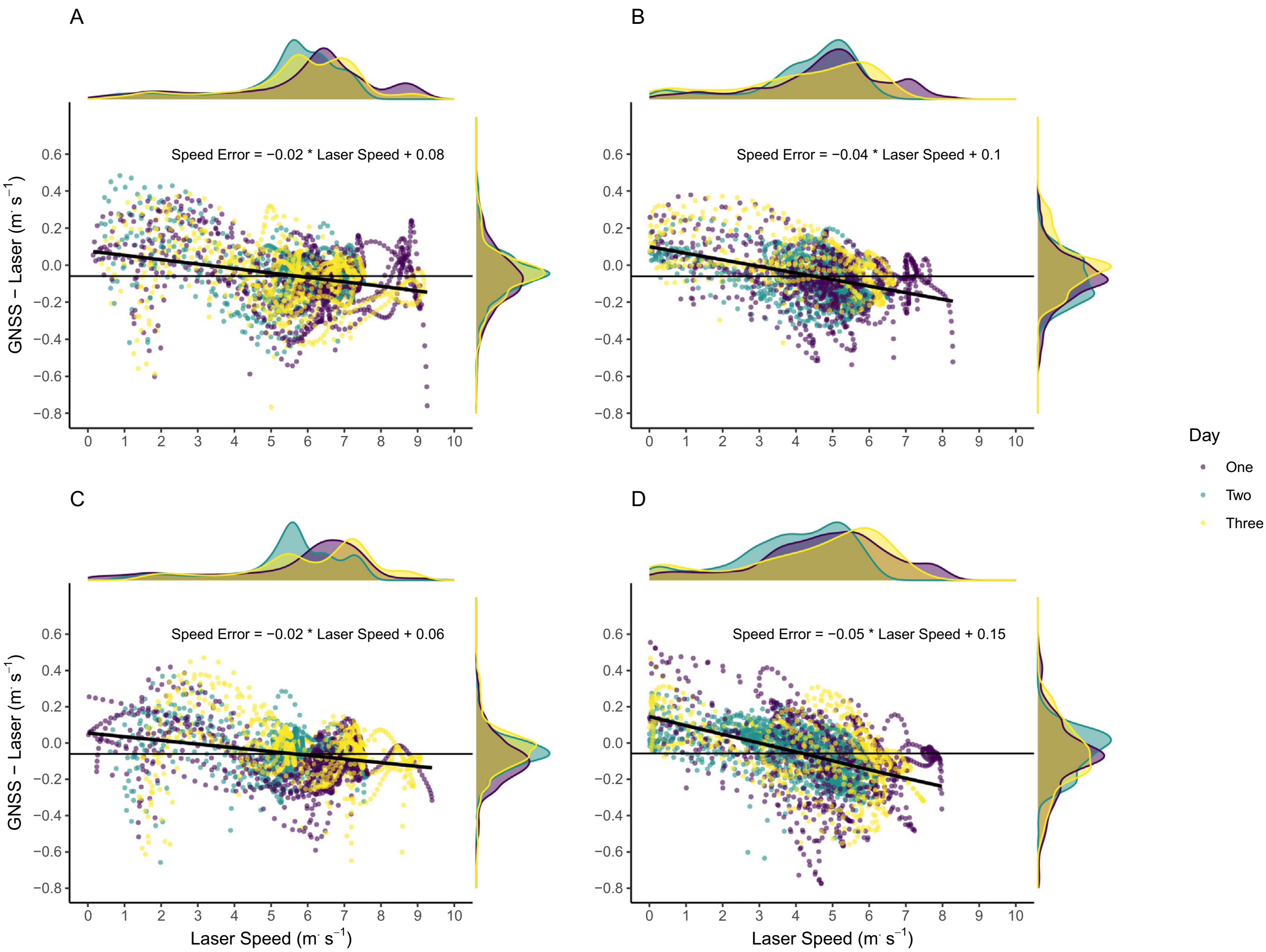

Fig. 1. Laser instantaneous speed (m·s^{-1}) compared to GNSS devices during sprints (A, C) and change of pace (B, D) movement for Statsports (A, B) and Catapult (C, D). GNSS = Global Navigation Satellite System.

Whilst there was no difference to criterion on each day, there were small fluctuations in the agreement across days, which tended to be higher for Catapult devices. It is important to understand though that even the largest error observed for instantaneous speed and acceleration is still small based on the authors' clinical judgement. For example, the range of speeds commonly observed in team sports range from 0 to 10 m·s^{-1}, meaning the RMSE of 0.17 m·s^{-1} is only 1.7 % of the maximal speed likely to be observed. The absolute variation in error is also not clinically meaningful, with a variation of 0.15 m·s^{-1} and 0.14 m·s^{-2} for instantaneous speed and acceleration, respectively. Statsports devices appear to have a greater number of satellites available compared to Catapult across days as well, which may contribute to the consistency in the validity for these devices. This also gives insight into the within-device reliability, suggesting that these devices would be able to produce repeatable measures when exposed to similar movements on different occasions. Overall, practitioners can be confident that the outcomes derived from the wearable units will not vary considerably from a criterion measure across days.

The error between laser and GNSS when measuring peak speed, acceleration and deceleration is suitable. Compared to the laser, there does appear to be a slight overestimation of peak speed by Statsports during sprinting. This doesn't occur during the change of pace movements, which may be explained by the greater speeds attained during the sprint. Peak acceleration appears to be slightly underestimated by both manufacturers. This is explained by the previous suggestions of this study that instantaneous speed is influenced most when the change in speed (i.e., acceleration) from datapoint to datapoint is at its greatest (e.g., at the beginning of the movements in this study). Given acceleration is derived from speed, it is realistic that there is a consistent error, albeit small, of GNSS when measuring peak acceleration. Nonetheless, it appears that GNSS can provide suitable measures of peak speed, acceleration and deceleration during straight-line movements.

One limitation of this study was that it was conducted on a field with an un-obstructed view to satellites, as such the testing was always performed in ‘optimal’ conditions. Whilst applicable to most field-based invasion team sport training sessions (e.g., rugby league), competition generally takes place in large stadiums which may decrease the satellites available and device accuracy. Future research should focus on conducting similar protocols in large sports stadiums, where the environmental conditions may not be optimal. Further, sessions were only conducted in the morning, meaning whilst unlikely, validity of the devices may be different in the afternoon or evening. The maximal decelerations observed in this study are not performed from high speeds, meaning greater decelerations are likely to occur in training and match-play. Therefore, future research is required to determine the validity of these devices to measure large decelerations. Another

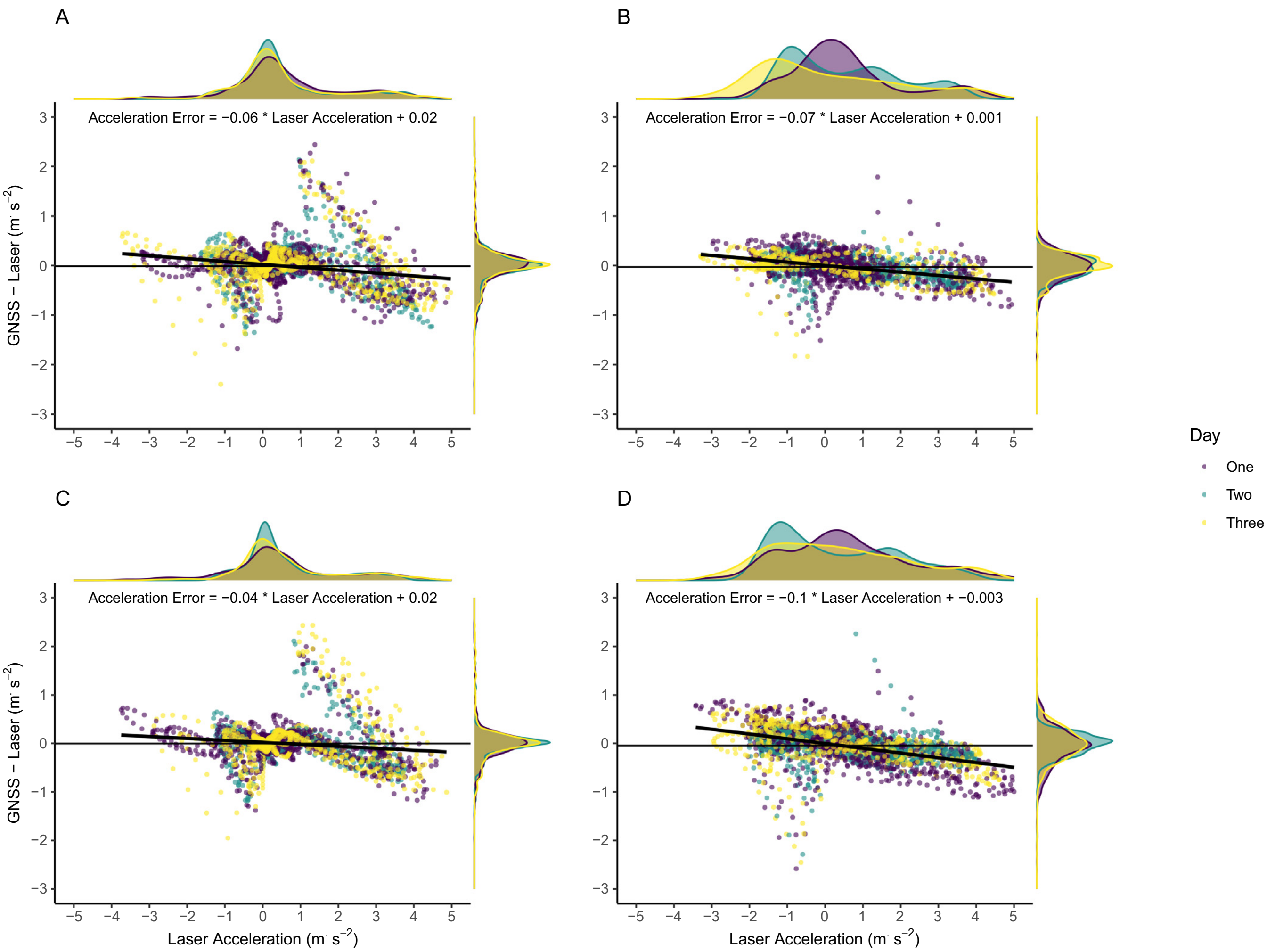

Fig. 2. Laser instantaneous acceleration ($m \cdot s^{-2}$) compared to GNSS devices during sprints (A, C) and change of pace (B, D) movements for Statsports (A, B) and Catapult (C, D). GNSS = Global Navigation Satellite System.

limitation is the use of the laser as the criterion measurement, which only allows for movements to be performed in a straight line. The use of 3D motion capture systems would be another step forward in being able to provide information on validity over a range of multi-directional movements, though this could be difficult to achieve given the number of cameras needed to cover a large area. Furthermore, whilst the laser was used as the criterion, they are not without their limitations and may be less accurate over the first few steps of a sprint, although the sampling rate of the current laser device was much higher than other studies. The laser used in this study offers excellent agreement in measuring body position compared to force platforms for deriving stride variables at high velocities.[19] Given it uses change in position to calculate velocity, we can be confident in the accuracy of the device for measuring velocity. Within field testing, these devices have often been considered as a superior method than GNSS devices, however this research supports the concurrent validity of using GNSS for measuring instantaneous speed and acceleration during straight-line movements.

5. Conclusion

These devices from Catapult (Vector S7) and Statsports (Apex Pro) appear to have suitable validity when measuring instantaneous speed and acceleration across multiple days. Periods of high acceleration may compromise the ability of these devices to measure instantaneous speed and subsequently derived instantaneous acceleration. Whilst the difference to criterion was not statistically different across days, the Catapult validity may vary by a small margin across days, though the validity of these devices is still deemed acceptable. Therefore, practitioners can be confident in the measures their Vector S7 or Apex Pro devices produce during straight-line movements (e.g., speed testing, MAS [maximal aerobic speed] prescription).

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Confirmation of ethical compliance

Ethical Guidelines: All procedures in this study were approved by the Australian Catholic University Human Research Ethics Committee (2020-38H).

CRediT authorship contribution statement

Zachary Crang contributed to the methodology design, data collection, analysis and writing of the manuscript. Rich Johnston contributed to the methodology design, data collection and manuscript review. Grant Duthie contributed to the methodology design, analysis and manuscript review. Michael Cole, Jonathon Weakley and Adam Hewitt contributed to the methodology design manuscript review.

Declaration of interest statement

The authors declare they have no financial or other interest in the products used in this study.

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