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## Original research

# The acceleration dependent validity and reliability of 10 Hz GPS

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## ABSTRACT

**Objective:** To examine the validity and inter-unit reliability of 10 Hz GPS for measuring instantaneous velocity during maximal accelerations.

**Design:** Experimental.

**Methods:** Two 10 Hz GPS devices secured to a sliding platform mounted on a custom built monorail were towed whilst sprinting maximally over 10 m. Displacement of GPS devices was measured using a laser sampling at 2000 Hz, from which velocity and mean acceleration were derived. Velocity data was pooled into acceleration thresholds according to mean acceleration. Agreement between laser and GPS measures of instantaneous velocity within each acceleration threshold was examined using least squares linear regression and Bland–Altman limits of agreement (LOA). Inter-unit reliability was expressed as typical error (TE) and a Pearson correlation coefficient.

**Results:** Mean bias  $\pm$  95% LOA during accelerations of 0–0.99 m s<sup>-2</sup> was 0.12  $\pm$  0.27 m s<sup>-1</sup>, decreasing to -0.40  $\pm$  0.67 m s<sup>-1</sup> during accelerations >4 m s<sup>-2</sup>. Standard error of the estimate  $\pm$  95% CI (SEE) increased from 0.12  $\pm$  0.02 m s<sup>-1</sup> during accelerations of 0–0.99 m s<sup>-2</sup> to 0.32  $\pm$  0.06 m s<sup>-1</sup> during accelerations >4 m s<sup>-2</sup>. TE increased from 0.05  $\pm$  0.01 to 0.12  $\pm$  0.01 m s<sup>-1</sup> during accelerations of 0–0.99 m s<sup>-2</sup> and >4 m s<sup>-2</sup> respectively.

**Conclusion:** The validity and reliability of 10 Hz GPS for the measurement of instantaneous velocity has been shown to be inversely related to acceleration. Those using 10 Hz GPS should be aware that during accelerations of over 4 m s<sup>-2</sup>, accuracy is compromised.

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## 1. Introduction

The utilisation of global positioning system (GPS) technology is now widespread within team sports, allowing practitioners and researchers to measure and monitor the movement patterns of training and competition.<sup>1–3</sup> Accelerations and decelerations are frequent within team sports,<sup>3–5</sup> and can elicit a high metabolic and neuromuscular demand,<sup>6,7</sup> making the accuracy of their measurement of practical importance to practitioners and researchers.<sup>3,5</sup> However it is unclear whether commercially available 10 Hz GPS are valid and reliable for measuring the spectrum of accelerations seen within maximal sprinting.<sup>1,8</sup>

To date fourteen studies examining the validity or reliability of various versions of commercially available GPS for measuring distance and speed have been published (for reviews see Aughey<sup>1</sup> and Cummins et al.<sup>9</sup>). Common findings of validation studies include

measurement accuracy being related to the speed and distance of the measurement, with accuracy compromised when measuring short distances and/or high speeds. To date only the work of Varley et al.,<sup>8</sup> has examined the validity of GPS during maximal acceleration, finding the accuracy of instantaneous velocity decreases as acceleration increases. However, due to differences in GPS manufacturer, latitude, the criterion task, utilised methodology, GPS sampling rate, and statistical analysis, a global statement on the validity of GPS for measuring team sports movements is not possible.

Some researchers have utilised precision instruments such as VICON tracking systems,<sup>10</sup> Theodolite<sup>11</sup> and radar guns<sup>8,12</sup> as criterion measures. However we believe that the methodology employed in previous validation studies may limit the extent to which findings can be accepted. For example, all previous studies have had human participants travel at various speeds over a pre-determined distance whilst wearing one or more GPS devices. This approach may be problematic as movement patterns such as medio-lateral displacement during gait<sup>13,14</sup> and leaning during changes of direction<sup>15</sup> create discrepancies between the trajectory of the GPS receiver (worn between the scapulae of the participant)

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and the intended trajectory.<sup>10</sup> Whilst the ecological validity is important, the criterion validity must also be understood in order to appreciate the contextual efficacy of GPS technology.

A further consideration is the method used to demarcate the task within the GPS manufacturers' software.<sup>1</sup> The most commonly employed method is to utilise timing gates to measure the duration of the trial,<sup>16–18</sup> which is then applied to the GPS velocity trace beginning when reported velocity rises above zero. However, measurement artefacts caused by leading/trailing limbs can affect the reliability of the time measurement. We believe a more accurate approach is to utilise the tri-axial accelerometer present in many GPS devices to demarcate the start and end of the trial. We have found (unpublished data) that visual inspection of the anteroposterior force curve provides an objective and reliable marker of the beginning and end of the trial (Supplementary Figure 1)

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The aim of this study was to examine the acceleration dependent criterion validity and inter-unit reliability of 10 Hz GPS for measuring instantaneous velocity during maximal acceleration using a highly standardised protocol to eliminate extraneous movement.

## 2. Methods

A custom aluminium monorail system was built to provide a linear track with a 10 m working length. Two GPS receivers (MinimaxX S4, firmware 6.75, Catapult Innovations, Melbourne, Australia) spaced 30 cm apart were securely mounted in an upright position to a platform with the antenna free from obstruction. The platform was able to move freely along the rail on bearings (Fig. 1). All testing took place on an outdoor natural grass football pitch in an open space free from tall buildings.

GPS receiver velocity was recorded using a laser which sampled at 2000 Hz (optoNCDT ILR 1191, Micro-Epsilon Messtechnik GmbH & Co, Germany). The laser provided displacement to a resolution of 0.001 m with manufacturer reported typical error of  $\pm 0.002$  m. The laser was positioned 5 m behind the start of the track with the sighting beam focussed on the centre of a 0.1 m  $\times$  0.2 m reflective panel secured to the platform.

Maximum displacement was limited to precisely 10 m using steel brackets at either end of the monorail. The distal bracket was fitted with steel compression springs to dampen the impact of the platform. The distance of 10 m from the starting position to first contact with the springs was verified first by tape measure and later by laser measurement.

To produce ecologically valid acceleration profiles, displacement of the GPS receivers was achieved via towing the sliding platform during maximal 10 m sprints. One male professional football (soccer) player (21 y, 85 kg, 1.79 m) volunteered to take part and provided written informed consent. Experimental procedures received approval from the Institutional Ethics Committee. The participant completed 15 trials of 10 m maximal sprints from a stationary 2-point athletic stance, each separated by a recovery period of 1 min, towing the platform via a lightweight 10 m non-stretch cord combined with a 2 m stretchable cord fastened around the waist with a customised harness. The participant wore studded football boots and was instructed to sprint maximally for 10 m, and to come to a complete stop within a marked 2 m deceleration zone. Although the compliance of the stretchable cord was minimal, it was included to prevent discomfort resulting from recoil caused by the platform striking the distal compression springs.

Data from each trial was identified in the respective manufacturer supplied software and exported to Microsoft Excel. Laser data consisted of time and displacement measured at 2000 Hz, which was then re-sampled via rolling average and exported at 100 Hz using the manufacturer's software. For laser data, the beginning of the trial was identified when platform displacement increased above 5.00 m (laser was positioned precisely 5 m behind the platform). From this point, data was then re-sampled to 10 Hz by selecting every 10th data point to provide data that could be compared directly with 10 Hz GPS data. The end of the trial was taken as the moment displacement reached 15.00 m.

GPS data consisting of time, "raw" and "smooth" velocity was exported at 10 Hz. Raw velocity (GPS<sub>RAW</sub>) refers to the velocity calculated only from time and GPS positional data. Smooth velocity (GPS<sub>SMOOTH</sub>) refers to the velocity calculated from time, GPS positional data, plus a unique manufacturer specific algorithm designed to improve accuracy (algorithm unknown). Within the GPS software (Sprint 5.0, Catapult Innovations, Melbourne, Australia) the onset of a trial was identified as the instant anteroposterior force measured by the integrated 100 Hz tri-axial accelerometer increased above zero (as shown by the "forward" trace within the software). The end of the trial was taken as the instant anteroposterior force was seen to sharply increase as the result of impact with the distal compression springs (Supplementary Figure 1)

10 Hz velocity data from GPS and laser were synchronised for each trial. Additionally, synchronised velocity data from both GPS devices was pooled according to the calculated mean acceleration taken from criterion 10 Hz data. For example, all data points that were collected when mean acceleration was between 0 and 0.99 m s<sup>-2</sup> were grouped for analysis of



**Fig. 1.** Photograph of the 12 m monorail (A) with sliding platform (B) which was towed by the athlete during the 10 m sprints. Two GPS devices spaced 30 cm apart were secured to a bracket which was bolted to the platform.

**Table 1**  
 Validity of 10 Hz GPS receivers for measuring instantaneous velocity during a 10 m maximal sprint.

Acceleration (m s <sup>-2</sup> )	Intercept ± 95% CI		Slope ± 95% CI		SEE ± 95% CI (m s <sup>-1</sup> )		Bias ± 95% LOA		Samples (n)
	GPS <sub>SMOOTH</sub>	GPS <sub>RAW</sub>	GPS <sub>SMOOTH</sub>	GPS <sub>RAW</sub>	GPS <sub>SMOOTH</sub>	GPS <sub>RAW</sub>	GPS <sub>SMOOTH</sub>	GPS <sub>RAW</sub>	
0–1	0.11 ± 0.09	0.14 ± 0.11	0.99 ± 0.02	1.00 ± 0.02	0.12 ± 0.02	0.19 ± 0.02	0.12 ± 0.27	0.13 ± 0.37	185
1–2	0.01 ± 0.09	0.22 ± 0.9	0.98 ± 0.02	1.01 ± 0.02	0.16 ± 0.02	0.17 ± 0.02	0.08 ± 0.31	0.20 ± 0.32	141
2–3	-0.10 ± 0.10	-0.03 ± 0.17	0.97 ± 0.03	0.93 ± 0.04	0.18 ± 0.03	0.30 ± 0.04	0.02 ± 0.35	0.32 ± 0.63	69
3–4	-0.77 ± 0.10	-0.20 ± 0.19	0.81 ± 0.04	0.88 ± 0.05	0.19 ± 0.02	0.29 ± 0.04	-0.10 ± 0.28	0.22 ± 0.70	32
>4	-0.64 ± 0.28	-0.59 ± 0.23	0.86 ± 0.16	0.70 ± 0.08	0.32 ± 0.06	0.36 ± 0.06	-0.40 ± 0.62	0.28 ± 0.94	30
All data	0.27 ± 0.05	-0.09 ± 0.07	0.93 ± 0.01	0.97 ± 0.02	0.19 ± 0.01	0.29 ± 0.01	0.03 ± 0.43	0.20 ± 0.57	457

Data presented are the intercept, slope and standard error of the estimate (SEE) of the least squares linear regression calculated for the agreement between 10 Hz GPS data and criterion data. Mean bias and 95% limits of agreement (LOA) are also presented.

acceleration-dependent validity. For the current study, acceleration zones were operationally defined, and the following thresholds were examined: 0.0–0.99 m s<sup>-2</sup> (0–1), 1.0–1.99 m s<sup>-2</sup> (1–2), 2.0–2.99 m s<sup>-2</sup> (2–3), 3.0–3.99 m s<sup>-2</sup> (3–4), and 4.0–7.0 m s<sup>-2</sup> (>4). Data from 4.0–7.0 m s<sup>-2</sup> were combined within one group due to the low number of data points present for accelerations in excess of 4 m s<sup>-2</sup>. Thresholds were chosen based upon previous research by Osgnach et al.,<sup>7</sup> and unpublished data collected from our group demonstrating the frequency and magnitude of accelerations during football training and match play.

Least squares linear regression was conducted to establish the agreement between criterion and GPS measures. Intercept and slope of the regression line ±95% confidence intervals were determined. Standard error of the estimate (SEE) ±95% confidence intervals and bias ±95% limits of agreement (LOA) were also calculated to provide measures of agreement between the criterion and practical measures. Inter-unit reliability was expressed as typical error (TE) and as a coefficient of variation (CV). Pearson product moment correlation coefficients were also calculated to provide a measure of inter-unit agreement. All statistical procedures were conducted in PASW Statistics v18.0 for Windows and Microsoft Excel.<sup>19,20</sup>

### 3. Results

Mean ± SD laser derived peak velocity achieved was 6.6 ± 0.2 m s<sup>-1</sup> with a mean trial duration of 2.19 ± 0.03 s. Mean ± SD acceleration at t = 0.2 s was 5.93 ± 0.1 m s<sup>-2</sup>. Testing was conducted under a clear blue sky with no cloud cover. Mean ± SD number of connected satellites and horizontal dilution of position (HDOP) for both GPS devices was 13 ± 1 and 0.9 ± 0.1 respectively.

Mean ± 95% CI distance reported by the GPS devices was 9.99 ± 0.08 m. SEE ± 95% CI for distance measurement was 0.0 ± 0.0 m. Mean bias ± 95% LOA was -0.01 ± 0.43 m. Inter-unit reliability as expressed by TE ± 95% CI was 0.03 ± 0.03 m. The Pearson correlation coefficient was 0.98 ± 0.02.

**Table 2**  
 Inter-unit reliability of 10 Hz GPS receivers for measuring instantaneous velocity during acceleration.

Acceleration (m s <sup>-2</sup> )	TE (m s <sup>-1</sup> )		CV (%)		Pearson correlation		Samples (n)
	GPS <sub>SMOOTH</sub>	GPS <sub>RAW</sub>	GPS <sub>SMOOTH</sub>	GPS <sub>RAW</sub>	GPS <sub>SMOOTH</sub>	GPS <sub>RAW</sub>	
0–1	0.05 ± 0.01	0.11 ± 0.02	0.7 ± 0.1	1.8 ± 0.3	0.96 ± 0.01	0.79 ± 0.1	60
1–2	0.06 ± 0.01	0.18 ± 0.04	1.1 ± 0.1	3.5 ± 0.7	0.95 ± 0.01	0.76 ± 0.15	56
2–3	0.09 ± 0.01	0.16 ± 0.03	2.2 ± 0.2	3.7 ± 0.7	0.91 ± 0.02	0.87 ± 0.09	52
3–4	0.10 ± 0.01	0.44 ± 0.15	3.9 ± 0.4	31.2 ± 12	0.91 ± 0.02	0.70 ± 0.50	33
>4	0.12 ± 0.01	0.43 ± 0.15	9.1 ± 1.0	47.4 ± 8.	0.87 ± 0.04	0.75 ± 0.20	32
All Data	0.08 ± 0.00	0.21 ± 0.04	3.1 ± 0.2	15.6 ± 2.5	0.99 ± 0.00	0.98 ± 0.00	233

Data presented are comparisons of inter-unit reliability from the two GPS devices used in the current study. Reliability is expressed as absolute typical error (TE), a coefficient of variation (CV) and a Pearson product moment correlation statistic.

An acceleration dependent shift in measurement bias was observed within the GPS<sub>SMOOTH</sub> measurements. Velocity tended to be overestimated during low accelerations (0–1 and 1–2), and underestimated during greater accelerations as shown by the mean bias, regression slope and y-intercept (Table 1 and Supplementary Figure 2). The regression slope ± 95% CI of GPS<sub>SMOOTH</sub> included the value of 1.0 for all acceleration thresholds except 3–4 and >4 m s<sup>-2</sup>.

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Validity was greatest during accelerations of 0–1 m s<sup>-2</sup> and decreased in an acceleration-dependent manner (Table 1). Overall, GPS<sub>SMOOTH</sub> demonstrated increased accuracy compared to GPS<sub>RAW</sub>. Mean SEE ± 95% CI was greater in GPS<sub>RAW</sub> compared to GPS<sub>SMOOTH</sub> (0.29 ± 0.01 m s<sup>-1</sup> vs. 0.19 ± 0.01 m s<sup>-1</sup>) as was bias ± LOA (0.20 ± 0.57 m s<sup>-1</sup> vs. 0.03 ± 0.43 m s<sup>-1</sup>)

There was a shift in the intercept of the regression line from positive to negative suggesting that the small systematic over-estimation of instantaneous velocity during lower accelerations transitions to an under-estimation during higher acceleration for both GPS<sub>SMOOTH</sub> and GPS<sub>RAW</sub> (Table 1). There was a similar shift in measurement bias from positive to negative as calculated by the Bland–Altman analysis (Supplementary Figure 3). However this trend was evident only in GPS<sub>SMOOTH</sub>, with GPS<sub>RAW</sub> bias remaining positive for all acceleration categories. 95% limits of agreement increased in a broadly acceleration dependent pattern for both GPS measures.

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Absolute and relative inter-unit reliability was found to decrease with increasing acceleration for both GPS<sub>SMOOTH</sub> and GPS<sub>RAW</sub>. Typical error was lower in GPS<sub>SMOOTH</sub> compared to GPS<sub>RAW</sub> in all acceleration bands (Table 2). The Pearson product-moment correlation coefficient exhibited a trend to decrease as acceleration increased for GPS<sub>SMOOTH</sub>. An acceleration dependent reduction in the correlation coefficient was not evident for GPS<sub>RAW</sub> (Table 2).

#### 4. Discussion

This study is the first to examine the acceleration-dependent criterion validity and inter-unit reliability of Catapult S4 10 Hz GPS receivers for measuring instantaneous velocity. The primary finding was that validity and inter-unit reliability of the 10 Hz GPS devices tested appears acceleration-dependent, with greater acceleration reducing the validity and reliability of velocity measurement.

The difference in  $SEE \pm 95\%$  CI of measurements taken during accelerations ranging from 0 to  $1 \text{ m s}^{-2}$  and 3 to  $4 \text{ m s}^{-2}$  was low ( $0.12 \pm 0.02 \text{ m s}^{-1}$  vs.  $0.19 \pm 0.04 \text{ m s}^{-1}$ ). However, the non-overlapping confidence intervals suggest that the differences are true (Table 1). Similarly, differences in SEE between  $GPS_{SMOOTH}$  and  $GPS_{RAW}$  also demonstrate true differences. SEE for  $GPS_{SMOOTH}$  measurement in the  $>4 \text{ m s}^{-2}$  category was  $0.32 \pm 0.06 \text{ m s}^{-1}$ , a marked increase from the broadly similar SEE values of the preceding acceleration categories which strongly suggests compromised validity above  $>4 \text{ m s}^{-2}$ .

The slope of the regression line  $\pm 95\%$  CI for  $GPS_{SMOOTH}$  did not differ from the line of identity for categories up to and including accelerations of  $3 \text{ m s}^{-2}$  (Table 1). For accelerations over  $3 \text{ m s}^{-2}$  the slope  $\pm 95\%$  CI was less than 1.0, indicating a true underestimation of instantaneous velocity during higher accelerations. The slope of  $GPS_{RAW}$  regressions demonstrated a similar trend, however the true deviation from the line of identity occurred for accelerations over  $2 \text{ m s}^{-2}$ .

Inspection of the calculated inter-unit reliability expressed as a coefficient of variation (TE as a percentage of the mean) suggests that  $GPS_{SMOOTH}$  is more reliable than  $GPS_{RAW}$  (Table 2).  $GPS_{SMOOTH}$  exhibits sufficient reliability (CV  $< 5\%$ ) for accelerations up to and including  $4 \text{ m s}^{-2}$ . For  $GPS_{RAW}$  the 5% threshold is breached for accelerations  $>3 \text{ m s}^{-2}$ . As with validity, inter-unit reliability appears acceleration dependent and is compromised at higher accelerations. Practitioners should be aware of the current findings, and in line with previous suggestions avoid using devices interchangeably.<sup>10,18</sup>

From examination of laser-derived acceleration, mean  $\pm$  SD acceleration at  $t=0.2 \text{ s}$  was  $5.93 \pm 0.1 \text{ m s}^{-2}$  which is similar but understandably lower than reported mean  $\pm$  SD values for peak acceleration of medium level male sprinters at  $t=0.2 \text{ s}$  of  $6.42 \pm 0.61 \text{ m s}^{-2}$ .<sup>6</sup> The similarity of these values provides strong support for the ecological validity of the protocol used for assessing brief maximal sprints.

Given the calculated validity of the GPS receivers examined for measuring 10 Hz instantaneous velocity, it is possible to make inferences regarding the efficacy of these devices for measuring acceleration. Error in mean acceleration ( $Error_a$ ) measurement by the devices used in the current study can be defined by Eq. (1).

$$Error_a = (Error_{v1} - Error_{v0}) \times 1/\Delta t \quad (1)$$

where  $Error_{v0}$  and  $Error_{v1}$  is the error for measuring initial and final instantaneous velocity respectively, and  $\Delta t$  = the time between  $v_0$  and  $v_1$  (dwell time). However, as demonstrated by Eq. (1), error in the measurement of instantaneous velocity does not necessarily result in an error in reported mean acceleration. For example, if both  $Error_{v0}$  and  $Error_{v1}$  are equal, the calculated mean acceleration will be correct. In practical terms, mean acceleration measurement accuracy increases as  $\Delta t$  increases, but sensitivity to brief peaks in acceleration will be compromised. To minimise error, the time period over which the acceleration is calculated ( $\Delta t$ ) can be increased. Due to the apparent reduction in validity during higher accelerations ( $>4 \text{ m s}^{-2}$ ) reported in the current study, it may not be advisable to use the studied 10 Hz GPS units to measure acute peak accelerations of such magnitude.

Direct comparison between the findings of the current study and previous studies is difficult due to differences in protocol and the categorisation of data into acceleration thresholds. In general agreement with the current study, Varley et al.,<sup>8</sup> found validity of the same 10 Hz devices to be greater during lower changes in velocity, although data was not categorised in acceleration thresholds but rather by starting velocity of the acceleration effort. Additionally, in the study of Varley et al.,<sup>21</sup> acceleration did not commence from a stationary start but from a “rolling” start of at least  $1 \text{ m s}^{-1}$ . Thus, peak acceleration, although not reported, was likely lower than in the current study. The current study builds on the study of Varley et al.,<sup>21</sup> to provide a better understanding of the efficacy of 10 Hz GPS for measuring instantaneous velocity and therefore acceleration.

The experimental protocol utilised in the current study allows for a more confident interpretation of the findings through the combination of an appropriate criterion measure, precise methods of demarcation for synchronisation of data points, and the elimination of measurement error due to the standardisation of GPS receiver trajectory. The current study employed linear 10 m maximal accelerations from a stationary start as they represent sport-specific situations in which the greatest accelerations occur. Validity and reliability during decelerations were not examined as it was not possible with the current protocol. However, as the variable examined was instantaneous velocity, it may be reasonable to assume that the current findings also extend to decelerations. With the continual development and refinement of GPS technology, future validation studies will be warranted. Researchers should seek to standardise experimental protocols where possible to allow for greater confidence in the interpretation of results.

#### 5. Conclusion

The validity and inter-unit reliability of 10 Hz GPS for the measurement of instantaneous velocity has been shown to be inversely related to acceleration. Those using the Catapult S4 10 Hz model of GPS should be aware that during accelerations of over  $4 \text{ m s}^{-2}$ , accuracy is compromised. In the examined GPS unit,  $GPS_{SMOOTH}$  offers enhanced validity and inter-unit reliability in comparison to  $GPS_{RAW}$ . Researchers using GPS should select and justify both the acceleration thresholds and the time period over which mean acceleration is calculated.

#### Practical implications

- Practitioners should be aware that the GPS technology used in the current study may be unsuitable for the measurement of instantaneous velocity during high magnitude ( $>4 \text{ m s}^{-2}$ ) accelerations.
- Practitioners and researchers investigating team sports should be aware of the impact of dwell time duration ( $\Delta t$ ) on the accuracy and sensitivity of measuring acceleration derived from instantaneous velocity.
- To eliminate inter-unit variation, GPS devices should not be used interchangeably.

#### Conflicts of interest

None of the authors have any conflicts of interest to declare.

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