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Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion

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Abstract

In this study, we assessed the validity and reliability of 5 and 10 Hz global positioning systems (GPS) for measuring instantaneous velocity during acceleration, deceleration, and constant velocity while straight-line running. Three participants performed 80 running trials while wearing two GPS units each (5 Hz, V2.0 and 10 Hz, V4.0; MinimaxX, Catapult Innovations, Scoresby, VIC, Australia). The criterion measure used to assess GPS validity was instantaneous velocity recorded using a tripod-mounted laser. Validity was established using the standard error of the estimate ($\pm$90% confidence limits). Reliability was determined using typical error ($\pm$90% confidence limits, expressed as coefficient of variation) and Pearson's correlation. The 10 Hz GPS devices were two to three times more accurate than the 5 Hz devices when compared with a criterion value for instantaneous velocity during tasks completed at a range of velocities (coefficient of variation 3.1–11.3%). Similarly, the 10 Hz GPS units were up to six-fold more reliable for measuring instantaneous velocity than the 5 Hz units (coefficient of variation 1.9–6.0%). Newer GPS may provide an acceptable tool for the measurement of constant velocity, acceleration, and deceleration during straight-line running and have sufficient sensitivity for detecting changes in performance in team sport. However, researchers must account for the inherent match-to-match variation reported when using these devices.

Keywords: *Instantaneous velocity, accuracy, motion analysis*

Introduction

The ability to increase velocity or accelerate (Little & Williams, 2005) is decisive in critical activities such as being first to the ball, moving into space before an opponent, and creating and stopping goal-scoring opportunities during team sports (Carling, Bloomfield, Nelsen, & Reilly, 2008; Reilly, Bangsbo, & Franks, 2000). To accelerate is more energetically demanding than constant velocity movement (Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2009), but to date no method has been satisfactorily validated for the measurement of accelerations in team sports (Reilly, Drust, & Clarke, 2008). Decelerations are just as common as accelerations in team sports (Osgnach et al., 2009; Spencer et al., 2004) and can place significant mechanical stress on the body (Thompson, Nicholas, & Williams, 1999). The eccentric muscle actions required to decelerate can lead to exercise-induced muscle damage, ultimately limiting an athlete's physical performance (Howatson & Milak, 2009). Quantification of the acceleration and deceleration demands of team sports would add great value to the existing body of knowledge if a satisfactory measurement tool was available. Little is known about the ability of global positioning systems (GPS) to measure these qualities.

The use of GPS technology to quantify the physical demands of team sports athletes is now commonplace during training and match-play (Aughey, 2010; Brewer, Dawson, Heasman, Stewart, & Cormack, 2010; Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010; Duffield, Coutts, & Quinn, 2009; Farrow, Pyne, & Gabbett, 2008; Wisbey, Montgomery, Pyne, & Rattray, 2009). Running velocity and acceleration efforts are often reported using user-defined velocity thresholds (Aughey, 2010; Farrow et al., 2008; Wisbey et al., 2009). However, to date only GPS sampling at 1 and

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5 Hz has been used (Aughey, 2010; Brewer et al., 2010; Coutts et al., 2010; Duffield et al., 2009; Farrow et al., 2008; Wisbey et al., 2009), although 10 Hz GPS units are now commercially available. According to the manufacturer, these units have both an increased GPS sample rate and an updated chipset that provides a more sensitive GPS receiver and improved algorithms for determining position. Comparisons between 1 Hz and 5 Hz GPS for measuring distance have reported an increased accuracy and improved reliability with greater sampling frequencies (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010a) with even further improvement when using a 10 Hz sampling frequency (Castellano, Casamichana, Calleja-Gonzalez, San Roman, & Ostojic, 2011).

The reliability and validity of the superseded GPS devices such as the MinimaxX V2.0 and V2.5 for measuring team sport running activities have recently been established (Coutts & Duffield, 2010; Gray, Jenkins, Andrews, Taaffe, & Glover, 2010; Jennings et al., 2010a; Jennings, Cormack, Coutts, Boyd, & Aughey, 2010b). Each of these studies compared GPS distance to known distances either previously measured or derived from timing gates. The reliability and validity of these units was acceptable for measuring longer efforts, but limited for the assessment of brief, high-speed straight-line running, accelerations or efforts involving a change of direction (Jennings et al., 2010a). Another study reported the ability of GPS to assess mean velocity when passing through timing gates during a team sport circuit as adequate (MacLeod, Morris, Nevill, & Sunderland, 2009). Finally, GPS was found to underestimate mean and peak velocity during court-based team sport movement patterns compared with a high-resolution motion analysis device (VICON) (Duffield, Reid, Baker, & Spratford, 2010). However, none of these studies compared instantaneous GPS velocity or change in velocity to a criterion value.

Laser measurement devices produce valid and reliable estimates of distance from which velocity data can be derived (Harrison, Jensen, & Donoghue, 2005). Compared with timing gates, which can only determine average velocity based on a limited number of samples, laser devices sample at 50+ Hz allowing the collection of practically instantaneous velocity data. This allows a more sensitive measure of the changes in velocity during rapid actions such as accelerations and decelerations. Therefore, the laser should provide more reliable and valid measures than timing gates.

The aim of the present study, therefore, was to determine the validity and reliability of 5 and 10 Hz GPS for measuring instantaneous velocity during the acceleration, deceleration, and constant velocity phases of straight-line running.

Methods

Three sub-elite team sport athletes (age 27 ± 3 years) volunteered and provided written consent to participate in the study. As the primary measure of this study was the raw GPS data, the number of participants does not reflect the sample size, as it is the number of samples collected and trials undertaken that are of most importance. The study was approved by the Victoria University Human Research Ethics Committee and conformed to the Declaration of Helsinki.

Experimental design

To determine the validity and reliability of 5 and 10 Hz GPS for measuring changes in velocity, participants were asked to perform straight-line running along a marked line. Each trial required the participant to establish and maintain a constant running velocity before performing an acceleration effort and finally decelerating to a complete stop. In total, 80 straight-line running trials were undertaken.

Running velocity was recorded using a Laveg laser (LAVEG Sport, Jenoptik, Jena, Germany) sampling at 50 Hz, which was the criterion measure during all testing. The error of the laser for determining distance travelled has been identified as 0.10 ± 0.06 m over 100 m (Arsac & Locatelli, 2002) with a coefficient of variation of up to 0.2% over 10, 30, 50, and 70 m (Harrison et al., 2005). Similarly, the laser has a reported average velocity error of $<2\%$ (Turk-Noack & Schmalz, 1994). Reliability of the laser for measuring velocity has been assessed through repeated running trials giving a typical error of $0.05 \text{ m} \cdot \text{s}^{-1}$ and an interclass correlation (r) of 0.98 (Duthie, Pyne, Marsh, & Hooper, 2006). The laser was positioned on a tripod 2 m behind the starting point and aligned with the centre of the participant's back to ensure they remained in focus throughout each trial. In addition, participants wore a white shirt during all testing as this offered an appropriate reflective surface for the laser signal.

During each trial, the participants wore two 5 Hz or two 10 Hz GPS units (MinimaxX V2.0 and V4.0 respectively; Catapult Innovations, Scoresby, VIC, Australia) positioned approximately 25 cm apart on the upper back in a custom-made vest. The antennas of each unit were exposed to allow clear satellite reception (Jennings et al., 2010a). Participants were asked to produce an acceleration effort from a range of starting velocities common in team sports ($1–6 \text{ m} \cdot \text{s}^{-1}$).

Participants were provided with instant feedback on their running velocity during each trial. A computer was connected to the laser and, using custom software, instantaneous velocity data were obtained during each trial. The velocity bands for the desired constant velocity were entered into the software and feedback transmitted via a two-way radio device (TX670 UHF Handheld Transceiver, GME, Sydney, NSW, Australia). Participants were given a radio device to hold throughout each trial, which provided feedback through several audio cues. Participants heard a low pitch if their starting velocity before acceleration was too low, a high pitch if too fast, silence if they were within the required velocity threshold, and an alternating pitch once the appropriate constant velocity had been maintained for a minimum of 2 s. Participants were informed to accelerate maximally for several seconds upon hearing the alternating pitch before decelerating to a complete stop to conclude the trial.

The mean ($\pm$standard deviation) number of satellites during data collection was 12 ± 1.5. The horizontal dilution of position is an indication of the accuracy of the GPS horizontal positional signal determined by the geographical organization of satellites. Values range from 1 to 50, with 1 indicating an ideal positional fix and increasing values signifying positional unreliability (Witte & Wilson, 2004). The mean horizontal dilution of position during data collection was 0.9 ± 0.2.

Laser velocity data were re-sampled to 5 Hz and 10 Hz for comparison with the respective GPS device and synchronized at the first movement recorded above $0\ \mathrm{m \cdot s^{-1}}$ to account for processing phase delays inherent with these GPS systems. The re-sampling technique involved taking a sample from the laser data corresponding to the equivalent sample at the slower frequency. For example, when re-sampling to 10 Hz every fifth sample was taken from the 50 Hz data. This was deemed to be the best method to simulate a true reflection of the slower sampling frequency. Raw laser data were clipped above 12 and below $-1\ \mathrm{m \cdot s^{-1}}$ respectively to account for errors where the participant may have moved outside the sight of the laser. Trials were divided into three phases: constant velocity, acceleration, and deceleration. Constant velocity was categorized as 1–3, 3–5, and 5–8 $\mathrm{m \cdot s^{-1}}$; acceleration as commencing from 1–3, 3–5, and 5–8 $\mathrm{m \cdot s^{-1}}$; and deceleration as commencing from 5–8 $\mathrm{m \cdot s^{-1}}$.

Statistical analyses

All data were log-transformed to reduce bias due to non-uniformity of error. Validity was calculated by the standard error of the estimate and expressed as a standard deviation ($\pm$90% confidence limits) of the percentage difference between criterion velocity (laser) and GPS velocity. In addition, bias was reported as the percentage difference between the reference velocity and GPS velocity. Finally, a Pearson product–moment correlation between criterion and GPS velocity was calculated.

Inter-unit reliability (10 Hz–10 Hz), (5 Hz–5 Hz) was assessed and expressed as the typical error and a coefficient of variation ($\pm$90% confidence limits). The utility of the devices for use in team sports was assessed by comparing the calculated smallest worthwhile change ($0.2 \times$ between-participant standard deviation; Batterham & Hopkins, 2006) to the coefficient of variation.

Results

Higher starting velocities improved the measurement accuracy for detecting accelerations with both 5 and 10 Hz GPS (Table I). Similarly, validity improved during higher constant velocities and with an increased sampling rate for measuring constant velocity, acceleration, and deceleration (Table I).

Both 5 and 10 Hz GPS underestimated the criterion velocity during the acceleration phase (Table I). Constant velocity was underestimated at 5–8 $\mathrm{m \cdot s^{-1}}$ for 5 Hz GPS and 3–5 and 5–8 $\mathrm{m \cdot s^{-1}}$ for 10 Hz GPS. In contrast, constant velocity was overestimated at 1–3 and 3–5 $\mathrm{m \cdot s^{-1}}$ for 5 Hz GPS and 1–3 $\mathrm{m \cdot s^{-1}}$ for 10 Hz GPS. Lower errors were associated with constant velocity running (Table I). Instantaneous velocity was overestimated during the deceleration phase. The magnitude of the error was reduced with an increased sampling frequency across all phases.

The criterion and GPS velocities were strongly correlated for all phases when sampling at a higher rate (Table I). Weaker correlations were associated with higher constant and starting velocities during all phases in 5 Hz GPS units.

Reliability improved at higher starting velocities during both the constant velocity and acceleration phases irrespective of sampling rate (Table II). A higher sampling rate did, however, demonstrate improved reliability during the constant velocity and acceleration phase and deceleration phase (coefficient of variation $<5.3\%$ and $<6\%$ respectively; Table II), compared with a lower sampling rate (Table II).

GPS sampling at 5 Hz was incapable of detecting the smallest worthwhile change during all phases of these tests (coefficient of variation > smallest worthwhile change; Table II). In contrast, 10 Hz GPS was able to detect the smallest worthwhile change during the constant velocity and acceleration phase for 1–3 $\mathrm{m \cdot s^{-1}}$ and during the deceleration phase. Similarly, 10 Hz GPS was acceptable for detecting the smallest worthwhile change during the constant velocity and acceleration phase for 3–5 and 5–8 $\mathrm{m \cdot s^{-1}}$

Table I. Validity of 5 and 10 Hz GPS devices for measuring instantaneous velocity.

	Starting velocity ($m \cdot s^{-1}$)	CV as %		Bias as %		Pearson correlation		No. of trials		No. of samples		Mean time (s)		Mean distance (m)	
		5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz
Constant velocity	1–3	11.1 ± 0.58	8.3 ± 0.27	2.4 ± 0.8	0.6 ± 0.4	0.91 ± 0.01	0.96 ± 0.00	26	43	561	1348	4.01	3.15	8.0	6.5
	3–5	10.6 ± 0.59	4.3 ± 0.15	0.3 ± 0.8	−0.2 ± 0.2	0.77 ± 0.03	0.95 ± 0.00	22	45	485	1119	3.34	2.53	13.5	10.6
	5–8	3.6 ± 0.26	3.1 ± 0.13	−0.5 ± 0.8	−0.2 ± 0.2	0.28 ± 0.09	0.92 ± 0.01	11	34	266	755	3.33	2.24	18.2	12.9
Acceleration	1–3	14.9 ± 1.16	5.9 ± 0.23	−9.6 ± 1.3	−2.9 ± 0.3	0.9 ± 0.02	0.98 ± 0.00	26	45	259	929	1.84	2.17	8.8	11.4
	3–5	9.5 ± 0.79	4.9 ± 0.21	−5.0 ± 1.0	−3.6 ± 0.3	0.82 ± 0.04	0.98 ± 0.00	22	43	220	772	1.52	1.70	8.4	10.3
	5–8	7.1 ± 0.87	3.6 ± 0.18	−5.2 ± 1.4	−2.1 ± 0.2	0.5 ± 0.12	0.92 ± 0.01	11	36	103	537	1.29	1.57	8.2	10.9
Deceleration	5–8	33.2 ± 1.64	11.3 ± 0.44	19.3 ± 2.1	8.9 ± 0.8	0.83 ± 0.02	0.98 ± 0.00	59	46	735	986	2.07	2.70	8.55	12.0

Note: All data are comparison of GPS data with criterion values obtained from instantaneous velocity recorded by laser. Data are expressed as a coefficient of variation (CV), percent bias, and a correlation statistic.

Table II. Reliability of 5 and 10 Hz GPS devices for measuring instantaneous velocity.

	Starting velocity ($m \cdot s^{-1}$)	TE ($m \cdot s^{-1}$)		SWC as %		CV as %		Pearson correlation		No. of trials		No. of samples		Mean time (s)		Mean distance (m)	
		5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz	5 Hz	10 Hz
Constant velocity	1–3	0.21 ± 0.02	0.12 ± 0.00	5.91	6.66	12.4 ± 1.18	5.3 ± 0.22	0.80 ± 0.05	0.97 ± 0.00	10	20	171	837	3.91	3.09	7.6	6.3
	3–5	0.27 ± 0.03	0.13 ± 0.01	3.38	2.85	6.7 ± 0.68	3.5 ± 0.20	0.83 ± 0.04	0.94 ± 0.01	10	19	145	448	3.77	2.46	14.9	10.3
	5–8	0.35 ± 0.05	0.11 ± 0.01	1.43	1.92	6.3 ± 0.83	2.0 ± 0.12	0.22 ± 0.18	0.96 ± 0.01	5	15	80	365	3.76	2.19	20.5	12.6
Acceleration	1–3	0.50 ± 0.06	0.18 ± 0.01	9.07	8.21	16.2 ± 1.99	4.3 ± 0.24	0.84 ± 0.05	0.98 ± 0.00	10	20	108	486	1.67	2.13	7.8	11.3
	3–5	0.43 ± 0.05	0.20 ± 0.01	3.64	3.64	9.5 ± 1.18	4.2 ± 0.26	0.74 ± 0.08	0.94 ± 0.01	10	19	100	364	1.32	1.68	7.2	10.1
	5–8	0.60 ± 0.12	0.13 ± 0.01	2.2	1.86	11.0 ± 2.29	1.9 ± 0.15	0.00 ± 0.27	0.95 ± 0.01	5	15	39	240	1.20	1.64	7.9	11.5
Deceleration	5–8	0.83 ± 0.07	0.16 ± 0.01	12.46	14.99	31.8 ± 2.99	6.0 ± 0.33	0.69 ± 0.06	0.99 ± 0.00	25	17	206	475	2.01	2.80	8.2	12.5

Note: All data are comparison of one GPS device to a second device located on each participant during each trial. Data are expressed as a typical error (TE) and a coefficient of variation (CV). The smallest worthwhile change (SWC) was calculated as 0.2 × between-participant standard deviation (Batterham & Hopkins, 2006).

(similar coefficient of variation and smallest worthwhile change values; Table II).

Discussion

This study was the first to determine the validity and reliability of 5 and 10 Hz GPS units for measuring instantaneous changes in velocity. The major finding was that the V4.0 MinimaxX was two to three times more accurate than the V2.0 units at detecting change in velocity and up to six-fold more reliable. These newer devices provided an acceptable level of accuracy and reliability for determining instantaneous velocity for all phases of straight-line running.

During the constant velocity and acceleration phases, GPS accuracy increased at higher constant and starting velocities by up to 67% and 52% respectively, compared with at lower velocities. In contrast, the accuracy of GPS for measuring distance has been reported to decrease at higher running velocities (Jennings et al., 2010a; Petersen, Pyne, Portas, & Dawson, 2009). However, in these studies, trials were not separated into running phases, thus high-velocity trials contained large changes of velocity, as they were undertaken from low starting velocities (Jennings et al., 2010a; Petersen et al., 2009). In the present study, the increase in accuracy we report may be attributed to less variation in the change of velocity when starting from 5 to 8 $m \cdot s^{-1}$, as participants only achieved a maximal speed of $\sim$7.5 $m \cdot s^{-1}$. Incidentally, similar top speeds have been reported in team sport athletes, including elite soccer players ($\sim$7.6 $m \cdot s^{-1}$; Bradley et al., 2009) and Australian footballers ($\sim$8.6 $m \cdot s^{-1}$; Young et al., 2008). Therefore, the methods we used to assess GPS velocity measurements had an acceptable ecological validity, as the range of velocities undertaken by participants were representative of those performed by team-sports athletes.

The underestimation of true velocity during phases involving high-velocity movement was similar to 1 Hz GPS compared with speedometer velocity during track cycling (Witte & Wilson, 2004). The greatest over- and under-estimations of true velocity occurred with the older V2.0 MinimaxX units. Similarly, greater errors for measuring distance have been reported with 1 Hz versus 5 Hz GPS units, indicating that it may be sample rate that limits the accurate detection of both distance and velocity (Jennings et al., 2010a). This is supported by the validation of 10 Hz units for measuring sprint distance over 15 and 30 m with an improved coefficient of variation of $<$4% (Castellano et al., 2011). With the exception of low starting velocity accelerations (5 Hz) and decelerations (5 and 10 Hz), all velocity measures were less than 5% from criterion values. The magnitude of these errors may not be large enough to significantly affect the classification of movements when analysing the movement demands of team sports athletes, due to the inherent variability of match running performance. Only one study has determined the coefficient of variation of running in team sport from match to match using 5 Hz GPS. Both total and high-velocity running distance had a coefficient of variation of $\sim$10% and the number of maximal accelerations $\sim$51% (Aughey, in press). The coefficient of variation for both V2.0 and 4.0 MinimaxX for measuring constant velocity was either below or close to these values for match running, while the coefficient of variation for measuring acceleration was substantially lower than the variation in acceleration efforts. Therefore, researchers can use these units with confidence to detect changes in match running during team sports, as the signal is greater than the inherent noise. Although there were differences in the mean duration and distance over which accelerations occurred in the 5 and 10 Hz trials, the greatest discrepancy was 0.45 s (2 and 4 samples from each unit respectively). Given this small difference in samples, comparison between the 5 and 10 Hz units should not be unduly affected.

The strong validity and reliability correlations when comparing V4.0 MinimaxX velocity to the criterion suggest that although there is a degree of error when measuring instantaneous velocity, 10 Hz GPS can at least accurately determine that an acceleration or deceleration has occurred. This has implications for the analysis of team sports, as researchers can determine the number of accelerations or decelerations undertaken by athletes over the course of a match. Caution should be exercised when using V2.0 MinimaxX for measuring instantaneous velocity due to the weak correlation with the criterion measure. However, team sport data can still be analysed by accounting for match running variability.

The accuracy of GPS in measuring changes in velocity during deceleration was poor, with overestimations of up to 19.3%. In this study, decelerations contained the greatest rate of change in velocity, on average 17.4% greater than during accelerations. As is evidenced by similar high coefficients of variation in accelerations starting from 1–3 $m \cdot s^{-1}$, GPS accuracy is negatively affected by a high rate of change in velocity. Although an increased sampling rate improved accuracy, researchers may be limited to simply reporting the occurrence of decelerations, as opposed to quantifying their magnitude in terms of distance and duration.

The inter-unit reliability was superior in the more modern devices tested here. Importantly, 10 Hz GPS had a coefficient of variation less than or similar to the calculated smallest worthwhile change during all phases. Therefore, the V4.0 MinimaxX may provide sufficient sensitivity for detecting small and important changes in performance of accelerations, decelerations, and constant velocity movements common in team sports. However, future match analysis research should quantify the match-to-match variability in team sport running to support the ecological validity of these devices. While unable to detect the smallest worthwhile change in the tests employed in this study, 5 Hz GPS can be used to quantify team sport running as the coefficient of variation is less than or close to the reported match-to-match running variability (Aughey, in press). To remove as much associated error as possible, researchers should use the same devices on the same individuals when monitoring team sport athletes.

This study was limited in its specificity to team sport movement demands as athletes often change direction, whereas only straight-line running was reported. Future research should investigate the validity and reliability of GPS technology for measuring changes in velocity during non-linear movements.

Conclusion

The data presented detail the superior validity and inter-unit reliability of V4.0 MinimaxX compared with the older V2.0 units. While these improvements appear to be linked to the higher sampling frequency, the manufacturers claim that the advanced chipsets used with the latest models may be largely responsible. The latest V4.0 units sampling at 10 Hz produce sufficient accuracy to quantify the acceleration, deceleration, and constant velocity running phases in team sports.

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