

# Validity and Reliability of 5 Hz GPS for Measurement of Non-Linear Cycling Distance and Velocity

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**Abstract.** This study aimed to determine the validity and reliability of a 5 Hz GPS system for recording distance and velocity during non-linear cycling activity. One trained male cyclist (age 37 yrs; stature 172.4 cm; body mass 74.2 kg) took part in the study. Two non-differential GPS units (Minimax X3, Catapult) were attached securely into the rear pocket of a cycling shirt at approximately the T11-12 vertebrae. The participant performed 3 laps at each velocity of 10, 20 and 30 km.h<sup>-1</sup> on a tarmac track. GPS distance was contrasted to that recorded by a calibrated trundle wheel and cycle computer (COMP) (S710, Polar), whilst GPS velocity was compared simultaneously with the COMP. GPS and COMP velocities were strongly correlated at 10 km.h<sup>-1</sup> ( $r = .997$ ,  $R^2 = .993$ ,  $p < .05$ ) and 30 km.h<sup>-1</sup> ( $r = .955$ ,  $R^2 = .913$ ,  $p < .05$ ) and moderately correlated at 20 km.h<sup>-1</sup> ( $r = .539$ ,  $R^2 = .290$ ,  $p > .05$ ). No significant differences were revealed for distance between trundle wheel, GPS and COMP ( $p > .05$ ,  $\eta^2 = .152$ ) or GPS distance at different velocities ( $p > .05$ ,  $\eta^2 = .238$ ). Overall intra and inter-unit reliability for distance were 1.83 % and .90 % respectively, whilst overall intra and inter-unit reliability for velocity were 2.53 % and 2.03 % respectively. This study showed GPS provides a valid and reliable means of monitoring distance and velocity during non-linear cycling activity across a range of velocities.

**Key words:** Cycling, GPS, non-linear, validity, reliability.

## 1. Introduction

Over the past 30 years notational and video based analyses have been used to determine the time-motion analysis (TMA) patterns of various activities. Though these methods provide valid means of quantifying distances covered and intensities (Deutsch *et al.*, 2007), they are time consuming to conduct (Roberts *et al.*, 2006). In addition, these methods require a clear view of the playing area, making their use largely impractical for the analysis of sports such as cycling. As cycling is performed over a variety of geographical terrains and over vastly greater areas than team sports, notational and video analysis is not appropriate.

Recent advances in technology have led to the development of wearable global positioning systems (GPS). The use of these systems allow for quick and accurate analysis of the physical demands of various sports, both in training and in competition (Aughey, 2011). Global positioning systems are now used widely in a number of invasion sports such as rugby, Australian football, soccer and cricket (Cunliffe *et al.*, 2009; Portas *et al.*, 2010; Wisbey *et al.*, 2010; Petersen *et al.*, 2011).

The accuracy of GPS is affected by several factors including the number of satellites visible to the GPS receiver and the geometric configuration of the satellites (Schutz and Herren, 2000; Janssen and Sachlikidis, 2010). Global positioning systems determine position via a process known as triangulation, which works by taking the position of three satellites and then uses a fourth that acts as a correction factor. In essence, the distance measurement is determined by velocity x travel time, where velocity is the speed of light of radio signals travelling through space (Aughey, 2011). The arrangement of satellites is determined via dilution of precision (DOP). The longitude and latitude of satellite positioning is referred to as horizontal dilution of precision (HDOP), while the altitude of the satellites is termed vertical dilution of precision (VDOP) (Witte and Wilson, 2004). A DOP of 1 would represent the highest probability of accuracy, with one satellite positioned directly overhead and generally a minimum of three other satellites positioned equal distance around the horizon for 3D positioning (Witte and Wilson, 2004). Dilutions of precision values up to 5 are deemed acceptable, with accuracy diminishing as the values increase.

The validity and reliability of GPS has been well researched over the past decade for use in intermittent team sports. Petersen *et al.* (2009) reported the reliability (expressed as mean 90 % confidence limits) of estimating distance travelled in cricket by walking to striding ranged from 0.3 to 2.9 %, whilst mean reliability of estimating sprinting distances over 20 to 40 m ranged from 2.0 to 30.0 %. Similarly, Jennings *et al.* (2010) reported the standard error of estimation (SEE) for measuring distances walking through to sprinting over 40 m was 9.8 to 11.9. Other studies have also found comparable results, with accuracy being improved over longer distances (Edgecomb and Norton, 2006; MacLeod *et al.*, 2008; Coutts and Duffield, 2010).

In addition, the sampling rate of the GPS also affects distance measured (Aughey, 2011). When comparing distances covered by sprinting, the recorded errors reported in previous studies were higher when 1 Hz GPS were used, then when 5 or 10 Hz GPS were used (Coutts and Duffield, 2010; Jennings *et al.*, 2010; Duffield *et al.*, 2010; Castellano *et al.*, 2011). However, most research into the use of GPS in sport has involved running based activities. In addition, studies of validity have mostly used linear movement patterns unlike those observed in cycling. Gray *et al.* (2010) investigate the influence of both linear and non-linear running activity on GPS determined distance in field-based team sports. They found that whilst the 1 Hz GPS did provide a valid measure of distance during both linear and non-linear running patterns, the validity and reliability was reduced when quantifying non-linear movements, particularly those at higher running velocities.

Modern GPS units, such as the ones used in the present study, determine velocity via a Doppler shift method, which is calculated separately to position. This works by determining the changes in wave frequency of the radio waves due to movement in the GPS unit. To the author's knowledge, Witte and Wilson (2004) are the only researchers to investigate the accuracy of non-differential GPS for determining over ground velocity during cycling. They found that 45 % of GPS-based velocity values were within  $0.2 \text{ ms}^{-1}$  of those derived from a calibrated bicycle speedometer and a further 19 % were within  $0.4 \text{ ms}^{-1}$ . However, accuracy was shown to diminish when cycling around small radii corners, with only 16 % of values within  $0.2 \text{ ms}^{-1}$  of true velocity. They concluded that GPS provided an accurate measure of velocity when performance was on a relatively straight course. It would therefore appear that the accuracy of distance and velocity measured via GPS is also influenced by the velocity of the task. However, the majority of current research into GPS attests that these systems can provide an accurate measure of human locomotion during team sports activities.

Despite this agreement the level of errors previously reports and the sources of errors may have implications for the utilization of GPS to determine distance and velocity during cycling activity. Though Witte and Wilson (2004) investigated the validity of GPS for determining cycling velocity and distance during non-linear movement patterns, they did so by cycling in one direction round a 400 m running track and in straight line tests separately. As such the efficacy of this study is somewhat limited and it is somewhat lacking in ecological validity. It was therefore the aim of the current investigation to determine the accuracy of distance and velocity recorded by GPS during realistic cycling conditions involving non-linear directional changes and at different velocities.

## 2. Methods

### 2.1. Participants

A single male participant (age 37 yrs; stature 172.4 cm; body mass 74.2 kg) took part in the study. One participant was deemed acceptable, as the purpose of the study was to determine differences in GPS derived distance and velocity with those of a criterion measure. Thus the use of a sole participant reduced the level of variability between trials. The participant was a well-trained cyclist with over 15 years of racing experience at National level. Ethical approval for the study was granted by the University of Central Lancashire Ethics Committee and in accordance with the Declaration of Helsinki. The participant was informed both verbally and in writing of the test procedures and written informed consent was obtained.

### 2.2. Equipment

The participant rode a hard-tail cross-country mountain bike with 80 mm of front only suspension travel (Specialized Stumpjumper Expert, Specialized, UK). This was instrumented with a digital cycling computer (COMP) (Polar S710, Polar, Kempele, Finland) attached to the handlebar, which wirelessly connected to a speed sensor positioned on the right fork leg. A magnet was mounted to one of the front wheel spokes. Each time the magnet passed within 2 mm of the speed sensor an electrical impulse was transmitted to the receiver

unit and was converted into a velocity value. This was used as the criterion measure of velocity. To determine distance the cycle track was measure using a calibrated trundle wheel. The mean of three laps was used as the criterion measure to account for slight variation in walking path. Two 5 Hz GPS units (Minimaxx X3, Catapult, Australia) were then taped into the rear pocket of a cycling shirt at approximately the T11-12 vertebrae to determine the GPS derived measure of distance and velocity using Catapults' own proprietary software. Prior to testing the GPS units were switch on and left for 10 min to allow them to download the ephemeris data from the satellites. This data is used in the calculation of location and thus distance. In addition, distance recorded by the cycle computer was also compared to the GPS and trundle wheel values. The Polar S710 was calibrated in accordance to the manufacturers' guidelines.

The cycle route used was a purpose built tarmac track, composed of both straight sections and both left and right hand corners of differing radius. The course had previously been measured at 1591.60 m using the trundle wheel and was composed of both tree covered and open sections to more closely replicate true cycling conditions.

### 2.3. Test Protocols

The participant performed a 10 min self-paced cycling warm up followed by 5 min of dynamic stretching. The participant then performed 3 laps of the course at each of three velocities, 10, 20 and 30 km.h<sup>-1</sup>. Post testing, data were downloaded to a personal computer were mean velocity and distance for each lap were determined for the GPS units using the systems proprietary software (Logan Plus V4.6.1, Catapult, Australia), whilst mean velocity of the COMP were determined using Polar Protrainer 5 (Polar, Kempele, Finland). The mean and standard deviation for the number of satellites used during data collection and the HDOP were also calculated to provide an indication of GPS accuracy.

### 2.4. Statistical Analyses

Normality of data was confirmed using a Kolmogorov-Smirnov test. Validity of GPS velocity compared to the criterion measures at each intensity was determined using linear regression analyses, whilst a one-way analysis of variance (ANOVA) with Bonferroni post-hoc correction was used to determine differences in GPS distance at different cycling velocities and between distances recorded by the two GPS, cycle computer and trundle wheel.

Using the methods outlined by Gray *et al.* (2010), intra-unit reliability for both velocity and distance at each velocity was calculated using coefficient of variation (CV) (95 % confidence limits) between the repeated trials. The inter-unit reliability was also determined using CV (95 % confidence limits). Significance was accepted at the  $p \leq 0.05$  level and data are presented as mean  $\pm$  standard deviation. All statistical procedures were conducted using SPSS 19.0 (SPSS Inc., Chicago, IL, USA).

## 3. Results

The mean number of satellites used during GPS data collection across both units was  $12.01 \pm .81$  (range = 10 to 13.46) and mean HDOP was  $1.00 \pm 0.06$  (range = 0.92 to 1.15). Weather conditions during data collection were sunny with no cloud cover. With a mean HDOP of 1 and clear sky, the conditions for data collection were excellent.

Criterion (COMP) and GPS velocities were strongly correlated at 10 km.h<sup>-1</sup> ( $r = .997$ ,  $R^2 = .993$ ,  $p < .05$ ) and 30 km.h<sup>-1</sup> ( $r = .955$ ,  $R^2 = .913$ ,  $p < .05$ ), but only moderately correlated at 20 km.h<sup>-1</sup> ( $r = .539$ ,  $R^2 = .290$ ,  $p > .05$ ). No significant differences were revealed for distance measured between trundle wheel, GPS and COMP ( $F_{(2, 27)} = 2.419$ ,  $p > .05$ ,  $\eta^2 = .152$ ). Additionally, no significant differences were found for GPS derived distance recorded at different velocities ( $F_{(2, 15)} = 2.347$ ,  $p > .05$ ,  $\eta^2 = .238$ ). Table 1 presents the mean ( $\pm$  s.d.) velocity and distance recorded for each exercise intensity.

Table 1. Mean  $\pm$  s.d. GPS and COMP derived distance and velocity for each exercise intensity.

Intensity (km.h <sup>-1</sup> )	Distance (m)		Recorded Velocity (km.h <sup>-1</sup> )	
	GPS	COMP	GPS	COMP
10	1594.33 $\pm$ 14.28	1586.67 $\pm$ 5.77	9.61 $\pm$ .33	10.17 $\pm$ .12
20	1516.00 $\pm$ 54.10	1586.67 $\pm$ 5.77	19.31 $\pm$ .45	20.27 $\pm$ .06
30	1565.83 $\pm$ 15.28	1586.67 $\pm$ 5.77	29.29 $\pm$ .50	30.30 $\pm$ .10

Note: Actually distance was 1591.60 m using the trundle wheel.

The intra-unit CV for recording distance was less than 4 % across all intensities with an overall CV of 1.83 %. When analysing the velocity data, CV was again less than 4 % across the different intensity ranges, with an overall CV of 2.53 %. The inter-unit CV for distance was less than 2 % across all intensities, with an overall inter-unit CV of 0.90 %. The inter-unit CV for velocity was less than 4 % across all intensities, with an overall inter-unit CV of 2.03 %.

Table 2. Intra and inter-unit coefficient of variation for GPS derived velocity and distance for each exercise intensity.

	Distance at each intensity (km.h <sup>-1</sup> )				Velocity			
	10	20	30	Mean	10	20	30	Mean
Intra-unit	.90	3.60	1.00	1.83	3.50	2.40	1.70	2.53
Inter-unit	0.55	1.65	0.50	0.90	3.75	0.85	1.50	2.03

## 4. Discussion

The aims of this study were to determine the accuracy of distance and velocity recorded by GPS during non-linear cycling and the influence of different velocities on distance measured. This study represents the first investigation to determine the efficacy of GPS for cycling use under realistic multi-directional, varying speed riding conditions.

The validity of GPS velocity was high at both 10 and 30 km.h<sup>-1</sup>. However, it was only moderately correlated with the criterion measure of velocity at 20 km.h<sup>-1</sup>, though differences were less than 1 km.h<sup>-1</sup>. At all intensities GPS velocity was within 5 % of the criterion measures, with differences being smallest at the higher intensity. These findings are supported by Varley *et al.* (2011) who also reported differences in velocity of less than 5 % when compared to criterion values. However, similar to the findings of Varley *et al.* (2011) the results of the present study are in contrast to previous research, which have frequently shown errors in velocity measurement increase with increasing intensities (Petersen *et al.*, 2009; Jennings *et al.*, 2010).

As suggested by Varley *et al.* (2011) the greater errors observed in previous examinations compared to the present study may be the result of greater variability in exercise velocities within each intensity band. As can be seen from the present study the standard deviation for velocities recorded with both GPS and cycles computer was less than .50 across all velocities, indicating low variability between trials. As such, the results of the present study suggest that 5 Hz GPS can provide a valid measure of cycling velocity across a range of intensities.

Intra-unit reliability for velocity was less than 3.5 % across the range of intensities used and less than 3% overall. This was found to be similar to those previously published by Gray *et al.* (2010). The overall inter-unit reliability was again comparable to that reported by Gray *et al.* (2010). However, in contrast to previous research, both intra and inter-unit reliability was greater at higher velocities. The greater reliability in the present study may in part be attributed to improved satellite coverage than reported in previous studies. The mean number of satellites available in the present study was double that reported by Gray *et al.* (2010), whilst DOP values reported by Gray *et al.* (2010) were also less favourable than in the present study. As such, the findings of the present study indicate that GPS velocities can be reliably compared both within and between units when used for non-linear cycling activity. However, it remains unclear as to why values were lowest during 20 km.h<sup>-1</sup>.

No significant differences were revealed between GPS and COMP when compared to the criterion distance measure (trundle wheel). Likewise, there were no significant differences in distance recorded at different velocities. Despite this the cycle computer showed better agreement with the criterion measure, with a mean distance error of only .31 % (4.93 m) compared to 2.18 % (32.88 m) for GPS. The highest error with GPS was observed at 20 km.h<sup>-1</sup>. However, distance error generally increased with higher velocities and the highest error observed at moderate intensity may have been the result of some receiver error. This is again consistent with previous research (Witte and Wilson, 2004; Jennings *et al.*, 2010). The errors in distance measurement were lower than those reported by Gray *et al.* (2010). This may be due to the longer distances used in the present study, as previous research has shown accuracy of position measurements to be

improved over longer distances (MacLeod *et al.*, 2008; Coutts and Duffield, 2010).

The number of satellites used to triangulate position and their geometric distribution relative to the receiver have been shown to influence the accuracy of position determination (Schutz and Herren, 2000; Misra and Enge, 2006; Janssen and Sachlikidis, 2010). A minimum of four satellites are needed to determine position, with accuracy being improved the more satellites visible to the receiver. In the present study the mean number of satellites visible was twelve, with the lowest number at any point during testing being 10. Additionally, dilution of precision, the distribution of these satellites, also affects accuracy (Witte and Wilson, 2004). During the present study the horizontal dilution of precision ranged between 0.92 to 1.15. Taking into account the number of satellites visible, the HDOP values and the weather conditions, the conditions during testing for the present study were near perfect. As such, this would suggest that the errors in distance measurement observed were more associated with increases in velocity than satellite geometry. The higher errors reported in previous studies (Witte and Wilson, 2004; Petersen *et al.*, 2009) may have been contributed to by less than optimal geometric configurations.

Like Coutts and Duffield (2010), the present study found GPS to underestimate distance by ~2 % during non-linear activity compared to only .31 % for COMP when compared to the trundle wheel distance. Though this was not to a level of significance, this equated to mean underestimation of ~32 m over the 1591 m course. As such this error is too large to be ignored. As suggested by previous studies this underestimation may be affected in part by movement around bends due to upper body lean to maintain balance (Witte and Wilson, 2004; Townshend *et al.*, 2008; Gray *et al.*, 2010). As in the present study, cycling around corners induces body lean, which increases with increasing velocity. Witte and Wilson (2004) and Townshend *et al.* (2008) noted that this resulted in a difference in distance measured due to the GPS receiver being located in a different position to that of the criterion measurement tool. Such body lean would subsequently lead to a shorter travel path.

In the present study the criterion measure of distance was recorded at ground level with a trundle wheel, whilst the cycle computer also recorded distance based on wheel rotation distance per revolution at ground level. In contrast, the GPS receivers were positioned on the participants' back at approximately the T11-12 vertebrae and therefore were approximately 1.5 m above ground level. It is therefore plausible that the lean angles encountered during cycling in the present study contributed to the shorter recorded distances with GPS, and also explain why the cycle computer showed greater agreement with the criterion measure. In addition, as also noted by Witte and Wilson (2004), the shorter distances would also contribute to the underestimation of velocity by GPS. Therefore, users of GPS for distance and velocity measurements should carefully consider the positioning of the GPS units upon the body, whilst the use of GPS on courses with small radius corners may induce further error due to the need for greater body lean.

Intra-unit reliability for distance was again less than 3.5% across the range of velocities used and less than 2% overall, whilst inter-unit reliability was less than 2 % across the different intensities and less than 1 % overall. Again, the improved reliability reported over previous studies may be due to near optimal satellite coverage. These findings again, suggest GPS distances can be compared confidently within and between units during non-linear cycling.

## 5. Conclusions

The present study found that determination of distance using a 5 Hz GPS was not significantly affected by velocity. In addition, both GPS derived distance and velocities were found to be valid and reliable when compared to criterion values. However, it was also noted that though not to a level of significance, accuracy of distance determination did diminish at higher velocities, potentially the result of increased body lean. In conclusion, 5 Hz GPS can provide a valid and reliable tool for monitoring human locomotion during non-linear cycling activity, though users should endeavour to account for lean angle where possible. As the present study was conducted under realistic cycling conditions, these findings have good ecological validity and indicate the potential usefulness of GPS for performance monitoring of different cycling activities.

## 6. Conflict of Interest Statement

No conflict of interest.

## 7. References

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