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Accuracy of non-differential GPS for the determination of speed over ground

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Abstract

Accurate determination of speed is important in many studies of human and animal locomotion. Some global positioning system (GPS) receivers can data log instantaneous speed. The speed accuracy of these systems is, however, unclear with manufacturers reporting velocity accuracies of 0.1–0.2 $\mathrm{m\,s^{-1}}$. This study set out to trial non-differential GPS as a means of determining speed under real-life conditions.

A bicycle was ridden around a running track and a custom-made bicycle speedometer was calibrated. Additional experiments were performed around circular tracks of known circumference and along a straight road. Instantaneous speed was determined simultaneously by the custom speedometer and a data logging helmet-mounted GPS receiver. GPS speed was compared to speedometer speed. The effect on speed accuracy of satellite number; changing satellite geometry, achieved through shielding the GPS antenna; speed; horizontal dilution of precision and cyclist position on a straight or a bend, was evaluated. The relative contribution of each variable to overall speed accuracy was determined by ANOVA. The speed determined by the GPS receiver was within 0.2 $\mathrm{m\,s^{-1}}$ of the true speed measured for 45% of the values with a further 19% lying within 0.4 $\mathrm{m\,s^{-1}}$ ($n = 5060$). The accuracy of speed determination was preserved even when the positional data were degraded due to poor satellite number or geometry. GPS data loggers are therefore accurate for the determination of speed over-ground in biomechanical and energetic studies performed on relatively straight courses. Errors increase on circular paths, especially those with small radii of curvature, due to a tendency to underestimate speed.

Keywords: Biomechanics; Velocity; Locomotion; Running; Field measurement

1. Introduction

Accurate determination of an individual's speed is fundamental to many studies of human and animal locomotion. Speed is the rate of change of position and its determination requires measurements of distance and time components, which can be achieved directly or indirectly. Most commonly used methods for determining an individual's speed require direct measurement of both distance and time. Chronometry over a known distance using a simple stopwatch (Sharp, 1997) or by more accurate means such as light gates is limited to use under controlled conditions, on a pre-defined track. In addition, chronometry only determines average speed over the course; fluctuations of speed or route taken are ignored. Alexander used the time taken to pass a defined landmark on video film of free-running ungulates to calculate speed, but recognised the limited accuracy of the method due to the frame rate of the camera (Alexander et al., 1977) and parallax effects. High-speed video motion analysis and differentiation with respect to time of the position of a fixed marker can provide speed data many times per second, however, such systems are expensive, only effective within a limited volume and usually rely on infrared light, which limits their application outdoors. Indirect methods of predicting speed include foot-mounted pedometers (Saris and Binkhorst, 1977) or measurement of stance time via accelerometers (Weyand et al., 2001). Laser speed guns, which rely on the principle of Doppler shift, are commonly employed for the determination of vehicular

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speed, the velocity of ballistics and the speed of movement of small mammals (Marsden and King, 1979). However, these techniques are limited to single point, instantaneous measurements. Integration of body-mounted accelerometer signals is possible but error handling during integration is difficult (Perrin et al., 2000; Herren et al., 1999).

An increasingly popular method of determining an individual's position is the Global Positioning System (GPS). GPS was originally developed as a military tool. It comprises a network of ground-station controlled satellites, which emit low power radio signals containing atomic clock time data. Transit-time delays in these time signals are used by the ground-based GPS receiver to triangulate position. In order to limit the potential accuracy of the system, small random errors were introduced into the satellite clock signals by the US government (termed selective availability, or SA). This spurred the development of several approaches to enhance the accuracy of GPS. Differential GPS (dGPS) compares the known position of a fixed receiver with that determined by satellite triangulation. The difference is then used to correct the transit time of individual satellite signals either in real time via a radio link or, less commonly, in a collected data set during subsequent analysis. It is currently not clear, however, whether the improved positional accuracies of dGPS are mirrored by enhancements in the accuracy of speed determination, since GPS speed determination does not rely solely on differentiation of position data over time but also depends on Doppler shift of the carrier wave.

Further increases in positional accuracy can be achieved by determining the phase difference in the carrier wave signal from a satellite as seen by two neighbouring receivers (carrier wave differentiation). Sub-centimetre accuracies have been reported for this system (Leick, 1995) and it has been employed in studies for the measurement of both trunk position (Terrier et al., 2000, 2001) and speed (Larsson and Henriksson-Larsén, 2001). Schutz and Herren (2000) report accuracies with a standard deviation of $0.03\,\mathrm{m\,s^{-1}}$ for running with this system. The equipment is however both costly and bulky since units weigh 2 kg or more (Leica System 500, Leica Geosystems, Heerburg, Switzerland) and are therefore of limited potential for many studies of field locomotion. Further, the discontinuation of SA in May 2000 has meant that the accuracy of standard, non-differential GPS systems is improved for position and possibly for speed determination. The development of satellite-based differential systems such as Wide Angle Augmentation System (WAAS) and European Geostationary Navigation Overlay Service (EGNOS), which transmit correction data via satellite rather than land-based radio beacons, may mean that, in future, units the size of current non-differential units but with the accuracy of basic differential GPS will be available.

Improvements in technology, including reduced time-to-fix (TTF), as well as miniaturisation of GPS receivers for implementation in automobiles and mobile phones (7 g OEM modules are now available), has stimulated interest in GPS for applications in animal tracking (Steiner et al., 2000; von Hünerbein et al., 2000). Battery requirements are still a constraint, however, due to the high power consumption of GPS receivers. Low power duty cycling can be undertaken for studies in animal tracking; however, continuous data are often required for applications involving speed measurement. The positional accuracy of GPS systems since SA removal has been determined (Adrados et al., 2002) but validation of non-differential GPS for velocity determination has not been undertaken. Manufacturers quote accuracies in the region of $0.1–0.2\,\mathrm{m\,s^{-1}}$, with the specific algorithm employed being the variable which most influences accuracy between manufacturers. However, due to commercial confidentiality further information on how the system calculates speed and the limitations of the system are not forthcoming.

The accuracy of the Global Positioning System is influenced by several variables. The number of satellites available to the receiver is clearly important and a theoretical minimum of four satellites is required to obtain a 3D position fix. In addition, the geometrical arrangement of the satellites relative to each other and the receiver affects the quality of the triangulation for position. This is quantified in a measurement known as dilution of precision (DOP), which is inversely proportional to the volume of a cone delineated by the position of the satellites and the receiver. An ideal DOP of 1, i.e. the greatest predicted accuracy of triangulation, will be seen when one satellite is directly overhead and the remainder are equally spaced around the horizon. In contrast, higher DOP values will be seen if the satellites are tightly clustered overhead and the maximum value of 50 means that the fix is unreliable. Clearly, the orientation of the satellites and the identity of the satellites used changes over time and thus experimental conditions cannot be wholly standardised. The response of the GPS system to changing satellite availability is of interest for potential application of the system in conditions of less than ideal sky-view.

This study was designed to test the hypothesis that non-differential GPS is an accurate and reliable method for the determination of speed over ground.

2. Materials and methods

The speed of a cyclist was determined simultaneously by GPS and by a custom designed bicycle speedometer during a series of trials under varying conditions. These data were used to determine GPS accuracy during cycling at constant speed around a running track, on curves of two different radii, on a straight road and during rapid acceleration/deceleration.

A road-racing bicycle was instrumented with a Hall-effect proximity switch (RS Components Ltd., part no. 307–466, Northamptonshire, UK), which output a constant amplitude voltage spike each time a spoke-mounted magnet passed within 2 mm, i.e. once per wheel revolution. The voltage spike was radio-telemetered via a 100 mW UHF analogue radio link operating at 458.875 MHz (Wood and Douglas Ltd., Tadley, UK), amplified through a 12.5 × amplifier and logged at 1000 samples per second into custom software in LabVIEW (National Instruments Ltd., UK). The temporal location of each voltage spike from the bicycle wheel was identified using a peak detection algorithm written in MATLAB (The Mathworks, Massachusetts, USA). Thus, the number of wheel revolutions per second could be determined. The accuracy of the bicycle speedometer was therefore influenced by the wheel revolution frequency and cycle speed.

A GPS receiver (REB 2100 GPS engine consisting of SiRF star II chipset, RoyalTek, Taiwan) was mounted on the head of the cyclist in order to provide a consistent sky view at all times and was connected by a serial cable to a laptop computer carried by the cyclist in a backpack. The receiver was programmed to output NMEA0183 data at the maximum frequency of once per second. These data were logged using GPS evaluation software (μ-centre software, μ-blox, Switzerland). NMEA0183 is the National Marine Electronics Association standard protocol for the transmission of GPS data and includes time (Universal Time Constant; UTC), speed over ground (SoG), the number and identity of the satellite vehicles being used for the fix (SV used) and DOP. A hemi-cylindrical aluminium shield could be positioned on one side of the antenna in order to restrict the antenna's sky view and thus change satellite availability, depending upon track position. The latter experimental design was employed in order to produce a range of DOP and SV used values, enabling the influence of these variables on speed accuracy to be better assessed.

A commercially available speedometer provided feedback of speed (in $\mathrm{km\,h^{-1}}$) to the cyclist.

Two separate experiments were performed.

2.1. Experiment 1

Calibration of the bicycle speedometer and collection of GPS data during curve, straight and curve–straight transition cycling around a 400 m running track.

An infrared light gate (based on FE7B-TLX6GE-RS, RS, Northamptonshire, UK) was positioned at the start/finish line. This output a digital pulse and an audible signal when the beam was broken. The digital pulse was logged at 1000 samples per second simultaneously with the wheel revolution data and marked the start of each lap. Cycle data were synchronised with the GPS data by a time stamp in the wheel revolution data.

The cyclist was asked to perform four laps at each of 15, 20, 25, 30 and 35 $\mathrm{km\,h^{-1}}$ following the line delineating the 5th and 6th lanes. Knowledge of the number of revolutions per lap and track distance allowed calculation of a mean circumference of the bicycle wheel over the entire 20-lap data set. This approach reduced the effect of partial wheel revolutions missed at the beginning and end of a lap. Speed over each wheel revolution was then calculated from this circumference and the time between adjacent pulses. At the range of speeds performed, instantaneous speed was therefore determined 1.5–5 times per second, depending on actual speed. The wheel trigger was logged at 1000 samples per second and the time between revolutions varied from 300 ms at the highest speed to 700 ms at the lowest speed. Therefore, the range of possible error due to resolution of pulse timing was 0.33% (high speed) to 0.14% (low speed).

When following the bends in the track, and particularly at higher speeds, the cyclist will lean into the bend, producing an apparent reduction in the distance travelled by the GPS antenna compared to that travelled by the wheel. This may result in some underestimation of the distance travelled in a given time and thus an underestimation of speed by the GPS. This effect is velocity-dependant and was quantified as follows (see Fig. 1):

If vertical force:

$$F_v = mg$$

and centripetal force

$$F_c = \frac{mv^2}{r},$$

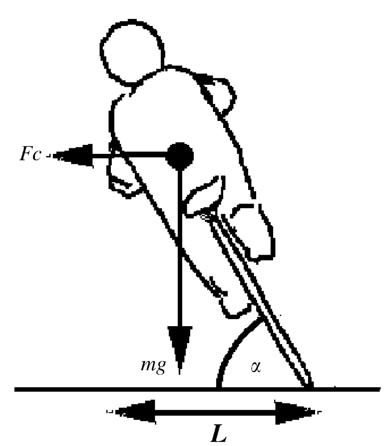

Fig. 1. Forces acting on the cyclist and bicycle during bend cycling (mg is the weight of cyclist, F_c is the centripetal force acting on cyclist around bend, α is the angle of lean with respect to ground and L is the distance from GPS unit to point of ground contact).

then

$$\frac{F_v}{F_c} = \tan\alpha.$$

Therefore angle of lean:

$$\alpha = \tan^{-1}\left(\frac{gr}{v^2}\right)$$

and horizontal distance of GPS receiver from point of ground contact:

$$L = 1.6\cos\alpha.$$

Thus, reduction in distance travelled during one lap of track

$$\partial d = 2\pi L.$$

and reduction in measured speed due to cyclist lean

$$\partial s = \frac{s_w(244 - \partial d)}{244},$$

where F_v is the vertical force, m is the mass of cycle plus rider, g is the gravitational constant, F_c is the centripetal force, v is the velocity, r is the radius of curvature of bend in track, α is the angle of lean of cyclist on bend, L is the lean distance; the height of head mounted GPS receiver above point of ground contact = 1.6 m; ∂s is the reduction in speed due to cyclist lean, s_w is the cycle wheel speed; the distance covered on bends during one lap in sixth lane of track = circumference of a circle of radius 38.83 m = 244 m, and ∂d is the distance reduction for a complete lap of the track.

The resultant speed reduction was used to correct all data collected during bend cycling.

2.2. Experiment 2

The effect of curved paths on the accuracy of GPS speed determination. In order to further evaluate the effect of curved versus straight paths on the accuracy of the GPS speed determination the following second set of experiments was performed:

(i) Cycling around two roundabouts of approximate diameter 16 and 30 m at speeds of 15, 20 and 25 km h^{-1}.
(ii) Cycling along a straight road at speeds of 10, 15, 20, 25, 30 and 35 km h^{-1} and performing rapid accelerations and decelerations.

Data collection, initial analysis and correction for cyclist lean were as described for experiment 1, above.

For both experiments 1 and 2 the time of each GPS speed determination was used to extract the actual cycle speed value from the speedometer data in a custom programme written in MATLAB. The difference between GPS and actual speed (speed error) was examined as a function of the following parameters:

- speed category—the target speed of the cyclist (km h^{-1});
- the number of satellites being used by the receiver (different from the number being tracked);
- the horizontal dilution of precision (HDOP);
- change in satellites used for speed determination due to receiver shielding;
- the path being followed by the cyclist, i.e. bend or straight. For track cycling, where both straights and bends were performed during a single trial, position (i.e. latitude and longitude) was used to extract these data.

Multivariate ANOVA analysis was performed in order to determine the effect of speed category, satellites used, HDOP and path type on overall speed accuracy.

3. Results

3.1. Experiment 1

A total of 5060 GPS speed values were recorded during the track study. The actual speeds achieved by the cyclist ranged from 2.1 to 10.8 m s^{-1}. The cyclist consistently failed to achieve the highest target speed of 35 km h^{-1}, dropping as low as 25% below it.

The speed determined by the GPS receiver was within 0.2 m s^{-1} of the true speed measured for 45% of the values (Fig. 2) with a further 19% lying within 0.4 m s^{-1}. A negative error (i.e. GPS underestimation of speed) of greater than 1.0 m s^{-1} was seen in 12.6% of samples and a positive error (i.e. GPS overestimation of speed) of greater than 1 m s^{-1} was seen in 2.9% of samples. Hence, the speed error was slightly skewed towards an underestimate of true speed (see below). Comparison of speed error with the number of satellites used in the

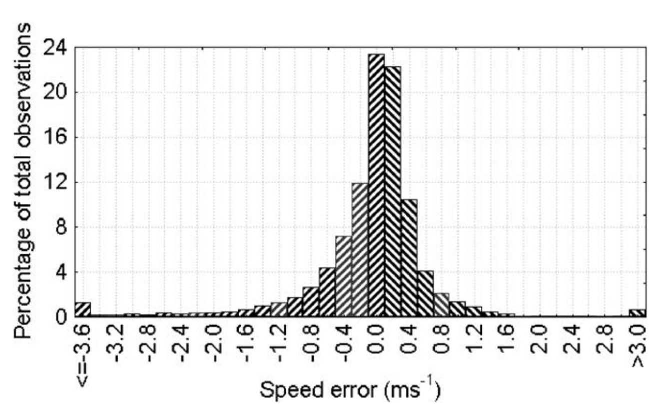

Fig. 2. Distribution of speed error (m s^{-1}; difference between wheel and GPS speed; positive value means GPS speed higher than wheel speed) for all data collected on the track ($n = 3723$). The scale of the x-axis indicates the upper boundary of each bin labelled. Bin width is 0.2 m s^{-1}.

speed determination demonstrated that speed error increased when the number of satellites used decreased. This effect was confirmed as significant ($p < 0.000$) when all other factors were taken into account during ANOVA analysis. However, whilst speed was most accurate with five or six satellites the median absolute error (i.e. ignoring if positive or negative) remained below $0.5\,\mathrm{m\,s^{-1}}$ even when only three satellites were used (Fig. 3a).

Horizontal dilution of precision (HDOP) is an error term determined from the geometry of the satellites used for the position fix. This is therefore dependent upon a combination of satellite position and the number of satellites used. A low HDOP is good with a minimum possible value of 1 and a maximum of 50. The range of values for HDOP was higher with less satellites but HDOPs as low as 6 were achieved even with only three satellites. Since HDOP is related to the accuracy of the position fix in terms of latitude and longitude, its value would be expected to be reflected in the speed accuracy. Fig. 3b shows the relationship between HDOP and speed error; there was only a minor effect up to a HDOP of 40. Data points with a HDOP of 50 produced no speed determination and were discarded. The effect of HDOP on overall speed accuracy when all other factors were taken into account in ANOVA was not significant (at $p < 0.05$).

The speed error data were subdivided into those collected on a bend and those collected on a straight. There was a consistent inaccuracy in speed determination seen during bend cycling (Fig. 4). Initially, the GPS is able to accurately determine the speed of the subject however shortly after the onset of the bend the GPS tends to overestimate speed. This is followed by a rapid fall in speed determined by the GPS and an underestimation for the remainder of the bend. Overall there is a tendency toward underestimation of speed during bend cycling. This is demonstrated by a left skew in the data in Fig. 2. Fig. 4 shows the GPS and speedometer speed data for two laps, i.e. four straights and four bends. This error appears to increase at the higher speeds as demonstrated in Fig. 3c.

Speed error was also determined when the satellites used for the position fix changed. This was anticipated to have an effect on the position data and hence should have produced a step in speed; however, there was only a change in speed with a change in the number of satellites used on some occasions. It appears that when a change of satellite number is combined with a transition from a bend to a straight this effect is most pronounced (Fig. 5).

In Fig. 6 speedometer and GPS speeds are shown during a series of rapid speed changes (the maximum the cyclist could achieve). The GPS followed acceleration and deceleration reasonably well but was less effective than the wheel speedometer in following the transitions from acceleration to deceleration.

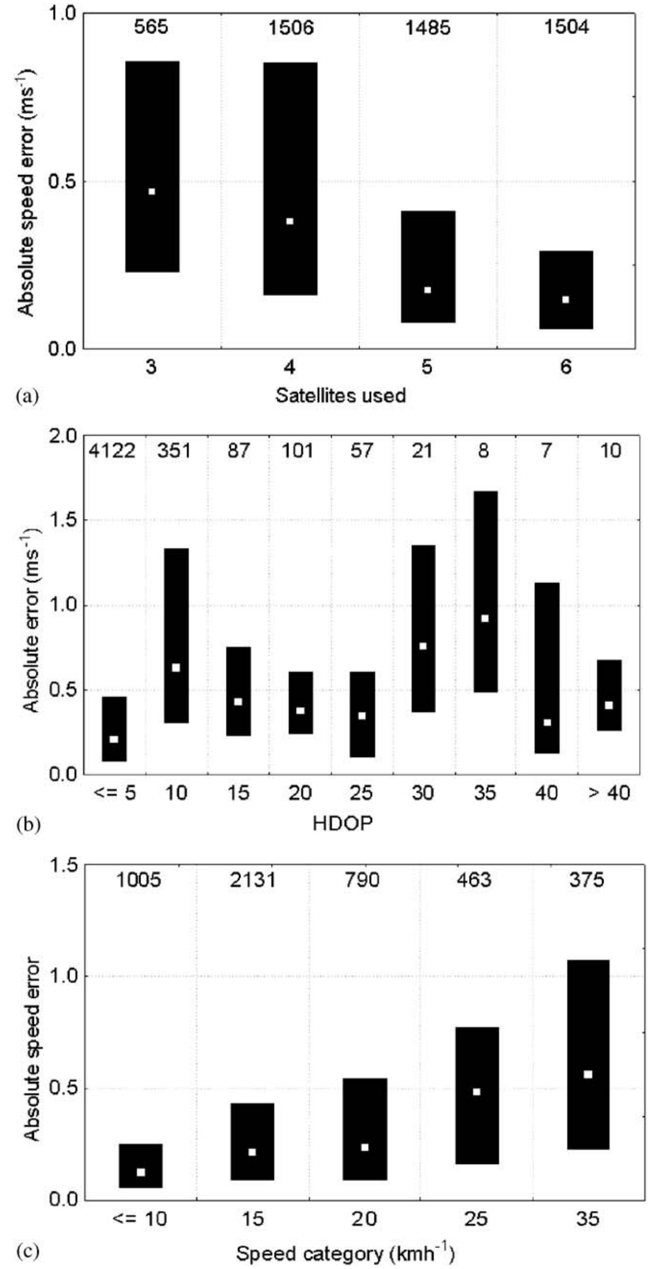

Fig. 3. Absolute speed error ($\mathrm{m\,s^{-1}}$) as a function of the number of satellites used in the determination of position (a), the HDOP (b) and mean actual speed (c). The number of satellites used was often less than the number of satellites tracked by the receiver. The square symbol indicates the median value and the shaded box the inter-quartile range. The figures at top indicate *n* for each group. These graphs include data from all sampling points, i.e. both bends and straight. Maximum speed error can be as high as the actual speed for occasions where no speed is determined.

3.2. Experiment 2

Fig. 7 displays error histograms for the speed error during circle cycling on circles of small (Fig. 7a) and large (Fig. 7b) radii and pure straight line cycling (Fig. 7c). Both circle data sets are left skewed with an apparently larger skew evident on the smaller circle. The

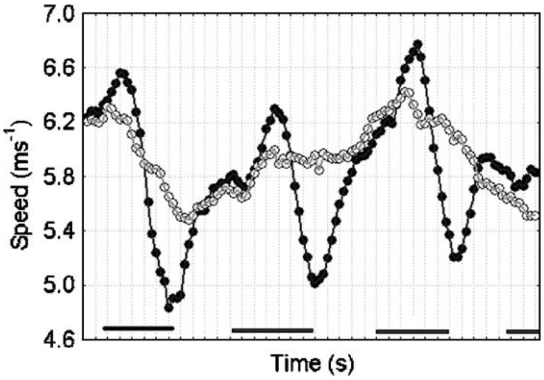

Fig. 4. Actual and GPS speed for two laps of the track at a speed of $15\,\mathrm{km\,h^{-1}}$. The empty circles represent actual bicycle speed ($\mathrm{m\,s^{-1}}$) and the filled circles represent the GPS speed ($\mathrm{m\,s^{-1}}$). The solid horizontal bars represent the time spent on the bends.

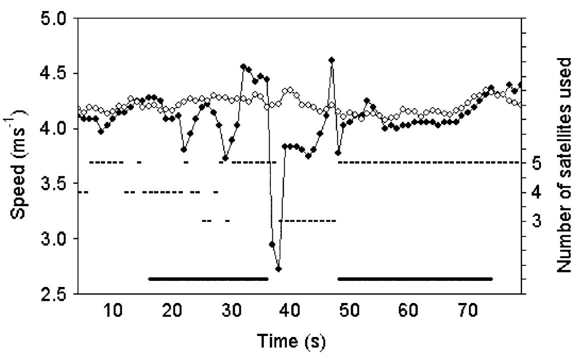

Fig. 5. The effect of changing satellite numbers on speed error ($\mathrm{m\,s^{-1}}$). This graph shows the data collected on one lap with the shield in place. The actual bicycle speed is represented by empty circles and the GPS speed by filled circles. The solid bars represent the time spent on the bends. The dashed line indicates the number of satellites being used (on the right-hand y-axis).

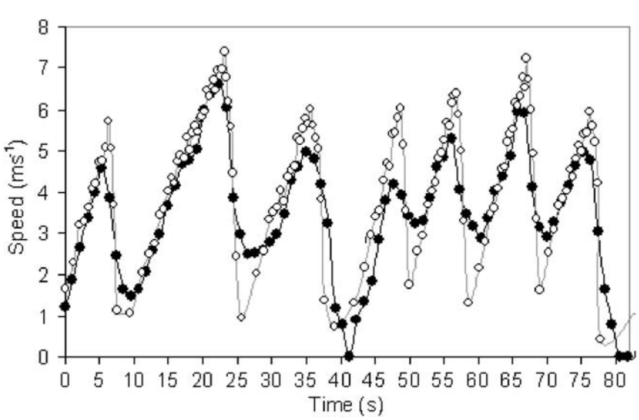

Fig. 6. Actual and GPS speed for a series of rapid stop–start events. The actual bicycle speed is represented by empty circles and the GPS speed by filled circles.

median error on the large circle is $-0.49\,\mathrm{m\,s^{-1}}$ and on the small circle is $-0.75\,\mathrm{m\,s^{-1}}$. Overall there were more inaccurate values during cycling on the smaller circle (16% of values within $\pm 0.2\,\mathrm{m\,s^{-1}}$ and 28% within $\pm 0.4\,\mathrm{m\,s^{-1}}$, cf. 23% within $\pm 0.2\,\mathrm{m\,s^{-1}}$ and 41% within

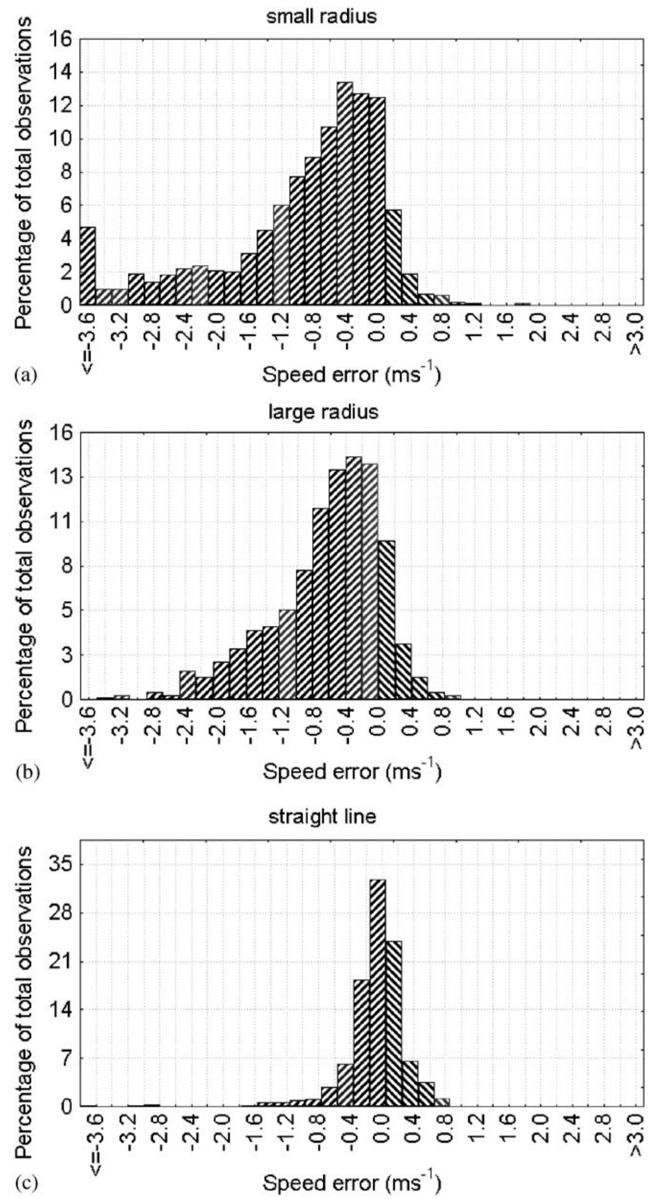

Fig. 7. Distribution of speed error ($\mathrm{m\,s^{-1}}$; difference between wheel and GPS speed; positive value means GPS speed higher than wheel speed) for data collected during circle cycling ($n = 1841$). Data are shown for a circle of diameter 16 m ($n = 1093$) (a) and for a circle of diameter 30 m ($n = 748$) (b) as well as for straight line cycling ($n = 566$) (c). The scale of the x-axis indicates the upper boundary of each bin labelled. Bin width is $0.2\,\mathrm{m\,s^{-1}}$.

$0.4\,\mathrm{m\,s^{-1}}$ on the large circle). The data from pure straight line cycling do not demonstrate a skew and show a higher accuracy (57% $\pm 0.2\,\mathrm{m\,s^{-1}}$ and 82% $\pm 0.4\,\mathrm{m\,s^{-1}}$).

4. Discussion

The hypothesis of this study was that GPS is an accurate and reliable method for the determination of speed over ground. The results show that GPS is generally accurate for speed determination under all conditions where a position fix is obtained although some erroneous values are generated.

The accuracy of the wheel speedometer is critical to the results of the study. Wheel diameter was determined from the running track experiments using the lap distance and the total number of revolutions over the entire data set. The number of wheel revolutions was within ± 1 on 17/20 laps. If the cyclist had consistently moved inside or outside the line during the 20 lap calibration, this would have resulted in a very small over- or underestimate in the calibration. For example, if he rode 10 cm outside the line for the whole 20-lap distance this would only correspond to an increase of 60 cm per lap, i.e. 0.1% of distance travelled. Moving away from the line would not have had an effect on the data in the actual experiment because instantaneous speed was based on the previously determined wheel circumference. The time taken for a wheel revolution is determined more accurately at low speed than at high (in percentage terms) so speed determination is more accurate at low speed (see Section 2).

The underestimate of speed, which occurred when the cyclist was following a curved path, and which increased at higher speeds, has two possible explanations. The first is that the cyclist was leaning into the bend. This reduces the radius of curvature of the route followed by the antenna (mounted on the cyclist's head) as compared to the actual route followed by the bicycle wheel. The contribution of this was calculated at the highest speed ($8.6\,\mathrm{m\,s^{-1}}$) and found to result in a reduction in the distance travelled of 2.26 m over a 444-m lap. This effect was found to be a lesser source of error than that observed, i.e. 0.5% compared to a median error of about 2% at $8.6\,\mathrm{m\,s^{-1}}$ for the whole lap. Fig. 7 shows the error due to underestimation when a continually curved path was followed. This error is apparently larger when a curve of smaller radius is followed. However, this may be a further effect of leaning into the bend whereby the sky view is altered as the cyclist's head changes orientation. This is borne out by the greater variability of HDOP seen during the small circle experiments (mean 3.3, median 2.5, range 1.1–22.7; cf. mean 2.9, median 2.5, range 1.9–13.2, for the larger circle). The 180° bends are rare in most non-track studies so the effect on typical experimental data would be smaller.

Secondly, if the GPS algorithm simply considered the change in position between subsequent fixes for the velocity determination then the route would appear as a series of chords inside the curves with a resultant underestimate of velocity that would become more marked at higher speeds. At a speed of $8\,\mathrm{m\,s^{-1}}$ a 120-m bend would be covered in 15 s. A route comprised of a series of chords would be some 1.8% shorter than that covered by the cyclist's head. This error would therefore be much larger than the error actually observed during the study. Although the contribution of corner cutting to inaccuracies in GPS speed determination cannot be entirely ruled out the system algorithm is obviously more sophisticated than simply differentiating position.

The actual method of determining speed is commercially sensitive and not published. It is, however, known that Kalman filtering is employed to remove the effects of the satellite's orbital velocity, the rotational velocity of the earth and the receiver's motions (Kalman, 1960). A Kalman filter is an optimal estimator in the least-squares sense, inferring parameters of interest from inaccurate and uncertain observations. It predicts an observation from previous observations and corrects its prediction parameters by comparing it to the actual observation. Although this appears to be very effective in improving the quality of the positional and hence speed data recorded, it is unclear if it is also the source of the "smearing/overshoot" effect seen in Fig. 4. The filter may extrapolate a straight path when the cyclist enters a bend until the errors become so large as to elicit major correction, resulting in a "jump" in the data.

The experimental set-up employed for this study enabled the receiver's sky view to be restricted by shielding, which forced the system to seek out new satellites as the original satellites became unavailable. The authors had anticipated a momentary jump in the position data at this time, and hence a significant effect on the overall speed determination, resulting in a step in the data. This occurred in some but not every case (Fig. 5). This confirms that differentiation of position is not the only factor contributing to the GPS calculation of speed and that the system is able to filter out significant jumps in position that may occur with changing satellites.

Satellite geometry is regarded as having a major influence on the accuracy of GPS positional data and hence speed determination. Under the conditions of this study, it was found to only have a minor effect on the accuracy of speed determination. Despite the increase in HDOP that occurred with reducing satellite number there was no significant effect on speed accuracy (Fig. 3b) and the system recovered within a few seconds. This, again, is attributed to the Kalman filter used.

The system also reproduced smooth accelerations and decelerations with reasonable accuracy, however, it was less able to reproduce transitions from acceleration to deceleration. This is due to a combination of the lower sampling frequency of the GPS (once per second compared to between zero (when stationary) and three speed determinations per second in the data shown for the speedometer) and speed data smoothing within the GPS receiver. This again may be attributable to Kalman filtering but it is not possible to infer the exact nature of the smoothing from the data presented here other than it does not result in a temporal displacement (i.e. a lag) of speed data.

5. Conclusion

The GPS is accurate for the determination of speed over ground (about 10 times more accurate than a car odometer) when moving at relatively constant speed in straight lines and is competent at determining speed on curved paths, although some overshoot does occur during transitions. Absolute error increases slightly at higher speeds but in percentage terms is less. In addition, when the system is tested under conditions of sudden changes in speed some inadequacies become evident. The system smooths the peaks and troughs of rapid accelerations and decelerations, which is attributed to inherent smoothing within the mathematical algorithm and the one sample per second output of the system. GPS is therefore ideal for the determination of speed under conditions of constant speed and steady acceleration over several seconds, however, is unable to resolve rapid changes in speed.

The latest developments in the field of GPS, including miniaturisation, increased accuracies and faster time to fix, mean that the system has great potential for applications in the field of biomechanics. Data logging GPS units weighing as little as 24 g are possible because of spare processing power and memory within the GPS engine modules. In the future, reductions in size and mass may be limited by the high power consumption of the modules, especially when used for continuous data logging applications, and the size of the antenna. However, further enhancements in position and possibly speed accuracy are on the horizon as WAAS and EGNOS technologies are implemented. Units will be the same physical size and a similar cost to standard units, whilst having the potential for improved accuracy.

The global positioning system therefore has enormous potential for applications in biology and biomechanics ranging from performance assessment in elite human athletes to monitoring training and racing performance in horses.

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