Full title: Validity and reliability of GPS units to monitor cricket-specific movement patterns

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Abstract

**Purpose:** Validity and reliability of three commercial Global Positioning System (GPS) units (MinimaxX, Catapult, Australia; SPI-10 & SPI-Pro, GPSports, Australia) were quantified. **Methods:** Twenty trials of cricket-specific locomotion patterns and distances (walking 8800m, jogging 2400m, running 1200m, striding 600m, sprinting 20–40m intervals and run-a-three) were compared against criterion measures (400m athletic track, electronic timing). Validity was quantified with the standard error of the estimate (SEE) and reliability estimated using typical error (TE) expressed as a coefficient of variation (CV). **Results:** The validity (mean ± 90% confidence limits) for locomotion patterns walking to striding ranged from 0.4 ± 0.1 to 3.8 ± 1.4%, while for sprinting distances over 20–40 m including run-a-three (approx 50 m) the SEE ranged from 2.6 ± 1.0 to 23.8 ± 8.8%. The reliability (expressed as mean (90% confidence limits)) of estimating distance travelled by walking to striding ranged from 0.3 (0.2 – 0.4) to 2.9% (2.3 – 4.0). Similarly, mean reliability of estimating different sprinting distances over 20-40 m ranged from 2.0 (1.6–2.8) to 30.0% (23.2–43.3). **Conclusions:** The accuracy and bias was dependent on the GPS brand employed. Commercially-available GPS units have acceptable validity and reliability for estimating longer distances (600-8800 m) in walking to striding, but require further development for shorter cricket-specific sprinting distances.
Introduction

Quantifying movement patterns based on game demands is important in developing sport-specific conditioning programmes and tailoring the length of recovery periods from game and training activities. Most commonly, this practice has been undertaken through time-motion studies conducted in real-time with pen, paper and stopwatch (notational) or post-game utilising video recordings with or without customised computer analysis (digitising). Time-motion analysis has been conducted in a number of sports including basketball, field hockey, futsal, handball, ice-hockey, rugby, soccer, taekwon-do and tennis.

The time-motion analysis process has traditionally been very time intensive as digitising takes approximately 8 hours to produce data for 1 player for a whole 80 min rugby match. While a high degree of validity (~2% typical error) has been reported for estimation of total distance, time-motion analyses can also have poor comparability between notational and digitising methods with one study reporting a 27.5% difference in estimating time spent in work.

The extended game duration and large playing field in cricket makes it difficult to conduct time-motion studies with pen and paper or video recordings. Accordingly, to date there is only one time-motion study examining batting requirements and one study on the fielding requirements of cricket. While these studies divided the fielding and batting requirements of cricket into component parts (standing, walking, jogging, striding, sprinting, playing a shot and lateral motion) the authors only reported temporal data with no estimates of distances covered in each movement category. With a lack of field markings accurate measures of distance are difficult to obtain with some forms of time-motion analysis; hence the need for GPS as opposed to time-motion analysis.

Recently improved miniaturisation and enhanced battery life has made Global Positioning System (GPS) athlete-tracking units a more convenient, less time-consuming and increasingly popular method to quantify movement patterns and physical demands in sport. GPS technology has been used to quantify the physiological demands of athletes training and/or competing in events such as horse racing, orienteering, triathlon, Australian football, Gaelic football, rugby, and soccer. These studies have employed several different commercially-available GPS brands including: Fidelak Equipilot, Polar, Garmin Forerunner, GPSports and FRWD. However currently in elite cricket there are only two brands of GPS unit in regular use (MinimaxX and GPSports). To date, only one study using the MinimaxX GPS unit has been published. A comparison was undertaken of four different tennis drills performed on a tennis court with six repetitions of 30 and 60 second work periods. The authors used distance covered and movement speed as measures of intensity, yet surprisingly no reliability data was reported. Another study investigated the validity of the GPSports SPI-10 unit, finding it overestimated distances by a mean of 4.8%. However the distances used only ranged from 128 – 1386 m, whereas it is likely that some cricket players cover distances at least 10-fold greater (~10,000-15,000 m). Furthermore, no account of possible variations in the accuracy of different movement velocities was reported. Coutts and Duffield compared different movement velocities between three different GPS models (including the GPSports SPI-10) from the same manufacturer and
reported a typical error (test retest reliability) of 5.3% in estimating the distance covered in low intensity activity. However the walking component of each 130 m lap was only 14 m, in cricket walking forms up to 90% of total movements and given that an innings typically lasts 3.5 hrs, walking needs to be assessed over an extended duration.

A recent study used a 487m lap repeated 14 times (total circuit distance = 6818m) with movement patterns simulating field hockey match play to assess validity of the GPSports SPI Elite 1 Hz GPS unit. The authors utilized only one unit and reported the validity of distance and mean speed for four types of hockey specific shuttles, total lap distance and overall total distance. While significant differences (p>0.01) were found from the criterion distance during the hockey specific shuttles (from a mean underestimation of 1.2% to an overestimation of 0.8%), the mean lap distance and total circuit distance were not significantly different from the criterion distance (mean overestimation of 0.04 and 0.06% respectively). What remains unknown from this investigation is the validity and reliability of the individual movement patterns (walking, jogging, cruise, sprint) comprising the hockey simulation circuit.

Although the interest in GPS monitoring of cricket is growing, the reliability and validity of this methodology have not yet been established. Cricket is characterised by long periods of low intensity activity interspersed with short bursts of high intensity activity. The patterns of the movement are presumably influenced by both the positional requirements and versions of the game. Fast bowlers appear to perform a large number of longer high intensity efforts compared with other players. In comparison, wicketkeepers appear to have a higher proportion of moderate intensity activity (jogging) with very few high intensity bursts. In terms of the different versions of the game: Twenty/20 cricket (T20) is the shortest form of the game and presumably more intensive than both One Day International (ODI) and First Class cricket. Therefore, it is prudent to assess the validity and reliability of GPS measurements over sport-specific distances and locomotion patterns to determine the measurement error in these measurements. If the measurement error is less than the within-player variability in movement patterns from game-to-game coaches and practitioners can confidently use the GPS measurements to estimate game distances and player movement velocities. An understanding of the game-to-game variation in individual distances and velocities in order to distinguish between heavy and light game load is necessary for prescription of individualised training. From our pilot data fast bowlers have within player game-to-game variability of ~20% in distances and velocities. The aim of this study is to determine the reliability and validity of GPS monitoring for quantifying the movement patterns of cricket. A secondary aim was to compare the reliability and validity of the three different GPS units (ranging from 1 - 5Hz).

**Methods**

**Experimental Design**

The viability of GPS monitoring for cricket applications was evaluated by separately investigating the validity, reliability and practicality of commercially-available GPS units. The same participant (male, aged 32 yrs) participated in all
of the measurement trials to eliminate between-subject variability in estimates of reliability and validity.

GPS units

Three different types of GPS units were used in this investigation: SPI-10 and SPI–Pro (GPSports, Canberra, Australia) and MinimaxX (Catapult, Melbourne, Australia). The MinimaxX and SPI-Pro units operate with a 5Hz GPS signal, whereas the SPI-10 uses only a 1 Hz GPS signal. Two individual MinimaxX units (MinimaxX-A and MinimaxX–B) and two individual SPI-Pro units (SPI-Pro–A and SPI-Pro–B) were used to determine the magnitude of between-unit variation. Both brands of GPS unit are currently used in elite Australian and New Zealand cricket to assess distances covered in various velocity bands (detailed below). The GPS unit under evaluation was positioned via an elasticised shoulder harness to sit between the scapulae of the participant at the base of the cervical spine. Two units separated horizontally by 10cm were worn simultaneously in each trial.

Distance trials

The estimated distance covered in different movement categories (walking, jogging, running and striding) by Academy fast bowlers were used to validate each GPS unit against the criterion distance covered on an internationally-certified synthetic 400m athletics running track. These velocity zones have been used in Australian cricket for the last two years. The criterion distance and velocity band for each movement category were: walking (up to 2 m.s\(^{-1}\)) 8800m, jogging (2 – 3.5 m.s\(^{-1}\)) 2400m, running (3.5 – 4 m.s\(^{-1}\)) 1200m and striding (4 – 5 m.s\(^{-1}\)) 600m. Twenty trials were conducted for each unit for each distance. Pacing feedback was given every 200m to ensure adherence to the specified locomotion speed, while timing was conducted with a manual stopwatch. Since 400m athletics tracks are measured 30cm from the inner edge of lane one, the participant was instructed to try to maintain this radius (with the centre of his shoulders) around the track.

Sprint trials

The two MinimaxX units and the two SPI-Pro units were used in 20 trials with sprints conducted from a standing start over 20, 30 and 40 m. Electronic timing gates were used to obtain a criterion sprint time accurate to 0.01 s. The estimated sprint distance was determined with Logan plus v4.0 (Catapult, Melbourne, Australia) or Team AMS v2.0 (GPSports, Canberra, Australia) software for each trial. The start time was determined by the first increase above zero on the velocity trace and then using each associated sprint time (from timing gates) the associated distance was determined. It was not possible to test the SPI-10 in the sprint trials given the limitations of a 1 Hz (1 cycle.sec\(^{-1}\)) sampling rate for sprints lasting ~3 s.

A cricket-specific run-a-three test was also used to evaluate the ability of the GPS units to monitor sprinting activities. Batsmen often complete multiple runs at a time in a game involving changing direction 180° at each turn. While the
length of the pitch between crease lines is 17.68 m, a batsman will use their bat to touch over the crease line so they generally run a shorter distance. The run-a-three test involved a set of electronic light-gates positioned on both the crease marks and one camera placed perpendicular to each crease mark to record where the batsman turned. A one metre calibration mark was made from the crease mark to calibrate the distance for software analysis (SiliconCoach, New Zealand). The horizontal displacement of the MinimaxX or SPI-Pro units’ position from the crease lines was determined. Twenty trials of the run-a-three test were used to validate each MinimaxX or SPI-Pro unit. The criterion distance covered in each particular run-a-three test trial was determined using the video recordings, and these were compared to the distances obtained from the GPS units.

**Between-unit variation and time of day**

To assess the variation between different GPS units a custom-designed platform was attached to a calibrated trundle-wheel (refer to Figure 1). Nine MinimaxX units were placed in a vertical position on the platform. The trundle-wheel was then wheeled over 1200 m at a walking speed around an athletics track with three trials performed at 4:00pm, and a further three trials at 9:30am on the next morning. This method permitted the assessment of the effect of time of day on reliability and validity.

**Figure 1 near here**

**Statistical analyses**

Validity was estimated by subtracting the estimated distance travelled for each trial from the associated criterion distance. For each locomotion pattern, the standard deviation of the percentage errors for each unit gave the standard error of the estimate (SEE). Precision of estimation was indicated with 90% confidence limits. Reliability was estimated using the typical error (TE) expressed as the coefficient of variation (with 90% confidence limits). Bias was determined by subtracting the criterion distance from the GPS estimated distance, and then dividing the difference score by the criterion distance. The data were tested for heteroscedasticity by plotting a figure of absolute difference against the mean and computing the correlation.

**Results**

**Validity**

Validity was assessed over a range of distances and locomotion patterns specific to cricket. Using all distances, the Pearson correlation (r) for the distance around the track and the estimated distance from the GPS units was 0.99. The data displayed a trivial amount of heteroscedasticity $R^2=0.03$, indicating that as the size of the measurement increases there are only trivial measurement differences. The degree of validity varied as a function of distance and intensity of the locomotion pattern (Table 1). The validity of the SPI-10 unit during walking to striding locomotion patterns ranged from 0.5 to 2.1%. Estimation of running had more than twice the error of walking, jogging or striding (Table 1). The mean SEE of the SPI-Pro units for the same locomotion patterns varied between 0.4 to
3.7% with estimation of jogging having the greatest error. Larger errors were evident in sprinting short distances (20-40 m) where the SEE for the SPI-Pro units ranged between 3 and 11%. Similarly the SEE for the MinimaxX units varied between 2 and 4% for walking to striding and 5 and 24% for sprinting. The validity of the MinimaxX units improved the greater the sprint distance in the range of 20 – 40 m.

Reliability

Similar to validity, the reliability of GPS estimation of locomotion patterns was better for longer distances (Table 2). The SPI-10 had good reliability with the TE <2% over the different distances walking to striding, while the SPI-Pro was <4%. The MinimaxX units displayed similar reliability over the same locomotion patterns with TE <4%. The reliability of the SPI-Pro units during sprinting ranged from 2-13%, with the shorter sprints (20m) tending to be less reliable compared to the longer (40 m and run-a-three) sprints. The reliability of the MinimaxX units during sprinting ranged from 4-43%, again with estimation of the shorter sprints (20m) less reliable than the longer (40 m and run-a-three) efforts.

Bias

The SPI-10 unit underestimated the criterion distance of walking through to striding by 1-3% (Table 3). Similarly the SPI-Pro units underestimated the criterion distance of walking through to striding by 1-4%. In sprinting the SPI-Pro units substantially underestimated the sprinting distances by between ~6-20%. In contrast, the MinimaxX units overestimated the criterion distance of walking to striding by up to 3%. However the MinimaxX units substantially underestimated the sprinting distances by between ~20-40%.

Inter-unit variability and Time of day effects

There were minimal differences in validity and reliability measures calculated from MinimaxX GPS data collected in the morning compared with the afternoon. The SEE was 1.7 ± 0.5 and 1.8 ± 0.6 (mean ± 90% confidence limits) while the TE was 1.3 (1.0–1.8) and 1.5 (1.2–2.0) respectively for morning and afternoon data. Movement data collected in the morning displayed an underestimation bias of 1% whereas in the afternoon there was an overestimation bias of 1% (Figure 2).

Discussion

With rapid commercial advancements (and increased commercial competition) in GPS microtechnology, it is important to ensure that the validity, reliability and practicality to athletic training also improves from the current state. Effective evaluation of the movement patterns and physical demands of cricket can benefit
the importance of the prescription of fitness and condition programmes. The
standard error of the estimate (validity) of distance for walking to striding ranged
from 0.4 to 3.8%; while the estimate of reliability ranged from 0.3 to 2.9%. Even
with the same type of GPS unit simultaneously receiving the same satellite
signals there were discernable differences in the estimated distances. A major
finding of this investigation was the shortcomings in confidently measuring short
sprint efforts. The typical errors of validity and reliability of estimating sprint
distances over 20-40 m ranged from 3 to 40%. The MinimaxX and SPI-Pro units
consistently underestimated short sprint distances. The magnitude of errors
associated with particular GPS outputs should be clearly understood by
conditioning coaches in monitoring cricket workloads and prescribing training.
In particular conditioning coaches should be aware of the likely under-reporting
of high intensity activity, and the over-reporting of lower intensity activity.

There are obvious differences in outputs between different brands of GPS units,
even though the GPS receivers are receiving the same signals from the same
satellites. These errors are most likely attributable to variations in the calculation
of the receiver position from triangulation algorithms, or the Karroven (exclusion
criteria) formula used to determine the most logical position. Errors can also
occur in the smoothing techniques used by the software to exclude erroneous
data. The degree of smoothing inherent in the analysis will affect the accuracy of
the estimated distance or velocity measurements. Therefore, where possible, the
same type of unit should be used when making comparisons between athletes or
with repeated monitoring on the same athlete (or player) over time.

The validity of the GPS units measured here appears acceptable for longer
distances at the slower velocities of locomotion (up to striding) with values of
less than 5% fulfilling the criteria used by Duffield & Drinkwater14. The
MinimaxX units overestimated (by 0-3%) whereas the SPI-Pro and SPI-10 units
underestimated (up to 4%) these distances. However caution should be exercised
when interpreting short high intensity efforts by contemporary commercially-
available GPS units, as validity of sprinting distances ranged up to 24% with an
underestimation bias up to 37%. The type of GPS unit used must be accounted
for as this will determine the bias it expresses over different locomotion patterns.
Furthermore results from different GPS units should not be used interchangeably
when analysing high intensity running25.

Typical errors of ~2% with lower intensity activity (<4 m.s\(^{-1}\)) found in the
present study are less than half the error reported in a preliminary study25 that
evaluated three different models (SPI-10, SPI Elite and WiSPl) of GPS units
(GPSports, Canberra, Australia). The typical error of estimating very high
intensity running (>5.5 m.s\(^{-1}\)) in Coutts and Duffield’s study25 ranged from 12 to
30%, which is in agreement with our findings. Our data supports their finding of
reduced reliability with increased movement velocities. It is possible that because
the number of GPS signals is lower during shorter sprints, the distance of these
sprints is under-estimated and had reduced reliability. A report by the
manufacturers of the MinimaxX shows that the MinimaxX GPS unit has a typical
error of 0.8% for the criterion distance around a 400m track30. Interestingly, this
report indicated improved accuracy during jogging and running compared to
walking (3 x 3 laps around a small 10 x 10m square), and concluded that the
MinimaxX GPS accuracy typically improves at higher speeds\textsuperscript{30}. Our data does not support this conclusion and further refinement of this technology is required before coaches and scientists can be confident about the accuracy of GPS output to quantify short sprints in team sports.

One study reported validity results for measured distance at lower intensity activity far tighter than our current results (typical errors of less than \textasciitilde2\%. This study\textsuperscript{27} investigated variable movement speeds around a 6.8 km painted hockey-specific circuit (1 Hz GP Sports Spi Elite unit). The 7 km hr\textsuperscript{-1} average movement speed indicates an overall intensity of walking and with only 9 trials of the complete circuit (only one unit used) the authors reported a TE of 0.1\%. It would be interesting to see if this TE increased with a greater number of trials and with more regular high intensity efforts.

Cricket conditioning coaches currently utilise GPS microtechnology to track patterns of movements both in a game and between game variation to modify the type, duration and intensity of conditioning sessions\textsuperscript{26}. The reliability of estimating longer distances is acceptable for game and training applications. However the underestimation bias displayed with the GPS units studied here during sprinting may mean that total game sprint distance is under-reported, while the total game distance may be over-reported when using MinimaxX units. The noise of up to 30\% in the measurements of cricket specific-sprinting distances is too large for identifying the smaller within player game-to-game variability of 20\% established with our pilot game data. Conditioning coaches should focus on game-to-game variations in total distance covered rather than the sprinting workload when prescribing and evaluating interval training drills.

In a comparison study of GPS technology (SPI-10) to computer-based tracking software (Trakperformance), Edgecomb and Norton\textsuperscript{20} concluded that computer-based tracking was as accurate as GPS technology. Their reliability results (TEM of 5.5\%) for movements up to a running intensity were more than twice the value found in our present study for the equivalent SPI-10 GPS unit. Improvements made in the intervening period to the GPS technology (updates in firmware or software) may be the reason for these improved results. With the increased reliability and the practical convenience of GPS monitoring, it appears that notational analysis and manually-controlled computer tracking software will soon be superseded in sports allowing GPS technology. However notational analysis and manually-controlled computer tracking software is often the only option for indoor sports, certain contact sports (safety of landing on unit) and sports that impose restrictions on using GPS technology in-competition.

**Practical Applications**

The estimations of distance with GPS were remarkably consistent between the morning and afternoon. This finding confirms those of MacLeod et al\textsuperscript{27}, who also reported that different configuration of satellites at different times of the day did not substantially affect the GPS output. Our results indicate that temporal longitudinal comparison of GPS data can be made with confidence. However, it is noticeable to any frequent user of GPS technology that satellite reception can vary with location. Therefore, we advise practitioners to routinely check
indicators of signal quality and number of satellites being utilised when interpreting GPS data. It is also advisable for coaches to check their own units to establish individual unit bias and where possible use the same unit for a particular player (where possible do not use units interchangeably).

In conclusion, in comparison to other workload monitoring techniques, GPS athlete tracking technology is practically superior. This technology can provide acceptable validity and reliability for estimating longer distances of walking to striding intensity. However there are shortcomings in the ability of the technology to reliably quantify shorter cricket-specific sprinting distances. Further improvements are required for detailed analysis of high intensity efforts in the disciplines of batting, bowling and fielding.

References


Table 1. Standard error of the estimate of commercially-available GPS units in cricket-specific movement patterns and distances (percent standard error of the mean ± 90 % confidence limits).

<table>
<thead>
<tr>
<th>Movement Pattern</th>
<th>MinimaxX–A</th>
<th>MinimaxX–B</th>
<th>SPI-10</th>
<th>SPI-Pro–A</th>
<th>SPI-Pro–B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking 8800 m (up to 2 m/s)</td>
<td>3.8 ± 1.4</td>
<td>2.0 ± 0.8</td>
<td>0.6 ± 0.2</td>
<td>1.0 ± 0.4</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>Jogging 2400 m (2 – 3.5 m/s)</td>
<td>2.6 ± 1.0</td>
<td>1.8 ± 0.7</td>
<td>0.5 ± 0.2</td>
<td>3.7 ± 1.4</td>
<td>1.5 ± 0.5</td>
</tr>
<tr>
<td>Running 1200 m (3.5 – 4 m/s)</td>
<td>2.8 ± 1.0</td>
<td>3.0 ± 1.1</td>
<td>2.1 ± 0.8</td>
<td>2.4 ± 0.9</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>Striding 600 m (4 – 5 m/s)</td>
<td>1.7 ± 0.6</td>
<td>1.8 ± 0.7</td>
<td>0.8 ± 0.3</td>
<td>3.0 ± 1.1</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>Sprinting 20 m (+ 5 m/s)</td>
<td>15.2 ± 5.6</td>
<td>23.8 ± 8.8</td>
<td>5.5 ± 2.0</td>
<td>10.5 ± 3.9</td>
<td></td>
</tr>
<tr>
<td>Sprinting 30 m (+ 5 m/s)</td>
<td>14.4 ± 5.3</td>
<td>19.7 ± 7.2</td>
<td>4.2 ± 1.5</td>
<td>7.6 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>Sprinting 40 m (+ 5 m/s)</td>
<td>14.9 ± 5.5</td>
<td>16.1 ± 5.9</td>
<td>2.9 ± 1.1</td>
<td>7.7 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>Sprinting Run-a-three (+ 5 m/s)</td>
<td>12.7 ± 4.7</td>
<td>5.3 ± 2.0</td>
<td>6.7 ± 2.5</td>
<td>2.6 ± 1.0</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Reliability of commercially-available GPS monitoring (coefficient of variability with 90% confidence limits) of cricket-specific movement patterns and distances.

<table>
<thead>
<tr>
<th>Activity</th>
<th>MinimaxX–A</th>
<th>MinimaxX–B</th>
<th>SPI-10</th>
<th>SPI-Pro–A</th>
<th>SPI-Pro–B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking 8800m (up to 2m/s)</td>
<td>2.6 (2.1 – 3.6)</td>
<td>1.4 (1.1 – 2.0)</td>
<td>0.4 (0.3 – 0.6)</td>
<td>0.7 (0.6 – 1.0)</td>
<td>0.3 (0.3 – 0.5)</td>
</tr>
<tr>
<td>Jogging 2400m (2 – 3.5 m/s)</td>
<td>1.8 (1.5 – 2.5)</td>
<td>1.3 (1.0 – 1.7)</td>
<td>0.4 (0.3 – 0.5)</td>
<td>2.9 (2.3 – 4.0)</td>
<td>1.1 (0.9 – 1.5)</td>
</tr>
<tr>
<td>Running 1200m (3.5 – 4 m/s)</td>
<td>2.0 (1.6 – 2.7)</td>
<td>2.0 (1.6 – 2.8)</td>
<td>1.5 (1.2 – 2.1)</td>
<td>1.8 (1.4 – 2.5)</td>
<td>0.5 (0.4 – 0.7)</td>
</tr>
<tr>
<td>Striding 600m (4 – 5 m/s)</td>
<td>1.2 (1.0 – 1.7)</td>
<td>1.3 (1.0 – 1.8)</td>
<td>0.5 (0.4 – 0.7)</td>
<td>2.3 (1.8 – 3.1)</td>
<td>0.3 (0.2 – 0.4)</td>
</tr>
<tr>
<td>Sprinting 20 m (+ 5 m/s)</td>
<td>19.7 (15.3 – 27.9)</td>
<td>30.0 (23.2 – 43.3)</td>
<td>4.8 (3.8 – 6.6)</td>
<td>9.3 (7.3 – 13.0)</td>
<td></td>
</tr>
<tr>
<td>Sprinting 30 m (+ 5 m/s)</td>
<td>15.8 (12.4 – 22.3)</td>
<td>21.3 (16.5 – 30.3)</td>
<td>3.4 (2.7 – 4.7)</td>
<td>6.3 (5.0 – 8.7)</td>
<td></td>
</tr>
<tr>
<td>Sprinting 40 m (+ 5 m/s)</td>
<td>16.1 (12.5 – 22.6)</td>
<td>17.1 (13.4 – 24.2)</td>
<td>2.3 (1.8 – 3.1)</td>
<td>5.8 (4.6 – 8.1)</td>
<td></td>
</tr>
<tr>
<td>Sprinting Run-a-three (+ 5 m/s)</td>
<td>13.6 (10.7 – 19.1)</td>
<td>5.3 (4.2 – 7.3)</td>
<td>6.3 (5.0 – 8.7)</td>
<td>2.0 (1.6 – 2.8)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Percent (%) bias (± 90 % CL) of GPS measured distances from criterion distances.

<table>
<thead>
<tr>
<th>Activity</th>
<th>MinimaxX–A</th>
<th>MinimaxX–B</th>
<th>SPI-10</th>
<th>SPI-Pro–A</th>
<th>SPI-Pro–B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking 8800m (up to 2 m/s)</td>
<td>2.1 ± 1.4</td>
<td>3.2 ± 0.8</td>
<td>-0.8 ± 0.2</td>
<td>-1.1 ± 0.4</td>
<td>-0.8 ± 0.2</td>
</tr>
<tr>
<td>Jogging 2400m (2 – 3.5 m/s)</td>
<td>0.3 ± 1.0</td>
<td>0.8 ± 0.7</td>
<td>-0.9 ± 0.2</td>
<td>-2.8 ± 1.4</td>
<td>-2.7 ± 0.5</td>
</tr>
<tr>
<td>Running 1200m (3.5 – 4 m/s)</td>
<td>0.4 ± 1.0</td>
<td>2.6 ± 1.1</td>
<td>-1.0 ± 0.8</td>
<td>-3.8 ± 0.9</td>
<td>-1.2 ± 0.2</td>
</tr>
<tr>
<td>Striding 600m (4 – 5 m/s)</td>
<td>0.3 ± 0.6</td>
<td>0.0 ± 0.7</td>
<td>-1.7 ± 0.3</td>
<td>-2.7 ± 1.1</td>
<td>-1.0 ± 0.1</td>
</tr>
<tr>
<td>Sprinting 20 m (+ 5 m/s)</td>
<td>-37.3 ± 5.6</td>
<td>-24.3 ± 8.8</td>
<td>-15.3 ± 2.0</td>
<td>-13.6 ± 3.9</td>
<td></td>
</tr>
<tr>
<td>Sprinting 30 m (+ 5 m/s)</td>
<td>-27.4 ± 5.3</td>
<td>-20.4 ± 7.2</td>
<td>-10.3 ± 1.5</td>
<td>-11.5 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>Sprinting 40 m (+ 5 m/s)</td>
<td>-24.1 ± 5.5</td>
<td>-19.5 ± 5.9</td>
<td>-7.7 ± 1.1</td>
<td>-7.4 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>Sprinting Run-a-three (+ 5 m/s)</td>
<td>-28.9 ± 4.7</td>
<td>-28.1 ± 2.0</td>
<td>-20.0 ± 2.5</td>
<td>-6.1 ± 1.0</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Trundle-wheel with milk crate platform. Nine GPS units are positioned in cradles on this platform for simultaneous recording of distance travelled.
Figure 2. Inter-unit variation in estimated distance (mean ± 90 % CL) from 1200m walks with nine GPS units. The three AM trials were conducted at 9:30 am and three PM trials at 4 pm.