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Research article

Criterion validity and accuracy of global positioning satellite and data logging devices for wheelchair tennis court movement

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ABSTRACT

Purpose: To compare the criterion validity and accuracy of a 1-Hz non-differential Global Positioning System (GPS) and data logger device (DL) for measurement of wheelchair tennis court movement variables.

Methods: Initial validation of the DL device was performed. GPS and DL were fitted to the wheelchair and used to record distance (m) and speed (m·sec⁻¹) during a) tennis field b) linear track and c) match-play test scenarios. Fifteen participants were monitored at the Wheelchair British Tennis Open.

Results: Data logging validation showed underestimations for distance in right (DLR) and left (DLL) logging devices at speeds >2.5 m·sec⁻¹. In tennis field tests, GPS underestimated distance in five drills. DLL was lower than both a) criterion and b) DLR in drills moving forward. Reversing drill direction showed DLR was lower than a) criterion and b) DLL. GPS values for distance and average speed for match-play were significantly lower than equivalent values obtained by DL [distance: 2816 (844) vs. 3952 (1109) m, P=0.0001; average speed:
0.7 (0.2) vs. 1.0 (0.2) m·sec\(^{-1}\), P=0.0001]. Higher peak speeds were observed in DL [3.4 (0.4) vs. 3.1 (0.5) m·sec\(^{-1}\), P=0.004] during tennis match-play.

**Conclusions:** Sampling frequencies of 1 Hz are too low to accurately measure distance and speed during wheelchair tennis. GPS units with a higher sampling rate should be advocated in further studies. Modifications to existing DL devices may be required to increase measurement precision. Further research into the validity of movement devices during match-play will further inform the demands and movement patterns associated with wheelchair tennis.

**Key words:** Sports science; Aerobic fitness; Spinal cord injuries; Disability sport, tennis; Global positioning system; Wheelchair; Data logging, distance, speed
INTRODUCTION

An evaluation of the physiological demands and movement-based characteristics of match-play allows for the development of highly specialised training. Direct measurement during competitive match-play also ensures that training is aligned with the demands of competition and performance. Consequently, there has been an increasing interest amongst coaches and sports scientists in the area of physiological and movement-based profiling within both individual and team sports.

Wheelchair tennis play has been described as an intermittent activity and research has suggested that players demonstrate a moderate to high level of aerobic fitness. Players must overcome significant physiological and skill-based challenges during match-play. Players manoeuvre their wheelchair by planning and reacting to the speed and movement of the ball, and the actions of their opponent. Hence, demands are highly variable. The playing style of the opponent and match-play characteristics are likely to influence court positioning and movement response. In addition, recent findings indicate a strong effect for player ranking, with greater distances and average speeds associated with highly skilled players.

Physiological responses have been recorded during court-based sports such as tennis using measures of heart rate (HR), oxygen uptake, blood lactate concentration, ratings of perceived exertion and video analysis. Whilst these are accepted indicators of physical stress, the ability to measure physiological variables with precision during competitive match-play is influenced by impracticality, labour intensiveness and/or inaccuracy, with HR in particular affected in individuals with high-level lesions or athletes with complete spinal cord injuries.
The requirement for accurate match-play information, coupled with the difficulties of directly measuring physiological variables during match-play, has prompted interest in alternative monitoring methods. A telemetry-based velocometer attaches to the rear wheel of the chair and provides data on propulsion velocity.\(^{16}\) Whilst this device demonstrates good validity, a number of limitations are associated with its practical application. First, as device mass is ~1.1-1.4% of total wheelchair-wheelchair user mass, disruption to normal propulsion technique may be implied. Second, velocometer calibration and wheel fitment is time consuming. Third, data turnaround time for coaches and athletes is typically protracted. Hence, the device may be more useful as a research tool than a practical device for field-based movement assessment.\(^{17}\) A video-tracking method based on image-processing technology has been used for elite male wheelchair rugby players to record distance, average velocity and movement trajectories.\(^{18}\) This technology had previously been used in field assessments of soccer players.\(^{19}\) Whilst the technique was deemed appropriate for rugby, the automatic tracking rate of 20% was much lower than the 95% value observed for soccer players.\(^{19}\)

Global positioning satellite (GPS) systems offer an alternative means to quantify the physiological and movement challenges associated with sports activity such as wheelchair tennis,\(^1\) but do not function effectively indoors. Whilst data in wheelchair sports are limited, GPS has been validated for the collection of distance and speed in able-bodied populations participating in field sports.\(^ {2,20,21}\) With limited information on the demands of match-play, coaches can only apply a basic intervention. Short sprints, agility drills, hand cycling and general pushing are typically advocated by coaches to improve performance in wheelchair sports.\(^ {22}\) GPS systems track common movement patterns, allowing coaches to optimise
tactics and court movement strategies. Modern GPS devices also supply information on body load and the associated stresses linked to acceleration, deceleration and changes of direction, an important factor for tennis players who highly rate the ability to turn during play.\textsuperscript{7}

Whilst there appears to be a clear rationale for GPS application in tennis, underestimations for distance and speed have been noted in confined spaces using VICON motion analysis as the criterion.\textsuperscript{23} Tennis court size is standardised, with an active playing area of 11.0 by 8.2m for singles match-play.\textsuperscript{24} Such an area should be considered a confined space, and hence, validation of GPS is required. Criterion-related validity refers to the systematic relationship between an approved criterion measure and an alternate method used to measure the criterion.\textsuperscript{25} With criterion-related concurrent validity, the new method meets the criterion measures and can subsequently be used as an alternative technique.\textsuperscript{26} Data loggers (DL) have been validated for the collection of speed and distance data\textsuperscript{27} and used to monitor activity patterns of manual wheelchair users,\textsuperscript{28} children\textsuperscript{29} and wheelchair rugby players.\textsuperscript{30} DL could thereby be used as a reference measure for the validation of GPS. However, such a proposition is problematic. Validity and intra-model reliability (ie. comparison of data from two DL recording in tandem) were assessed during linear motion.\textsuperscript{27} As repeated turns and changes of direction are associated with court sports, DL accuracy in this context is unclear. Hence in the current study, validity for both devices was first determined using known distance as the criterion. Second, GPS and DL values for match-play were compared. Therefore, the purpose was threefold; to examine 1) criterion validity for GPS and DL against known distance, 2) intra-model reliability for DL and 3) differences between GPS and DL during match-play.
We hypothesise that there will be no difference 1a) between DL and known distance during treadmill validation, 1b) between GPS and DL for court movement variables during tennis field and linear track testing, and 2) between two DL devices placed on both the right (DLR) and left (DLL) wheels. Based on previously reported underestimations for distance and speed in GPS, we also hypothesize that 3) GPS will underestimate DL values during match-play.
METHODS

Participants

Fifteen participants (11 male & 4 female) volunteered for this study. All players had previously registered for tournament match-play, and gave consent for the attachment of GPS and DL units to their sports wheelchair. Individual physical and physiological characteristics have no effect on GPS accuracy or DL performance. Hence, player rank was not controlled. At the time of competition, twelve players held a world International Tennis Federation (ITF) rank of ≤25, whilst three held an ITF rank of <100. Approval was gained from the University Ethics Committee and written consent was obtained by all participants and their guardians (if <18 years) prior to testing.

Procedures

GPS unit

A lightweight (76 g), portable GPS tracking device with integrated accelerometer was used for data collection (SPI Elite™, GPSports System, Canberra, Australia). Sampling frequency for GPS was 1-Hz, whereas integrated accelerometer was defined at 100-Hz. The unit was securely taped to the sports wheelchair in clear view of the sky (Figure 1) and powered within 30 minutes prior to the official match start time. Once activated, the GPS unit calculated the precise distance to operational satellites based on receipt of satellite time and position data. By calculating distance to four satellites (minimum) the position of the GPS unit could be determined trigonometrically, generating an exact three-dimensional position. Distance was calculated from changes in position of the GPS. Speed was determined using the Doppler
shift. The unit was operational for the duration of the match, and switched off directly afterwards. Raw data were downloaded to a personal computer and analysed using GPS software (GPSports Team™, AMS V2.1, Canberra, Australia) to retrieve distance and speed.

**Data Logger**

The device, which is powered by a 1/6D wafer-cell lithium battery, is a self-contained, lightweight unit (96 g) measuring 6 cm in diameter and 3.5 cm in depth. The unit was attached to the inside spokes of the wheelchair using cable ties (Figure 2).

The DL contains three reed switches attached to a printed circuit board 120° apart. A magnet is located at the bottom of a pendulum. This magnetic pendulum retains its position due to the force of gravity. As the wheel rotates the magnet sweeps over the 3 reed switches at 120° intervals. Reed-switch activation marks a date and time stamp (hh:mm:ss:00) on a flash memory. Hence, sampling frequency is directly related to speed of wheel rotation. Raw output generated by the data logger was subsequently treated using a custom Matlab® programme. Values for distance and speed were obtained. Distance was calculated by multiplying number of reed switch triggers by 1/3 wheel circumference. Average speed was calculated by dividing distance by time. Maximum speed was the highest recorded interval. For match-play, these data were cross-compared to actual playing time (game time minus time spent between games) to generate per-game values for distance, average speed and maximum speed. Game distances were accumulated to allow a total value for each variable to be presented for each individual match.
**DL validation**

The DL has been used to measure distance and speed during wheelchair tennis\(^9\) and rugby,\(^{30}\) but only tested at moderate speeds ranging from 0.8 to 1.8 m sec\(^{-1}\).\(^{27}\) Consequently, an initial validation was performed. A sports wheelchair with a 26” wheel diameter (tyre pressure 120 PSI) was mounted onto a motor-driven treadmill (H/P/Cosmos Saturn, Nussdorf-Traunstein, Germany) to allow for passive wheel rotation. To examine intra-model reliability (ie. compare two DL devices of the same model), two DL units were attached to each wheel, and their data compared. Whilst the treadmill was programmed to cover 500 m, actual distance was also recorded to ensure precision in the comparison between wheel rotation and actual belt movement. Speed was increased for each bout by 0.5 m sec\(^{-1}\) (minimum to maximum: 0.5 to 5.0 m sec\(^{-1}\)). Range for speed was based on values reported for tennis players.\(^9\)

**Validation against criterion distance**

GPS and DL were compared using a) tennis field and b) linear track testing drills. To ensure consistency of pushing technique and speed, one male participant competent in wheelchair propulsion was selected at random to perform all tests. Forwards propulsion was adopted throughout, with the participant seated in the chair. GPS and DL were attached to a sports wheelchair (Figures 1 and 2). In tennis field testing, one DL was attached to each wheel to assess the impact of turning on movement variables. Three drills (I, II and III) were devised to replicate patterns associated with match-play (Figure 3). Distance was checked using an extendable tape measure. Ten sets of each drill were performed. Drills were then repeated for movement in the opposite direction (I*, II* and III*). Linear track testing involved repeated trials on an outdoor athletics track. Known distances were used (Trial A, 10x100m; Trial B, 10x200m; Trial C, 10x400m and Trial D, 10x800m).
Data collection took place at the 2010 Wheelchair Tennis British Open in Nottingham. Tournament format and match-play were in accordance with ITF rules. The start and finish time for each game was recorded and used to calculate game length. Actual playing time (APT) was the sum total of game length values for a given set. ITF time limits for changeovers and breaks were strictly enforced. With Organising Committee approval, each match was filmed using a Sony HDR HC7 Mini DV Handycam connected to a Raynox HD Superwide Angle Conversion Lens (0.5x conversion factor); video footage was used to cross-check all recorded times. A total of 26 tennis matches were tracked with 9 and 17 matches from the quadriplegic and open classes respectively. GPS was attached (Figure 1) and one DL to the wheel on the non-racquet side. All matches were won or lost in three sets.

Statistical Analyses

Data analyses were conducted using SPSS version 19.0 (SPSS, Inc., Chicago, IL). Descriptive statistics (mean, SD) were obtained for all participants. Normality and homogeneity of variance were confirmed by Shapiro-Wilk and Levene’s tests, respectively. Student’s paired t-tests were used to identify within group differences for DL treadmill testing. Intra-model reliability was determined using the typical error and coefficient of variation (CV). Ninety-five percent confidence intervals (95% CI) were calculated. GPS and DL values for distance were compared with known distances for tennis field and linear track tests using the Bland Altman method. Subsequent one-way analysis of variance (ANOVA) with Tukeys’ post hoc testing was used to examine the differences between measurement devices for distance and speed. Match-play data were presented independently for the open and quadriplegic classifications, with student’s paired t-tests used to identify
within group differences. In addition, combined values (open and quadriplegic) were presented. Statistical significance was accepted at a level of $P \leq 0.05$.

**RESULTS**

*DL validation*

Mean treadmill distance across all fixed speed conditions was 502 (2) m. During the treadmill test, lower values for distance were observed in right [434 (84) m; $t=2.525$, $P=0.032$] and left [451 (64) m; $t=2.488$, $P=0.035$] DL units when compared to fixed values. Figure 4 shows a progressive underestimation for distance and speed at treadmill speeds >2.5 m·sec$^{-1}$. The intra-model reliability for distance measured by left and right DL devices is shown in Table 1. Both DL units reported good reliability at speeds <2.5 m·sec$^{-1}$. Comparatively less stable scores were observed at higher speeds in both units.

*Tennis field testing*

Three drills (range, 27.4 – 69.5 m) were performed in two directions. GPS underestimated distance in five of six drills (Table 2) and recorded lower values than DLR in drills I, II and III, and DLL in drills I* and III*. Figure 5a shows DLR and DLL recorded distances closest to the criterion (drills I, II and III and I*, II* and III* respectively). DLL was significantly lower than criterion and DLR in drills I, II and III. Reversing the direction of movement resulted in the opposite effect, with a difference between the criterion and DLR, and higher values for DLL (drills I* and III*). The tendency for DLL underestimation in forwards and DLR underestimation in reversed movement directions can be seen in Figure 5a. Highest values for %CV were observed during drills involving a figure of 8 movement (Figure 3) for
all devices. A one-way analysis of variance with Tukeys’ post hoc test revealed a lower mean speed for DLR against GPS [1.62 (0.21) vs. 1.54 (0.14) m·sec\(^{-1}\), \(P=0.039\)].

**Linear track testing**

Four trials (range, 100–800 m) were performed in one direction. Figure 5b shows the agreement between measurement devices and the criterion during linear track testing. One-way ANOVA revealed GPS underestimated criterion distance at 100 m (\(P=0.001\)). At 200 m, values for DLL were lower than GPS (\(P=0.006\)). GPS distance at 400m was higher than values for DLR, DLL and the criterion (\(P=0.0001\)). At the same distance, DLL reported lower values than the reference value (\(P=0.001\)) and DLR (\(P=0.006\)). Both DLR and DLL significantly overestimated criterion distance at 800 m (\(P=0.0001\) and \(P=0.040\) respectively), with DLR reporting higher values than GPS (\(P=0.005\)). A decrease in %CV was observed with an increase in distance (100 to 400 m) for GPS. All trials were undertaken at speeds <2.5 m·sec\(^{-1}\). No significant difference was observed for average speed between measurement devices (\(P=0.474\)).

**Competitive match-play**

Table 3 presents descriptive statistics for tennis match-play. Significantly higher distances and average speeds were associated with DL for all playing categories. Peak speed was higher for GPS in both the open (\(P=0.035\)) and combined categories (\(P=0.004\)).

**DISCUSSION**

The purpose of the present study was to examine 1) criterion validity for GPS and DL against known distance, 2) intra-model reliability for DL and 3) differences between GPS and DL
during match-play. In the present study, significant differences were observed between DL and known distance during initial treadmill validation. In tennis field testing, GPS underestimated criterion distance. For DL, movement direction influenced the level of agreement with criterion distance values. In linear track tests, higher values for GPS and DL were noted at 400 and 800 m, respectively. Significant differences between distance and speed were observed between GPS and DL during tennis match-play, with GPS reporting lower values for distance and average speed, and higher values for peak speed.

The validity and accuracy of GPS systems for performance monitoring has been considered in a range of sports, including tennis. However, comparisons between sporting disciplines are problematic due to variation in systems used and methods employed for testing. In particular, differences exist between triangulation algorithms for calculation of receiver position, Kalman (exclusion criteria) formula for logical positioning, and smoothing techniques used to exclude anomalies. On an oval circuit, GPS distances of 125 to 1386 m are associated with a mean error of 4.8 ± 7.2 %, the magnitude of which decreases with an increase in distance. For track-based testing, our data shows a reduced %CV with increased distance for GPS within trials conducted over a similar range (100 to 800 m). Hence, GPS reliability is improved with increased distance. Comparatively smaller underestimations (0.4%) for measurement over longer distances (600-8800 m) suggest that accuracy is improved over increased distances. The results of the present study report a value of 2816 (844) m for combined distance during match-play (Table 3). GPS units thereby have a potential application for quantification of distance during tennis. However, such a proposition may be problematic. First, our data reveal a significant underestimation for GPS against criterion distance for five of six drills completed within the confines of a tennis court. This finding is consistent with previous findings reporting an increase in the mean difference
between GPS and reference values for distance during non-linear motion at increasing speeds.  

Second, a larger %CV was observed during tennis field testing for GPS, particularly for drills involving the figure 8 pattern. Such a drill is characterised by movement within a small space, and a complex series of sharp turns. This type of movement, which is typical in tennis, may represent a challenge to measurement precision for GPS.

GPS systems record non-linear movements as a sum of measured chords within the actual curve based on position estimates. Higher sample rates allow more chords to be measured and the path defined by the chords becomes closer to the actual curve. An increased circle diameter also allows for increased chord measurement and hence, a more accurate estimation. Tennis court movement is multidirectional and non-random, with repetitive sharp turns and alterations of pace. Hence, GPS may be unable to accurately track the entire distance covered, predicting the distance of several chords within these turns and leading to distance underestimation. Further, a moderate but significant correlation for satellite number and GPS accuracy suggests that the number of active satellites may also influence error magnitude. As horizontal dilution of precision (HDOP) is dependent on satellite geometric position and number, a reduction in active satellites therefore causes a reduction in HDOP. Greater variability is seen in HDOP during small circle experiments, and side-to-side movements may influence measurement accuracy. Satellite recruitment data was not collected in the present study. Consequently, this cannot be confirmed as a contributing factor. However, the enclosed space of a tennis court could theoretically influence the number of satellites that the GPS is able to utilise, and therefore increase HDOP. This seems plausible as GPS has been shown to underestimate distance in confined tennis court drills at varied speeds when compared to a highly accurate VICON motion analysis system.
In the track trials, no significant difference was observed for average speed between measurement devices. These findings are in agreement with values presented for linear movement in hockey.\(^1\) GPS system accuracy has been confirmed for speed determination in curved-path (16 and 30 m diameter), and straight-line trajectories.\(^3\) However, curves were much larger in circumference than those associated with the current study. As discussed previously, a larger circumference means more chords are sampled, which in turn influences the accuracy of the prediction. Speed is calculated by dividing the distance by time taken. Hence, factors influencing distance determination have a direct impact on equivalent values for speed. In addition, the mathematical algorithm in the GPS system smoothes out the peaks and troughs for rapid accelerations and decelerations, causing further inaccuracies.\(^3\) With a 1-Hz sampling rate, one sample is recorded every second. Therefore, movements lasting less than this may be missed or underestimated.

Data generated from DL may also lead to inaccurate estimations of speed and distance. Our data shows agreement and good reliability between DL and treadmill for speeds <2.5 m·sec\(^{-1}\). This finding is consistent with initial validation of the device which reports agreement at speeds ranging from 0.8 to 1.8 m·sec\(^{-1}\).\(^2\) However, at higher speeds (>2.5 m·sec\(^{-1}\)), we report a decrease in measurement accuracy and reliability for DL, with the degree of underestimation increasing with an increasing speed. In addition, a lower average speed was noted for DLR against GPS in the more confined tennis drills. DL calculates speed and distance indirectly, through consecutive reed switch activation.\(^3\) If a reed switch is missed, a time stamp is not created, theoretically leading to underestimations for both distance and speed. Average speed during match-play was ~0.7 m·sec\(^{-1}\). Whilst this speed is consistent with those associated with the initial validation of the device, it is important to note that tennis is a highly intermittent sport, involving rapid movements interspersed with active rest.
Participants will clearly attain higher speeds as they respond to the movement of the ball. The present study reports peak speed values of ~3.5 m·sec$^{-1}$ for both classes. Hence, values reported for DL match-play distance and speed are likely to offer an underestimation of actual on-court movement dynamics, and a modified DL for use within sports may be required.

In the 100-m linear track trial, GPS underestimated criterion distance. However at 400 m, GPS provided an overestimation and yielded higher values than DLR and DLL. The reasons for this shift are not entirely clear but are most likely related to fluctuations in satellite availability. At 800 m, values for DLR and DLL were higher than the criterion. Whilst the mechanisms for DL underestimation are clear, the factors influencing overestimation are less obvious, although most likely related to the pendulum design of the device. DL is a sealed unit, and thus, reed switch position cannot be identified prior to testing. Lack of control over standardisation of reed switch positioning will inevitably cause a discrepancy. However, due to wheel sizes involved, such a discrepancy is likely to be small. Other factors may be related to inconsistencies relating to time stamping. Further work is required to assess such causes.

A tendency for a lower %CV was noted for linear track testing, suggesting that devices yield more reliable scores with straight-line movement. During tennis field testing, %CV was higher, hence a reduced reliability. DLL significantly underestimated criterion and DLR distance in drills containing left hand turns (I, II and III) whilst in contrast, DLR underestimated criterion and DLL distance values in drills containing right hand turns (drills I* and III*). These data suggest that the outside wheel a) covered greater distance and b) was more closely associated with criterion distances during turning movements. During left turns, the left wheel is likely to remain stationary to pivot whilst the right wheel continues to rotate
to make the turn. In addition, values for GPS were consistently lower than the outside wheel DL. These data suggest collectively that for tennis field drills in confined spaces, outside wheel DL offered the best representation of actual distance. However, due to the non-random nature of movement during match-play, the number of turns are not likely to be consistent or equal. This raises important considerations regarding DL placement on the chair, and the general application of DL systems for movement profiling within wheelchair sports. To counteract the effect of turns during match-play, and to ensure accurate movement profiling of the wheelchair user during sport, two DL devices (one on each wheel) should be used.

For match-play, our data show significantly higher distances and average speeds were associated with DL for all playing categories. Peak speed was higher for GPS in open (P=0.035) and combined categories (P=0.004), with higher average speeds for DL. However, concerns with GPS and DL accuracy add uncertainty to inferences on actual distance and speed covered during match-play. The relationship between GPS and reference values for maximal speed is stronger at higher distances using 1Hz systems. Criterion distances were not available for match-play. Future work should ensure that an appropriate reference measure is provided. The VICON motion analysis system, or a computer-based tracking system may be suitable options. However, the present study has identified important questions regarding the application of movement tracking systems in wheelchair tennis. For GPS, an appropriately high sample rate should be advocated. Sampling frequencies of 1 Hz and 5 Hz underestimate average and maximum speed by 10-30% in court-based movement drills, and may lack sensitivity for the monitoring of movement during tennis. GPS units sampling at 15Hz are now available and may give a more accurate estimation of distance and speed. Regarding application of DL, the purpose of monitoring is an important consideration. As differences between units were related to wheel movement, future studies should ensure
placement of two devices on one wheel for all test conditions. For movement profiling of
court-based sports, devices should be placed on each wheel to counteract the impact of turns.
However, it should be noted that neither strategy is likely to address DL validity concerns at
higher speeds. Modifications to existing technology are required to address reed switch
activation issues. DL devices incorporating six switches have been developed and are
currently undergoing preliminary testing. Whilst the accuracy of these devices is not yet
known, they offer potential for greater precision in the measurement of speed and distance.
Further research should address the accuracy and reliability of newly developed data logging
devices for movement profiling in wheelchair sports.

CONCLUSION

GPS and DL units provide quick and non-labour intensive methods of supplying information
on movement dynamics to enable coaches to effectively plan and monitor training. The
current study reports significant differences for distance and speed between devices in tennis
field, linear track and match-play test scenarios. Distance for GPS was underestimated in
tennis field tests. The requirement for repeated turns in a confined space may have influenced
measurement accuracy. Between-device differences were observed for DL units placed on
opposing wheels. In tennis field testing, DL placed on the outside wheel provided the most
accurate distances in comparison to reference values. At speeds \( >2.5 \text{ m\cdotsec}^{-1} \), values for DL
distance and speed were significantly lower than known values. However, whilst rapid
changes of pace may disrupt normal reed-switch activation and cause underestimations in
distance and speed, tennis players spend a limited time at top speed due to the confines of
court dimensions and the nature of play. Hence, DL devices may be more suitable for tennis
than for open-court sports such as rugby or basketball. When DL is used, consideration
should be given to placement and positioning to increase the precision of measurement.

Further testing and development of the DL is required to evaluate its application within a sporting context. For tennis match-play, GPS units with a higher sampling frequency may offer increased sensitivity for the quantification of movement patterns.

ACKNOWLEDGEMENTS

We thank the tournament organisers for their support. Appreciation is also extended to all sportsmen and sportswomen who volunteered to participate in this study.
REFERENCES


**TABLE 1** - Intra-model reliability measures for the DL during treadmill testing. Values are typical error (95%CI) [%CV].

<table>
<thead>
<tr>
<th>Treadmill speed (m·sec⁻¹)</th>
<th>DLL</th>
<th></th>
<th>DLR</th>
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<tbody>
<tr>
<td>&lt;2.5</td>
<td>2.1 (499 - 505) [0.4%]</td>
<td></td>
<td>0.3 (503 - 508) [0.1%]</td>
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<tr>
<td>&gt;2.5</td>
<td>17.5 (339 - 478) [4.4%]</td>
<td></td>
<td>72.3 (259 - 477) [19.9%]</td>
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<td>Distance (m)</td>
<td>Criterion</td>
<td>GPS</td>
<td>DLR</td>
<td>DLL</td>
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<tr>
<td><strong>Tennis Field Test</strong></td>
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<tr>
<td><strong>Drill</strong></td>
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</tr>
<tr>
<td>I</td>
<td>27.4</td>
<td>24.6 (1.3)</td>
<td>23.7 - 25.5 [5.2]</td>
<td>26.5 (0.7)</td>
</tr>
<tr>
<td>II</td>
<td>36.3</td>
<td>31.4 (1.3)</td>
<td>30.5 - 32.3 [4.3]</td>
<td>38.4 (3.0)</td>
</tr>
<tr>
<td>III</td>
<td>69.5</td>
<td>62.1 (1.3)</td>
<td>61.2 - 63.0 [2.1]</td>
<td>70.4 (0.7)</td>
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<td>27.4</td>
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<td>69.5</td>
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<td>61.0 - 65.2 [4.8]</td>
<td>65.8 (0.5)</td>
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<tr>
<td><strong>Trial</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>200</td>
<td>202 (7)</td>
<td>197 - 207 [3.4]</td>
<td>198 (4)</td>
</tr>
<tr>
<td>C</td>
<td>400</td>
<td>409 (4)</td>
<td>407 - 412 [0.9]</td>
<td>399 (5)</td>
</tr>
<tr>
<td>D</td>
<td>800</td>
<td>804 (15)</td>
<td>793 - 814 [1.8]</td>
<td>817 (5)</td>
</tr>
</tbody>
</table>

* Denotes drill repeated in the opposite direction

a Significantly different to criterion (P<0.05)
b Significantly different to GPS (P<0.05)
c Significantly different to DLR (P<0.05)
d Significantly different to DLL (P<0.05)
**TABLE 3** - Distance and speed for GPS and DL during competitive match-play. Values are mean (SD) 95%CI.

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>DL</th>
<th>t</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>2891 (1000)</td>
<td>2377 - 3405</td>
<td>3963 (1340)</td>
<td>3274 - 4652</td>
</tr>
<tr>
<td>Quad</td>
<td>2675 (438)</td>
<td>2339 - 3012</td>
<td>3931 (505)</td>
<td>3543 - 4319</td>
</tr>
<tr>
<td>Combined</td>
<td>2816 (844)</td>
<td>2475 - 3157</td>
<td>3952 (1109)</td>
<td>3504 - 4400</td>
</tr>
<tr>
<td><strong>Peak speed (m·sec⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>3.5 (0.4)</td>
<td>3.3 - 3.7</td>
<td>3.3 (0.6)</td>
<td>3.0 - 3.5</td>
</tr>
<tr>
<td>Quad</td>
<td>3.1 (0.2)</td>
<td>2.9 - 3.3</td>
<td>2.8 (0.4)</td>
<td>2.5 - 3.2</td>
</tr>
<tr>
<td>Combined</td>
<td>3.4 (0.4)</td>
<td>3.2 - 3.5</td>
<td>3.1 (0.5)</td>
<td>2.9 - 3.3</td>
</tr>
<tr>
<td><strong>Average speed (m·sec⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>0.8 (0.1)</td>
<td>0.7 - 0.9</td>
<td>1.0 (0.2)</td>
<td>0.9 - 1.1</td>
</tr>
<tr>
<td>Quad</td>
<td>0.6 (0.1)</td>
<td>0.5 - 0.7</td>
<td>0.9 (0.0)</td>
<td>0.8 - 0.9</td>
</tr>
<tr>
<td>Combined</td>
<td>0.7 (0.2)</td>
<td>0.7 - 0.8</td>
<td>1.0 (0.2)</td>
<td>0.9 - 1.1</td>
</tr>
</tbody>
</table>

* Significant difference between GPS and DL (P<0.05).
FIGURE 1 -  a) The position of the GPS unit on the back of the sports wheelchair, b) an anterior view of the SPI Elite™ GPS unit, c) a lateral view of the SPI Elite™ GPS unit.
**FIGURE 2** - The position of DL units on the inside spoke of the sports wheelchair (a & b), tilted anterior view of the DL unit (c).
**FIGURE 3** - Court movement drills. Dot indicates starting point. Arrow indicates wheelchair movement direction. Distance (m): $v=8.2$, $w=5.5$, $x=9.9$, $y=11.0$, $z=23.7$. Drill: **I**=Back court box (27.4 m), **II**=Figure 8 (36.3 m), **III**=Full court box (69.5 m).
FIGURE 4 - Distance and speed for DL during an incremental, passive wheel rotation validation test on a motor-driven treadmill. Values for right and left wheels (solid lines) are presented against fixed values for distance and speed (dashed line).
**FIGURE 5a** - Plot of mean difference (bias) during tennis field testing drills for GPS (▲), DLR (■) and DLL (●). Drill: *I*=Back court box (27.4 m), *II*=Figure 8 (36.3 m), *III*=Full court box (69.5 m). Error bars represent 95% limits of agreement. *Denotes drill repeated in the opposite direction.
FIGURE 5b - Plot of GPS (▲), DLR (■) and DLL (○) mean difference (bias) during linear track testing. Error bars represent 95% limits of agreement.