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

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Purpose: To compare the criterion validity and accuracy of a 1 Hz non-differential global positioning system (GPS) and data logger device (DL) for the 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/second) 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/second. 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 that 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/second, $P=0.0001$). Higher peak speeds were observed in DL (3.4 (0.4) vs. 3.1 (0.5) m/second, $P=0.004$) 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.

Keywords: 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 specialized training.¹ Direct measurement during competitive match-play also ensures that training is aligned with the demands of competition and performance.² Consequently, there has been an increasing interest among 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.^{3,4} Players must overcome significant physiological and skill-based challenges during match play.^{5,6} Players maneuver their wheelchair by planning and reacting to the speed and movement of the ball,⁷ and the actions of their opponent. Hence, demands are highly variable. The playing style of the opponent⁸ and match-play characteristics^{3,8} are likely to influence

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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.⁹

Physiological responses have been recorded during court-based sports such as tennis using measures of heart rate (HR),¹⁰ oxygen uptake,¹¹ blood lactate concentration,¹² ratings of perceived exertion,¹³ and video analysis.¹⁴ While 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.¹⁵

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 While 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 are 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 While 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. While 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 optimize 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.⁷

While 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 Systems as the criterion.²³ Tennis court size is standardized, with an active playing area of 11.0 × 8.2 m for singles match play.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.²⁵ With criterion-related concurrent validity, the new method meets the criterion measures and can subsequently be used as an alternative technique.²⁶ Data loggers (DLs) have been validated for the collection of speed and distance data²⁷ and used to monitor activity patterns of manual wheelchair users,²⁸ children,²⁹ and wheelchair rugby players.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 (i.e. comparison of data from two DL recording in tandem) were assessed during linear motion.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 three-fold; 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 hypothesize 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 males and 4 females) 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 accuracy³¹ or DL performance. Hence, player rank was not controlled. At the time of competition, 12 players held a world International Tennis Federation (ITF) rank of ≤ 25 , while 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 (Fig. 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,³² generating an exact three-dimensional position. Distance was calculated from changes in position of the GPS. Speed was determined using the Doppler shift.³¹ The unit was operational for the duration of the match, and switched off directly afterwards. Raw data were downloaded to a

personal computer and analyzed 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 (Fig. 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.²⁷ As the wheel rotates the magnet sweeps over the three reed switches at 120° intervals.³³ Reed-switch activation marks a date and time stamp (hh:mm:ss:00) on a flash memory. Hence, sampling frequency is directly related to the speed of wheel rotation. Raw output generated by the DL was subsequently treated using a custom Matlab® program. 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 (APT) (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.

Figure 1 (A) The position of the GPS unit (red (online version of paper) rectangle) 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).

DL validation

The DL has been used to measure distance and speed during wheelchair tennis⁹ and rugby,³⁰ but only tested at moderate speeds ranging from 0.8 to 1.8 m/second.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 (i.e. compare two DL devices of the same model), two DL units were attached to each wheel, and their data were compared. While 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/second (minimum to maximum: 0.5–5.0 m/second). 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 (Figs. 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 (Fig. 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, 10 × 100 m; Trial B, 10 × 200 m; Trial C, 10 × 400 m, and Trial D, 10 × 800 m).

Tennis match-play

Data collection took place at the 2010 Wheelchair Tennis British Open in Nottingham. Tournament format and match play were in accordance with ITF rules.³⁴ The start and finish time for each game was recorded and used to calculate game length. APT was the sum total of game length values for a given set. ITF time limits for changeovers and breaks were strictly enforced. With Organizing Committee approval, each match was filmed using a Sony HDR HC7 Mini DV Handycam connected to a Raynox HD Superwide Angle Conversion Lens (0.5× 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 (Fig. 1) and one DL to the wheel on the non-racquet side. All matches were won or lost in three sets.

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).

Statistical analyses

Data analyses were conducted using SPSS version 19.0 (SPSS, Inc. Chicago, IL, USA). 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).³⁵ Ninety-five percent confidence intervals (95% CI) were calculated.³⁶ GPS and DL values for distance were compared with known distances for tennis field and linear track tests using the Bland Altman method.³⁷ 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 with fixed values. Fig. 4 shows a progressive underestimation for distance and speed at treadmill speeds > 2.5 m/second. The intra-model reliability for distance measured by left

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).

Table 1 Intra-model reliability measures for the DL during treadmill testing

Treadmill speed (m/second)	Distance (m)	
	DLL	DLR
<2.5	2.1 (499–505) [0.4%]	0.3 (503–508) [0.1%]
>2.5	17.5 (339–478) [4.4%]	72.3 (259–477) [19.9%]

Values are typical error (95% CI) [%CV].

and right DL devices is shown in Table 1. Both DL units reported good reliability at speeds <2.5 m/second. 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*. Fig. 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 Fig. 5A. Highest values for %CV were observed during drills involving a figure of eight movement (Fig. 3) for all devices. A one-way ANOVA with Tukeys' *post hoc* test revealed a lower mean speed for DLR against GPS (1.62 (0.21) vs. 1.54 (0.14) m/second, $P = 0.039$).

Linear track testing

Four trials (range, 100–800 m) were performed in one direction. Fig. 5B shows the agreement between measurement devices and the criterion during linear track testing. A one-way ANOVA revealed that 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 400 m 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 (100–400 m) for GPS. All

trials were undertaken at speeds <2.5 m/second. 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.²³ 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.²⁰ On an oval circuit, GPS distances of 125–1386 m are associated with a mean error of $4.8 \pm 7.2\%$, the magnitude of which decreases with an increase in distance.² For track-based testing, our data shows a reduced %CV with increased distance for GPS within trials conducted over a similar range (100–800 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.²⁰ 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,

Table 2 Distance for devices GPS and DL during tennis field and linear track testing

		Distance (m)								
Criterion		GPS			DLR		DLL			
Tennis field test										
Drill	I	27.4	24.6 (1.3) ^{a,c,d}	23.7–25.5	[5.2]	26.5 (0.7) ^{b,d}	27.2–28.2	21.2 (0.7) ^{a,b,c}	20.7–21.7	[3.1]
	II	36.3	31.4 (1.3) ^{a,c}	30.5–32.3	[4.3]	38.4 (3.0) ^{b,d}	40.5–44.7	33.4 (1.9) ^{a,c}	32.1–34.7	[5.5]
	III	69.5	62.1 (1.3) ^{a,c,d}	61.2–63.0	[2.1]	70.4 (0.7) ^b	71.2–72.2	66.4 (1.3) ^{a,b,c}	65.5–67.3	[1.9]
	I*	27.4	25.0 (1.3) ^{a,c}	24.1–25.9	[5.1]	21.3 (0.8) ^{a,b,d}	20.7–21.9	25.2 (0.8) ^{a,c}	24.6–25.8	[3.3]
	II*	36.3	34.1 (2.7) ^{a,d}	32.2–36.0	[7.9]	34.2 (1.3) ^{a,d}	33.3–35.1	38.6 (0.6) ^{a,b,c}	38.2–39.0	[1.5]
III*	69.3	63.1 (3.0) ^{a,d}	61.0–65.2	[4.8]	65.8 (0.5) ^{a,d}	65.4–66.2	69.4 (0.8) ^{b,c}	68.8–70.0	[1.1]	
Linear track test										
Trial	A	100	96 (4) ^a	93–99	[4.3]	98 (1)	98–99	98 (2)	97–99	[1.6]
	B	200	202 (7) ^d	197–207	[3.4]	198 (4)	195–201	195 (4) ^b	192–198	[1.9]
	C	400	409 (4) ^{a,c,d}	407–412	[0.9]	399 (5) ^{b,d}	395–402	393 (5) ^{a,b,c}	389–396	[1.3]
	D	800	804 (15) ^e	793–814	[1.8]	817 (5) ^{a,b}	814–821	811 (7) ^a	806–816	[0.9]

Values are mean (SD) 95% CI [%CV].
 *Denotes drill repeated in the opposite direction.
^aSignificantly different to criterion ($P < 0.05$).
^bSignificantly different to GPS ($P < 0.05$).
^cSignificantly different to DLR ($P < 0.05$).
^dSignificantly different to DLL ($P < 0.05$).
^eSignificantly different to DLL ($P < 0.05$).

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.³⁸ Second, a larger %CV was observed during tennis field testing for GPS, particularly for drills involving the figure 8 pattern. Such a drill is characterized 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.³⁸ An increased circle diameter also allows for increased chord measurement and hence, a more accurate estimation. Tennis court movement is multidirectional and non-random,⁴ 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.³⁸ 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,³⁹ and side-to-side movements may influence measurement accuracy. Satellite recruitment data were 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 utilize, 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 with a highly accurate Vicon Motion System.²³

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.³⁸ However, curves were much larger in circumference than those associated with the current

Figure 5 (A) 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. (B) Plot of GPS (▲), DLR (■), and DLL (●) mean difference (bias) during linear track testing. Error bars represent 95% limits of agreement.

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.³⁸ 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 show agreement and good reliability between DL and treadmill for speeds <2.5 m/second. This finding is consistent with initial validation of the device which reports agreement at speeds ranging from 0.8 to 1.8 m/second.²⁷ However, at higher speeds (>2.5 m/second), we report a decrease in measurement accuracy and reliability for DL, with

Table 3 Distance and speed for GPS and DL during competitive match play

	GPS		DL		<i>t</i>	<i>P</i>
Distance (m)						
Open	2891 (1000)	2377–3405	3963 (1340)	3274–4652	8.67*	0.0001
Quad	2675 (438)	2339–3012	3931 (505)	3543–4319	14.144*	0.0001
Combined	2816 (844)	2475–3157	3952 (1109)	3504–4400	13.050*	0.0001
Peak speed (m/second)						
Open	3.5 (0.4)	3.3–3.7	3.3 (0.6)	3.0–3.5	−2.302*	0.035
Quad	3.1 (0.2)	2.9–3.3	2.8 (0.4)	2.5–3.2	−2.090	0.070
Combined	3.4 (0.4)	3.2–3.5	3.1 (0.5)	2.9–3.3	−3.129*	0.004
Average speed (m/second)						
Open	0.8 (0.1)	0.7–0.9	1.0 (0.2)	0.9–1.1	7.862*	0.0001
Quad	0.6 (0.1)	0.5–0.7	0.9 (0.0)	0.8–0.9	5.440*	0.001
Combined	0.7 (0.2)	0.7–0.8	1.0 (0.2)	0.9–1.1	9.600*	0.0001

Values are mean (SD) 95% CI.

*Significant difference between GPS and DL ($P < 0.05$).

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.³³ 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/second. While 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/second 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. While 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 standardization 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*) while 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 while 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,⁴ 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 significantly show that 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 1 Hz systems.⁴⁰ Criterion distances were not available for match-play. Future work should ensure that an appropriate reference measure is provided. The Vicon Motion System,²³ or a computer-based tracking system² 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 and 5 Hz underestimate average and maximum speed by 10–30% in court-based movement drills,²³ and may lack sensitivity for the monitoring of movement during tennis. GPS units sampling at 15 Hz 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. While 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 m/second, values for DL distance and speed were significantly lower than known values. However, while 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 are 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.

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References

- 1 MacLeod H, Morris J, Nevill A, Sunderland C. The validity of a non-differential global positioning system for assessing player movement patterns in field hockey. *J Sports Sci* 2009;27(2):121–8.
- 2 Edgecomb SJ, Norton KI. Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian football. *J Sci Med Sport* 2006;9(1–2): 25–32.
- 3 Croft L, Dybrus S, Lenton J, Goosey-Tolfrey V. A comparison of the physiological demands of wheelchair basketball and wheelchair tennis. *Int J Sports Physiol Perform* 2010;5(3):301–15.
- 4 Roy JLP, Menear KS, Schmid MMA, Hunter GR, Malone LA. Physiological responses of skilled players during a competitive wheelchair tennis match. *J Strength Cond Res* 2006;20(3):665–71.

- 5 Diaper NJ, Goosey-Tolfrey V. A physiological case study of a paralympic wheelchair tennis player: reflective practise. *J Sports Sci Med* 2009;8(2):300–7.
- 6 Goosey-Tolfrey V, Moss A. Wheelchair velocity of tennis players during propulsion with and without the use of racquets. *Adapt Phys Act Q* 2005;22(3):291.
- 7 Mason BS, Porcellato L, van der Woude LH, Goosey-Tolfrey VL. A qualitative examination of wheelchair configuration for optimal mobility performance in wheelchair sports: a pilot study. *J Rehabil Med* 2010;42:141–9.
- 8 Kovacs M. Tennis physiology. *Sports Med* 2007;37(3):189–98.
- 9 Sindall P, Lenton JP, Tolfrey K, Cooper RA, Oyster M, Goosey-Tolfrey VL. Wheelchair tennis match-play demands: effect of player rank and result. *Int J Sports Physiol Perform* 2012; Epub 2012 August 1. PMID: 22868894.
- 10 Christmass MA, Richmond SE, Cable NT, Arthur PG, Hartmann PE. Exercise intensity and metabolic response in singles tennis (intensité de l'effort et réponse métabolique au cours de matchs de tennis en simple). *J Sports Sci* 1998;16(8):739–47.
- 11 Smekal G, Von Duvillard SP, Rihacek C, Pokan R, Hofmann P, Baron R. A physiological profile of tennis match play. *Med Sci Sports Exerc* 2001;33(6):999–1005.
- 12 Fernandez-Fernandez J, Mendez-Villanueva A, Fernandez-Garcia B, Terrados N. Match activity and physiological responses during a junior female singles tennis tournament. *Br J Sports Med* 2007; 41(11):711–6.
- 13 Fernandez-Fernandez J, Sanz-Rivas D, Fernandez-Garcia B, Mendez-Villanueva A. Match activity and physiological load during a clay-court tennis tournament in elite female players. *J Sports Sci* 2008;26(14):1589–95.
- 14 Mendez-Villanueva A, Fernandez-Fernandez J, Bishop D, Fernandez-Garcia B, Terrados N. Activity patterns, blood lactate concentrations and ratings of perceived exertion during a professional singles tennis tournament. *Br J Sports Med* 2007;41(5): 296–300.
- 15 Janssen TWJ, Dallmeijer AJ, van der Woude LH. Physical capacity and race performance of handcycle users. *J Rehabil Res Dev* 2001;38(1):33–40.
- 16 Moss AD, Fowler NE, Goosey-Tolfrey VL. A telemetry-based velocometer to measure wheelchair velocity. *J Biomech* 2003;36(2):253–7.
- 17 Goosey-Tolfrey VT, Mason B, Burkett B. The role of the velocometer as an innovative tool for paralympic coaches to understand wheelchair sports training and interventions to help optimise performance. *Sports Technol* 2012; Epub 1 June 2012. DOI:10.1080/19346182.2012.686503.
- 18 Sarro KJ, Misuta MS, Burkett B, Malone LA, Barros RML. Tracking of wheelchair rugby players in the 2008 demolition derby final. *J Sports Sci* 2010;28(2):193–200.
- 19 Barros RML, Misuta MS, Menezes RP, Figueroa PJ, Moura FA, Cunha SA. Analysis of the distances covered by first division Brazilian soccer players obtained with an automatic tracking method. *J Sports Sci Med* 2007;6:233–42.
- 20 Petersen C, Pyne D, Portus M, Dawson B. Validity and reliability of GPS units to monitor cricket-specific movement patterns. *Int J Sports Physiol Perform* 2009;4(3):381–93.
- 21 Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. *J Sci Med Sport* 2010;13(1):133–5.
- 22 Goosey-Tolfrey V, Castle P, Webborn N, Abel T. Aerobic capacity and peak power output of elite quadriplegic games players. *Br J Sports Med* 2006;40(8):684–7.
- 23 Duffield R, Reid M, Baker J, Spratford W. Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. *J Sci Med Sport* 2010;13(5):523–5.
- 24 International Tennis Federation. Dimensions [document on the internet]. 2011a [updated 2011 March; cited 2011 Nov 22]. Available from: <http://www.itftennis.com/technical/equipment/itfguidetotestmethods/dimensions.asp>
- 25 Morrow JR, Jackson AW, Disch JG, Mood DP. Criterion-referenced reliability and validity. In: Morrow JR (ed.) *Measurement and evaluation in human performance*. Leeds: Human Kinetics; 2010. p. 115–31.
- 26 Safrit MJ, Wood TM. Validity and reliability of criterion-referenced tests. In: Safrit MJ (ed.) *Introduction to measurement in*

- physical education and exercise science. St. Louis, MO: Mosby; 1995. p. 174–94.
- 27 Tolerico ML, Ding D, Cooper RA, Spaeth DM, Fitzgerald SG, Cooper R. Assessing mobility characteristics and activity levels of manual wheelchair users. *J Rehabil Res Dev* 2007;44(4): 561–72.
- 28 Oyster M, Karmarkar AM, Patrick M, Read M, Nicolini L, Boninger ML. Investigation of factors associated with manual wheelchair mobility in persons with spinal cord injury. *Arch Phys Med Rehabil* 2011;92:484–90.
- 29 Cooper RA, Tolerico M, Kaminski BA, Spaeth D, Ding D, Cooper R. Quantifying wheelchair activity of children: a pilot study. *Am J Phys Med Rehabil* 2008;87(12):977–83.
- 30 Spornier ML, Grindle GG, Kelleher A, Teodorski EE, Cooper R, Cooper RA. Quantification of activity during wheelchair basketball and rugby at the national veterans' wheelchair games: a pilot study. *Prosthet Orthot Int* 2009;33(3):210–7.
- 31 Schutz Y, Herren R. Assessment of speed of human locomotion using a differential satellite global positioning system. *Med Sci Sports Exerc* 2000;32(3):642–6.
- 32 Townshend AD, Worringham CJ, Stewart IB. Assessment of speed and position during human locomotion using non-differential GPS. *Med Sci Sports Exerc* 2008;40(1):124–32.
- 33 Ding D, Leister E, Cooper R, Spaeth D, Cooper R, Kelleher A. A wheelchair usage monitoring/logging system. Conference Proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. *IEEE Eng Med Biol Society Conf* 2005;7:6897–9.
- 34 International Tennis Federation. Rules of Tennis [document on the internet]. 2011b [updated 2011 February; cited 2011 Nov 23]. Available from: <http://beta.itftennis.com/wheelchair/organization/rules-regs.aspx>
- 35 Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med* 2000;30(1):1–15.
- 36 Armitage P, Berry G, Matthews JNS. Analysing means and proportions. In: Armitage P (ed.) *Statistical methods in medical research*. Oxford: Blackwell; 2002. p. 90–146.
- 37 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1:307–10.
- 38 Gray AJ, Jenkins D, Andrews MH, Taaffe DR, Glover ML. Validity and reliability of GPS for measuring distance travelled in field-based team sports. *J Sports Sci* 2010;28(12):1319–25.
- 39 Witte TH, Wilson AM. Accuracy of non-differential GPS for the determination of speed over ground. *J Biomech* 2004;37(12): 1891–8.
- 40 Barbero-Alvarez JC, Coutts A, Granda J, Barbero-Alvarez V, Castagna C. The validity and reliability of a global positioning satellite system device to assess speed and repeated sprint ability (RSA) in athletes. *J Sci Med Sport* 2010;13(2):232–5.