Title: The validity and reliability of a novel indoor player tracking system for use within wheelchair court sports

Running Title: Radio-frequency player tracking system

Keywords: disability sport, field-based testing, accuracy, radio-frequency, performance analysis

Abstract

The aim of the current study was to investigate the validity and reliability of a radio-frequency based system for accurately tracking athlete movement within the wheelchair court sports. Four wheelchair specific tests were devised to assess the system during i) static measurements ii) incremental fixed speeds iii) peak speeds, and iv) multi-directional movements. During each test, three sampling frequencies (4, 8 & 16 Hz) were compared to a criterion method for distance, mean and peak speeds. Absolute static error remained between 0.19-0.32 m across the session. Distance values (test ii) showed greatest relative error in 4 Hz tags (1.3%), with significantly lower errors seen in higher frequency tags (< 1.0%). Relative peak speed errors of < 2.0% (test iii) were revealed across all sampling frequencies in relation to the criterion (4.00 ± 0.09 $m \cdot s^{-1}$). Results showed 8 and 16 Hz sampling frequencies displayed the closest to criterion values, whilst intra-tag reliability never exceeded 2.0% coefficient of variation (% CV) during peak speed detection. Minimal relative distance errors (< 0.2%) were also seen across sampling frequencies (test iv). To conclude, the indoor tracking system is deemed an acceptable tool for tracking wheelchair court match-play using a tag frequency of 8 or 16 Hz.

Introduction

Understanding the movement demands placed upon an athlete during competition is a fundamental requirement for the prescription of specific, individualised training programmes. Player tracking has been extensively used within able-bodied (AB) team sports to explore movement demands, with basic notational techniques employed since the mid-1970's (Reilly & Thomas, 1976; Sanderson & Way, 1977). Advances in technology introduced more objective methods of player tracking, such as manual (O'Donoghue, 2002; Bloomfield, Polman, & O'Donoghue, 2004) and automatic video tracking techniques (Figueroa, Leite, & Barros, 2006; Barros et al., 2007). Currently, the use of Global Positioning Systems (GPS) has emerged as the most practical method ~~for~~ of player tracking ~~multiple player movements~~ to obtain a real time analysis of key performance variables (e.g. distance covered and speed profiles) ~~and movement patterns~~ during team sports (Cummins, Orr, O'Connor, & West, 2013). ~~This technology was first utilised to understand more about sports performance in the late 1990's (Schutz & Chambaz, 1997) and has been increasingly used by sport scientists in team sports environments since (Cummins, Orr, O'Connor, & West, 2013).~~

The validity of GPS during high intensity, intermittent sports~~ing~~ ~~environments~~ has been comprehensively examined (MacLeod, Morris, Nevill, & Sunderland, 2009; Duffield, Reid, Baker, & Spratford, 2010; Coutts & Duffield, 2010; ~~Portas, Harley, Barnes, & Rush 2010;~~ Johnston et al., 2012). ~~These i~~Investigations suggest that GPS accurately tracks players during low-speed (< 1.8 m·s⁻¹) movements (Portas, Rush, Barnes, & Batterham, 2007),~~.~~ ~~However, during high-speed movements (> 4 m·s⁻¹) greater~~ with distance and speed errors (5-20%) increasing exponentially during high-speed (> 4 m·s⁻¹) movements ~~were reported~~ (~~Petersen, Pyne, Portus, & Dawson, 2009;~~ Duffield et al., 2010;~~ Gray, Jenkins, Andrews, Taaffe, & Glover, 2010;~~ Johnston et al., 2012). Recent studies have also revealed that the validity and reliability of GPS improves when higher sampling frequencies (10 Hz) are used, ~~which is likely to have contributed~~ contributing towards the magnitude of these aforementioned errors (~~Petersen et al., 2009;~~ Jennings, Cormack, Coutts, Boyd, & Aughey, 2010; Castellano et al., 2011; Varley, Fairweather, & Aughey, 2012).

A major limitation with GPS is its reliance on satellite signals, restricting its use to an outdoor environment only (Larsson, 2003). As a result, indoor team sports such as wheelchair basketball and wheelchair rugby (known collectively as the wheelchair court sports), cannot utilise GPS. Consequently, image-based processing techniques (Sarro, Misuta, Burkett, Malone, & Barros, 2010) and wheel mounted magnetic reed-switch devices (Sporner et al., 2009; Sindall et al., 2013a) have been employed in an attempt to determine the demands of the wheelchair court sports. ~~Unfortunately, there are limitations associated with both these techniques.~~ However, ~~I~~image-based processing techniques require time consuming analysis to be performed post event (Barris & Button, 2008), which introduces accuracy and reliability issues due to a heavy reliance on manual digitisation (Lames & Siegle, 2011) along with a delay in feedback time to coaches. Subsequently, data collection is often restricted to small sample sizes, affecting the power of such investigations. Substantial errors in measurement reliability (19.9% coefficient of variation [% CV]) have also been reported within magnetic reed-switch devices at speeds in excess of 2.5 $m \cdot s^{-1}$ (Sindall et al., 2013b). Such speeds are frequently exceeded by elite wheelchair athletes (Goosey-Tolfrey & Moss, 2005; Mason et al., 2009; 2012), which questions the suitability of existing reed-switch devices for use within elite wheelchair court sport applications.

Radio-frequency tracking systems have emerged, which gather similar data to GPS, with both the Local Position Measurement (LPM) system (Frencken, Lemmink, & Delleman, 2010; Ogris et al., 2012) and the Wireless Ad-hoc System for Positioning (WASP) (Hedley et al., 2010; Sathyan, Shuttleworth, Hedley, & Davids, 2011) currently available. These systems rely on distance measurements between known fixed base stations and mobile tags worn by the athlete (Leser, Baca, & Ogris, 2011). A key advantage of ~~these~~ radio-frequency systems is that they can function indoors (Sathyan, Humphrey, & Hedley, 2011). Unfortunately, these systems are still in their relative infancy, particularly for sporting applications and as a result little is known about their validity and reliability. Initial validation of the LPM system when sampling at 45 Hz, highlighted the typical error of the estimate increased (1.8-3.9% CV) at higher movement speeds (Frencken et al., 2010). In support of this, Ogris et al. (2012) confirmed error values increased (10% error) during high speed movements, yet the LPM system provided valid speed estimations at low speeds (< 6 $km \cdot h^{-1}$). More recently, validation of the WASP system when sampling at 10 Hz, revealed an overestimation (2.7%) in distance travelled during dynamic testing (Sathyan et al., 2012). Unfortunately, the analysis was confined to a basic linear and non-linear drill at self-regulated speeds (not defined), which may not adequately reflect athlete movements seen during match-play.

A new, radio frequency-based indoor tracking system (ITS) has recently been developed, which utilises ultra-wideband (UWB) signals to communicate with compact tags worn by athletes, providing real-time analysis on movement parameters. The additional benefit of the ITS is the incorporation of smaller, lightweight tags (size = 40 x 40 x 10 mm; mass = 25 g), opposed to the larger tags used with the ~~WASP (90 x 50 x 25 mm; mass = 50 g)~~

~~and~~ LPM (92 x 57 x 15 mm; mass = 60 g) and WASP (90 x 50 x 25 mm; mass = 50 g) systems. Subsequently, the ~~system~~ ITS may be a more practical solution since minimal disruption would be imposed on athletes during competition and training environments. T~~herefore t~~he aims of the current study were: (1) to investigate the validity and reliability of the ITS during movements and speeds specific to the wheelchair court sports and (2) to determine the effect of different sampling frequencies on the system's measurement accuracy.

Methods

Participants

Two physically active, able-bodied males (age: 30.0 ± 2.0 years, mass: 82.5 ± 9.2 kg, height: 1.81 ± 0.04 m) with extensive experience of wheelchair propulsion volunteered to participate in the current investigation. The study was approved by the University's local ethical advisory committee, with informed consent gained prior to participation.

Equipment

The ITS (Ubisense, Series 700 IP, Cambridge, UK) is a wired radio-frequency based real-time location system. The system has an overall bandwidth of 137 Hz and is comprised of six sensors that communicate with compact tags. The sensors detect UWB signals from the tags, measuring both the angle-of-arrival and the time-difference-of-arrival to generate an accurate tag location. This provides raw data on the positional coordinates of a tag in three dimensions. Raw data is then filtered using a 3-pass sliding-average filter with a window width proportional to the tag frequency.

The validity and reliability of the ITS was assessed during one session using four separate tests i) static measurements; ii) incremental fixed speeds; iii) peak speeds; iv) multi-directional movements. Movement parameters detailed by the ITS were derived using software developed specifically for wheelchair court sports at the University of Nottingham. All dynamic tests (ii, iii & iv) were performed in a rugby wheelchair (Melrose Wheelchairs, New Zealand: mass = 12.7 kg; wheel size = 0.591 m; tyre pressure = 120 psi; camber = 18º). The criterion measurement for distance (tests ii & iv) was provided by a laser total station (Leica TS-30, Leica Geosystems, UK), more commonly used within a professional surveying environment. The Leica system utilises high quality angle and distance measurements with automatic target tracking to produce accurate coordinates (~0.004 m) about the point of interest (Bayoud, 2006). The total station was positioned on a balcony overlooking the entire court, ensuring a consistent, unobstructed view throughout each test. Wireless timing gates (Brower Timing Systems, Draper, UT) were used to record the mean speed (tests ii and iv), whilst a wireless inertial sensor (Ellul, Lo, & Yang, 2011), attached to the right axle of the wheelchair provided the criterion measurement for peak speed (test iii). In brief, the inertial sensor is a small, lightweight device (size = 20 x 30 x 17 mm; mass = 10 g) that transmits data wirelessly at a sampling frequency of approximately 50 Hz. This device has previously been validated during linear wheelchair propulsion (Mason, Rhodes, & Goosey-Tolfrey, 2013a), reporting speed errors < 0.9% CV observed across a range of speeds up to 6 $m \cdot s^{-1}$.

Procedures

The ITS was set up in an indoor sports hall equipped with wooden sprung flooring to replicate the playing surface used during wheelchair basketball and wheelchair rugby. The six sensors were located around the perimeter of a regulation size wheelchair basketball and wheelchair rugby court (28 x 15 m). The sensors were positioned at each of the four corners of the court, with two additional sensors positioned at the half-way line. Each sensor was mounted on an extendable tripod, elevated approximately 4 m high. The orientation of each sensor was configured so that the pitch was 40° from the horizontal and the rotation about the perpendicular line from the sensor face was fixed at 0°, maximising court coverage. Prior to data collection the system was calibrated using two reference points of known coordinates, which were calculated by a laser distance measurer (PLR 50, Bosch, Germany). This enabled precise sensor locations to be determined. A static tag placed in another known location was then used to calibrate the system. This procedure takes multiple measurements from the static tag using its known x, y and z coordinates to determine the orientation and offset off each sensor (Mandeljc, Perš, Kristan, & Kovačič, 2012). During all dynamic tests (tests ii, iii & iv) nine tags were monitored, with three tags sampling at a low (4 Hz), medium (8 Hz), and high (16 Hz) frequency, which were secured to the wheelchair as demonstrated in Figure 1.

****INSERT FIGURE 1 HERE****

i) Static measurements

The accuracy of a motionless tag was assessed by individually placing three tags of different sampling frequency (low, medium and high) in each of the four corners of the court (where known coordinates exist). Based on previous protocols (Frencken et al., 2010; Sathyan et al.,

2012) data was collected from each tag for 20 seconds. This assessment was performed at the beginning of the session (pre) and then repeated 4 hours later at the end of the session (post) to determine whether the system was prone to drift over time.

ii) Incremental fixed speeds

The accuracy of the system for detecting distance measurements was assessed over increasing fixed speeds using a 'figure of eight' course (Figure 2). One participant completed five laps of the course at three fixed sub-maximal speeds (4 $km \cdot h^{-1}$, 6 $km \cdot h^{-1}$, and 8 $km \cdot h^{-1}$), with five trials conducted at each speed. The speeds selected are commonly used within previous sub-maximal wheelchair propulsion literature (Vanlandewijck, Spaepen & Lysens, 1994; Mason, Lenton, Leicht, & Goosey-Tolfrey, 2013b). This range also covers the speeds typically averaged during wheelchair court sports match-play (Sporner et al., 2009; Sarro et al., 2010). The speeds were averaged throughout each trial through using a Raleigh SP-20 speedometer (Raleigh Ltd, Nottingham, UK). The display monitor was secured to the participant's knee, providing instantaneous feedback about their average speed. The participant was instructed to maintain these speeds, on average, throughout each trial.

****INSERT FIGURE 2 HERE****

iii) Peak speeds

To assess the accuracy of the system for the detection of peak speeds, a 20 m linear wheelchair sprint was performed. One participant completed all ten trials from a standstill. After each maximal effort, sufficient recovery time was permitted before each subsequent sprint.

iv) Multi-directional movements

In order to determine the accuracy of a player tracking system, the experimental design has to satisfy the demands of the activity to which the system will be exposed (Siegle et al., 2013). A multi-directional drill was performed aimed to replicate the frequency and intensity of movements performed during wheelchair court sports match-play. Two participants performed 4 x 8-min trials in an alternate order to avoid the possibility of fatigue affecting the quality of the trials, resulting in a total of 8 x 8-min trials. The participants were instructed to incorporate numerous changes in speed and direction to replicate the acceleration, agility and sprinting manoeuvres deemed vital to wheelchair court sport athletes (Vanlandewijck, Theisen, & Daly, 2001). The total distances covered and mean speeds were collected during each trial.

Statistical analysis

Data analysis was performed using the Statistical Package for the Social Sciences (SPSS version 19, Chicago, IL). Normality and homogeneity of variance were confirmed by Shapiro-Wilk and Levene's tests, respectively.

Criterion validity of the performance variables measured by the ITS were analysed using 95% limits of agreement (LOA), displaying the systematic bias ± random error demonstrated for each variable (Bland & Altman, 1986). During test ii, validity was also compared to criterion measures using the typical error of the estimate (TEE) and expressed in raw units (± 95% confidence limits). A one-way repeated measures analysis of variance (ANOVA) was used to examine the mean differences in performance variables within and between each of the three different sampling frequencies compared to criterion measures across all tests. Statistical significance was accepted when $P < 0.05$. Effect sizes (ES) were calculated to determine the meaningfulness of any differences, whereby ES < 0.3 reflected a small effect (Cohen, 1992), with 95% confidence intervals for differences (95% CI) also presented ~~analysed~~. Intra-tag reliability was reported as a coefficient of variation (% CV) between the tags for each specific test.

Results

(i) Static measurements

The mean absolute error during pre-session measurements did not significantly differ between low (0.24 ± 0.27 m), medium (0.26 ± 0.25 m) and high (0.32 ± 0.25 m) frequency tags ($P \geq 0.72$; ES ≤ 0.1), as demonstrated in Figure 3. No significant differences in post session values were revealed between low (0.26 ± 0.24 m), medium (0.26 ± 0.24 m) or high frequency (0.19 ± 0.20 m) tags ($P \geq 0.92$; ES ≤ 0.2). No significant differences between pre and post session measurements were found at any sampling frequency ($P \geq 0.15$; ES ≤ 0.2). Intra-tag reliability results revealed that sampling frequency had no effect on reliability with a 1.0% CV demonstrated across all frequencies during pre and post session measurements.

****INSERT FIGURE 3 HERE****

(ii) Incremental fixed speeds

The TEE for distance revealed that minimal errors existed during high and medium fixed speeds (0.98-1.09 m), however values increased during low fixed speed (1.85-2.11 m) as displayed in Table 1. A significant difference existed between criterion measures and low (P = 0.0005; ES = 0.9; 95% CI = 7.3 to 10.4), medium (P = 0.005; 95% CI = 6.2 to 8.2; ES = 0.8~~; 95% CI = 6.2 to 8.2~~), and high (P = 0.005; 95% CI = 4.5 to 6.6; ES = 0.8~~; 95% CI = 4.5 to 6.6~~) sampling frequencies during low fixed speeds. However, no significant differences were observed during the medium and high fixed speeds ($P \geq 0.12$; ES ≤ 0.7). Typical error of the estimate values for mean speed demonstrate the ITS to be consistent (0.01 $m \cdot s^{-1}$) across all sampling frequencies at each fixed speed. Although low frequency tags displayed the greatest absolute differences to criterion values (Table 1), no statistically significant difference was observed between sampling frequencies for mean speed ($P \geq 0.15$; ES ≤ 0.4). Intra-tag reliability results indicated that the error range across fixed speeds to be greatest within low frequency tags (0.1-0.6% CV). This error range decreased at both medium (0.2-0.4% CV) and high (0.2-0.3% CV) sampling frequencies.

****INSERT TABLE 1 HERE****

(iii) Peak speeds

Mean criterion values were found to be 4.00 ± 0.09 $m \cdot s^{-1}$ during maximal sprint trials. In comparison, mean tag values for each sampling frequency were 4.07 ± 0.14 $m \cdot s^{-1}$ (low), 4.05 ± 0.15 $m \cdot s^{-1}$ (medium), and 4.00 ± 0.12 $m \cdot s^{-1}$ (high). A significant difference was revealed between both low (P = 0.001; 95% CI = -0.17 to -0.01; ES = 0.3~~; 95% CI = -0.17 to -0.01~~) and medium (P = 0.005; 95% CI = -0.19 to -0.03; ES = 0.2~~; 95% CI = -0.19 to -0.03~~) sampling frequencies in relation to the criterion measure, with positive systematic bias ± random errors of 0.08 ± 0.17 $m \cdot s^{-1}$ and 0.05 ± 0.10 $m \cdot s^{-1}$ respectively (Figure 4). Intra-tag reliability was greater within low frequency tags (2.7% CV), and improved as sampling frequency increased (medium = 2.0% CV; high = 1.6% CV).

****INSERT FIGURE 4 HERE****

(iv) Multi-directional movements

Mean criterion distance measurements were 999 ± 65 m during the multi-directional test. In comparison, mean distance values for each sampling frequency were 997 ± 63 m (low), 999 ± 63 m (medium) and 998 ± 62 m (high). Criterion values for mean speed were 2.08 ± 0.14 $m \cdot s^{-1}$. Alternatively, ITS mean speed values showed 2.08 ± 0.13 $m \cdot s^{-1}$ (low), 2.08 ± 0.13

$m \cdot s^{-1}$ (medium), and 2.07 ± 0.13 $m \cdot s^{-1}$ (high). Systematic bias and random error values for distance and mean speed during the 8-minute multi-directional test are illustrated in Figure 5. Distance results show the low and medium frequency tags to demonstrate similar systematic bias ± random error (5 ± 10 m), which were improved in the high frequency tags (3 ± 6 m). Yet, no significant difference was observed between any tag frequency and the criterion measure for distance covered ($P \geq 0.54$; ES ≤ 0.1). Systematic bias ± random error results for mean speed remained consistent across all sampling frequencies (0.01 ± 0.02 $m \cdot s^{-1}$). Again, no significant differences were identified between all sampling frequencies and the criterion measure for mean speed ($P \geq 0.71$; ES ≤ 0.1). Intra-tag reliability results revealed 0.5% CV for both distance and mean speed in low and medium frequency. High frequency tags revealed values of 0.2% CV and 0.4% CV for distance and mean speed respectively.

****INSERT FIGURE 5 HERE****

Discussion

The aim of the current study was to investigate the validity and reliability of a radio-frequency based system for accurately tracking wheelchair athletes during their expected movements of on-court match-play. The results confirmed that the ITS was a suitable system for quantifying both static and dynamic measurements specific to wheelchair court sports. It was also revealed that sampling frequency influenced validity, particularly at peak speeds, which has implications on optimal tag frequency selection for wheelchair court sports applications.

Static measurements

The ITS elicited static errors ranging between 0.19-0.32 m and were not found to be influenced by tag sampling frequency. These values are higher than those previously reported for the LPM (0.02 m) and WASP (0.12-0.18 m) radio frequency systems (Frencken et al., 2010; Sathyan et al., 2011). Despite this, the current investigation repeated the static measurements at the end of the testing session and importantly revealed that error did not significantly drift over a 4 hour time period. From a practical perspective, this demonstrates that the ITS is capable of working effectively for the duration of wheelchair basketball (~90 minutes) and wheelchair rugby (~60 minutes) match-play. In addition, the ITS can also be used during prolonged periods, such as multiple tournament games (3-4 matches per day) and training camps, without the concern of measurement drift.

Incremental fixed speeds

Under controlled testing at incremental fixed speeds (test ii) the ITS demonstrated extremely low errors for the assessment of distance covered. As expected, these errors were influenced by movement speed. However, it was observed that the magnitude of error was reduced at the higher speed, which contradicts the patterns observed by previous GPS (Peterson, Pyne, Portus, & Dawson, 2009; Gray, Jenkins, Andrews, Taaffe, & Glover, 2010), radio-frequency (Frencken et al., 2010; Ogris et al., 2012), and magnetic reed-switch device literature (Sindall et al., 2013b). These differences may be attributed to the filtering process used by the ITS, as if a small error exists in a specific court location, the filtering process used may exacerbate the error at low speeds, where more data points are collected for a given area. Since low point (< 1.5) wheelchair rugby players exhibit mean speeds of 0.78-1.12 $m \cdot s^{-1}$ during match-play (Sporner et al., 2009; Sarro et al., 2010), it is imperative that the system works effectively at these lower speeds. However, despite the fact the distance error was greater at low speeds it must be reinforced, that these errors were still extremely small (1.96-2.11 m TEE) and are therefore deemed acceptable for the current application.

The influence of sampling frequency can be seen during this drill, with low frequency tags demonstrating the greatest relative distance error values (1.3%), with significantly lower relative errors seen in medium (1.0%) and high frequency tags (0.8%). In agreement with this, mean speed results also revealed low frequency tags to display the greatest relative differences during fixed speed testing (1.4%), with significantly lower relative errors seen in medium (0.7%) and high frequency tags (0.5%). Nevertheless, TEE values for mean speed were minimal (0.01) and remained consistent across all fixed speeds regardless of sampling frequency.

Peak speeds

The current study revealed that during maximal sprinting, the ITS displayed relative errors < 2.0% in peak speeds. This compares favourably to the greater relative error of approximately 20% for GPS (Duffield et al., 2010), 10% in radio frequency (Ogris et al., 2012) and 10% for magnetic reed-switch devices (Sindall et al., 2013b). Previous research has discussed the importance of accurately quantifying high intensity movements to facilitate the design of athlete training programmes (Dwyer & Gabbett, 2012). Recent studies have implemented the use of speed zones relative to an individual's peak speed in order to monitor performance and prescribe training programmes (Venter et al., 2011; Cahill et al., 2013). In order for this approach to be effective, the system must be capable of accurately quantifying peak speeds, which the present results have confirmed.

It was also clear that tag frequency played a critical role in accurately identifying peak speeds. Higher tag frequencies (8 and 16 Hz) demonstrated a reduction in random error (< 0.10 $m \cdot s^{-1}$) compared to low frequency tags (0.17 $m \cdot s^{-1}$). Given the peak speed values obtainable by wheelchair basketball (4.45-4.53 $m \cdot s^{-1}$) and wheelchair rugby (3.56-3.69 $m \cdot s^{-1}$) players during maximal sprinting (Mason et al., 2009; 2012), coupled with the frequency with which high-intensity movements are likely to be performed (Vanlandewijck et al., 2001) low sampling frequency tags were therefore not deemed suitable for the current application.

Multi-directional movements

An advantage of the current investigation was the inclusion of a test which assessed the ITS during the type and intensity of movements that the system was intended to be used for (Siegle et al., 2013) i.e. wheelchair court sports. Distance errors revealed when performing multi-directional movements were very low, with absolute errors < 2 m across sampling frequencies, resulting in relative errors < 0.2%. The magnitude of error for the ITS was much smaller than the relative distance errors of 5.8% associated with GPS (Duffield et al., 2010), 4.8% with video tracking techniques (Edgecomb & Norton, 2006) and 1.6-2.7% found in radio-frequency systems (Frencken et al., 2010; Ogris et al., 2012) during sport specific movements.

During this drill, minimal absolute differences in distance (1-2 m) were seen when comparing sampling frequencies. Additionally, similar findings were observed in the mean speed results, with relative errors consistent (< 0.3%) irrespective of sampling frequency. Clearly, the influence of sampling frequency seems to be more prevalent during the incremental fixed speed test (test ii) than the current test. In line with previous research, this suggests that the validity of distance measures improves with longer duration activities (Jennings et al., 2011; Cummins et al., 2013). Accordingly, the selection of sampling frequency for the assessment of distance and mean speed may be less important during wheelchair court sport match-play. Despite this, optimal sampling frequency must be considered for an accurate detection of peak speeds during this application.

Determining the optimal tag sampling frequency depends on both the overall bandwidth of the system and the nature of the sport. The likelihood of competition testing during wheelchair court sports consists of monitoring 8-10 players at a given time, yet given the overall bandwidth of the system (137 Hz), high frequency tags (16 Hz) would not be feasible for all players. Hence, low or medium sampling frequency tags would be required. Yet, by varying the sampling frequencies within the present study, the differences observed have established that adopting a methodology that uses high (16 Hz) or medium (8 Hz) sampling frequency would be most acceptable for wheelchair court sports match-play.

Limitations and future recommendations

A limitation of the current study was the use of linear 20 m sprints to assess high intensity activities, since these movements are often multidirectional and interspersed in between lower intensity movements in wheelchair sports (Vanlandewijck et al., 2001). However owing to limitations with the availability of alternative equipment available to act as a valid and reliable criterion measure this was not possible. Previous research has also discussed the importance of quantifying activity into relative and arbitrary speed thresholds to facilitate training programme development (Dwyer & Gabbett, 2012; Cahill et al., 2013). It could be argued that an assessment of these parameters may have been beneficial in the context of the current investigation. However, given the favourable performance in the detection of peak speeds, it is anticipated that the ITS should adequately determine these parameters. Given the validity and reliability of the ITS in a wheelchair court sport setting, future investigations are recommended to utilise the system to quantify the demands of these sports. This would build on the limited existing knowledge within the wheelchair court sports (Sarro et al., 2010) and facilitate exercise prescription specific to the needs of individual athletes. D~~d~~espite the current focus on wheelchair courts sports, it is possible that the ITS can also be used successfully within other indoor ~~team~~ sports. However, it is highly recommended that a validation protocol specific to these sports are employed first.

Conclusion

The results of the present study revealed that a novel radio frequency ITS provided an accurate and reliable quantification of the movement parameters specific to the wheelchair court sports. Given the greater degree of accuracy for detecting peak speeds, a high sampling frequency (≥ 8 Hz) was recommended for use within wheelchair court sports.

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Figure Legends

Figure 1: The location of the nine tags fixed to the wheelchair during dynamic tests. Inset is the sampling frequency for each tag with regards to its location.

Figure 2: The 'figure of eight' drill used to assess distance during incremental fixed speeds. The solid middle horizontal line represents the location of the timing gates and the start/finish of the drill (a = 8 m, b = 12.25 m; lap = 81 m; total distance = 405 m).

Figure 3: Plot of mean static error for each sampling frequency during pre and post session. Error bars represent standard deviation.

Figure 4: Plot of mean error (bias) for each frequency during maximal sprint tests ($m \cdot s^{-1}$). Error bars represent 95% LOA. * represents a significant difference between sampling frequency and criterion.

Figure 5: Plot of mean error (bias) for distance (m) and mean speed ($m \cdot s^{-1}$) during the multi-directional test. Error bars represent 95% LOA.

Table 1. Distance and mean speed values during movement at incremental fixed speeds (test ii)

	Distance (m)							Mean Speed ($m \cdot s^{-1}$)						
Speed	Criterion	Low Freq	TEE	Med Freq	TEE	High Freq	TEE	Criterion	Low Freq	TEE	Med Freq	TEE	High Freq	TEE
Low	395	404 (399-409)	1.96	402 (399-406)	1.85	400 (398-404)	2.11	1.14	1.17 (1.15-1.19)	0.01	1.16 (1.14-1.18)	0.01	1.15 (1.14-1.17)	0.01
Med	394	398 (397-399)	1.03	398 (396-400)	1.04	396 (394-398)	1.09	1.55	1.57 (1.52-1.60)	0.01	1.56 (1.51-1.60)	0.01	1.56 (1.51-1.59)	0.01
High	394	397 (394-400)	1.06	397 (395-401)	1.00	396 (394-399)	0.98	2.01	2.03 (1.97-2.07)	0.01	2.02 (1.96-2.06)	0.01	2.01 (1.95-2.05)	0.01

Mean values (95% confidence limits)

TEE expressed as raw units