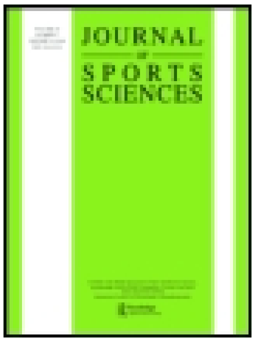

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Validity of an ultra-wideband local positioning system to measure locomotion in indoor sports

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ABSTRACT

The validity of an Ultra-wideband (UWB) positioning system was investigated during linear and change-of-direction (COD) running drills. Six recreationally-active men performed ten repetitions of four activities (walking, jogging, maximal acceleration, and 45º COD) on an indoor court. Activities were repeated twice, in the centre of the court and on the side. Participants wore a receiver tag (Clearsky T6, Catapult Sports) and two reflective markers placed on the tag to allow for comparisons with the criterion system (Vicon). Distance, mean and peak velocity, acceleration, and deceleration were assessed. Validity was assessed via percentage least-square means difference (Clearsky-Vicon) with 90% confidence interval and magnitude-based inference; typical error was expressed as within-subject standard deviation. The mean differences for distance, mean/peak speed, and mean/peak accelerations in the linear drills were in the range of 0.2–12%, with typical errors between 1.2 and 9.3%. Mean and peak deceleration had larger differences and errors between systems. In the COD drill, moderate-to-large differences were detected for the activity performed in the centre of the court, increasing to large/very large on the side. When filtered and smoothed following a similar process, the UWB-based positioning system had acceptable validity, compared to Vicon, to assess movements representative of indoor sports.

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KEYWORDS
Ultra-wideband; LPS; validity; tracking; Clearsky

Introduction

The ability to accurately quantify the position and locomotion of athletes can influence training prescription, load monitoring, injury prevention and rehabilitation processes, and tactical decisions during a match.

The technological advancement of tracking devices in the last two decades has resulted in both an increased scientific research activity and a wider adoption of this technology by sporting clubs and associations. In particular, there has been an exponential increase in the number of research studies investigating different applications and methodological aspects of commercial global positioning system (GPS) devices used for outdoor sports (Malone, Lovell, Varley, & Coutts, 2016). As a result of the significant body of knowledge with respect to GPS in sport, it is now well acknowledged that this technology has acceptable validity and reliability to measure locomotion in athletes when the sampling rate is at least 10 Hz (Scott, Scott, & Kelly, 2016; Varley, Fairweather, & Aughey, 2012).

Conversely to what has been described for outdoor positioning systems, there is very little research available regarding the accuracy, validity and reliability of indoor positioning systems (IPS) to track athletes in indoor sports such as futsal, basketball, handball and netball. Many different technologies are currently available to track objects and people in indoor environments, such as Radio Frequency Identification (RFID), Wireless Local Area Network (WLAN), Bluetooth®, optical methods such as computer vision, and Ultra-wideband (UWB). Most of these technologies are used in industries such as supply chain logistics and engineering, and have different advantages and disadvantages mainly in regards to their cost, the strength of the signal, the dependence on line-of-sight between receivers and transmitters, and the susceptibility to interference (Alarifi et al., 2016).

Radio Frequency Identification has been the main technology adopted by companies to provide the possibility to track athletes in indoor settings. This technology usually employs proximity as the main principle to detect position and it operates on a bandwidth up to 930 MHz (Mautz, 2012). The validity of RFID systems, such as Inmotiotec (Inmotiotec GmbH, Austria) and the Wireless Ad hoc System for Positioning (WASP, Commonwealth Scientific and Industrial Research Organisation, Australia (Hedley et al., 2010)) has been previously assessed (Ogris et al., 2012; Sathyan, Shuttleworth, Hedley, & Davids, 2012; Sweeting, Aughey, Cormack, & Morgan, 2017). These studies found an absolute error for positioning estimation between 11.9 ± 4.9 and 23.4 ± 20.7 cm (Ogris et al., 2012; Sathyan et al., 2012), a mean error for distance across different locomotion drills of 1.26 – 3.87 % (Sathyan et al., 2012), and a mean error for average and maximal velocity up to 3.54 % and 13.15 %, respectively (Ogris et al., 2012). While the results of these studies show an acceptable level of accuracy, RFID suffers from signal instability and is susceptible to interference (Alarifi et al., 2016).

A more recent technology, UWB, may overcome limitations of RFID related to signal instability and interference, and

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therefore have applications in indoor sport settings (Alarifi et al., 2016). Ultra-wideband is defined as a radiofrequency signal that has a fractional bandwidth ≥ 0.20 than the centre frequency, or has a bandwidth ≥ 500MHz irrespective of the fractional bandwidth (FCC; Mautz, 2012). Despite the high cost of UWB equipment, this technology offers the advantage of high precision, a signal that is capable of penetrating most materials, and less susceptibility to interference (Alarifi et al., 2016).

To the best of our knowledge, two studies have investigated the accuracy, validity and reliability of a UWB-based tracking system in indoor settings (Leser, Schleindlhuber, Lyons, & Baca, 2014; Rhodes, Mason, Perrat, Smith, & Goosey-Tolfrey, 2014). One study assessed validity of one system (Ubisense ltd., UK) during basketball-specific drills, and reported a relative error of 3.45 ± 1.99 % for distance (Leser et al., 2014). However, a trundle wheel was used as a criterion measure, distance was the only variable assessed, and the receiver tags were placed on the participant's head, therefore limiting the applicability of the results to real sporting settings. A more comprehensive study assessed the accuracy, validity and reliability of the same system for use in wheelchair sports (Rhodes et al., 2014). The results presented an absolute positioning error of 19–32 cm depending on the sampling rate, a relative error <1 % for distance and mean speed, and <2 % for peak speed during linear drills, with errors being as low as 0.3 % for multidirectional drills (Rhodes et al., 2014). The coefficient of variation assessing intra-tag reliability was <2 % in all conditions when sampling at 8 Hz or higher. However, due to the nature of the activity, only peak speeds of ~4 m.s^{-1} were achieved, perhaps limiting the generalisability of the findings.

Therefore, the aim of the present study was to assess the criterion validity of a new UWB positioning system during linear and change-of-direction drills for general application to indoor sports.

Methods

Participants and experimental overview

Six recreationally-active men (29.2 ± 4.1 years old, 179.0 ± 8.2 cm, 75.9 ± 7.3 kg) volunteered to take part in this study, which was approved by the investigators' university Human Research Ethics Committee. Participants were asked to attend two testing sessions separated by one week. In the first session, participants performed ten repetitions of four different locomotion activities (self-paced walking, jogging, maximal acceleration, and 45º change of direction) over a course located in the middle of an indoor, parquet-floor court. During the second session, participants repeated the exact same protocol with the activities performed on one side of the court, with the aim of investigating possible differences due to the location of the tags on the court in relation to the position of the anchors (Figure 1). During all trials participants wore a receiver tag (Clearsky T6, Catapult Sports, Australia) placed inside a vest between the scapulae, and two passive reflective markers were placed on the pouch containing the receiver tag to allow for comparisons with the positioning derived from the criterion system (Vicon). The two testing sessions were undertaken in separate days due to the length of the data collection process and to try minimise differences in the light, which could have occurred if data were collected in different moments of the day and could have affected the VICON setup.

Locomotion activities

Participants performed four different activities in the following order:

(i) a maximal change of direction at 45º either left or right (COD45) over a total distance of approximately 5.5 m,
(ii) a self-paced walk over a linear course of 12 m,

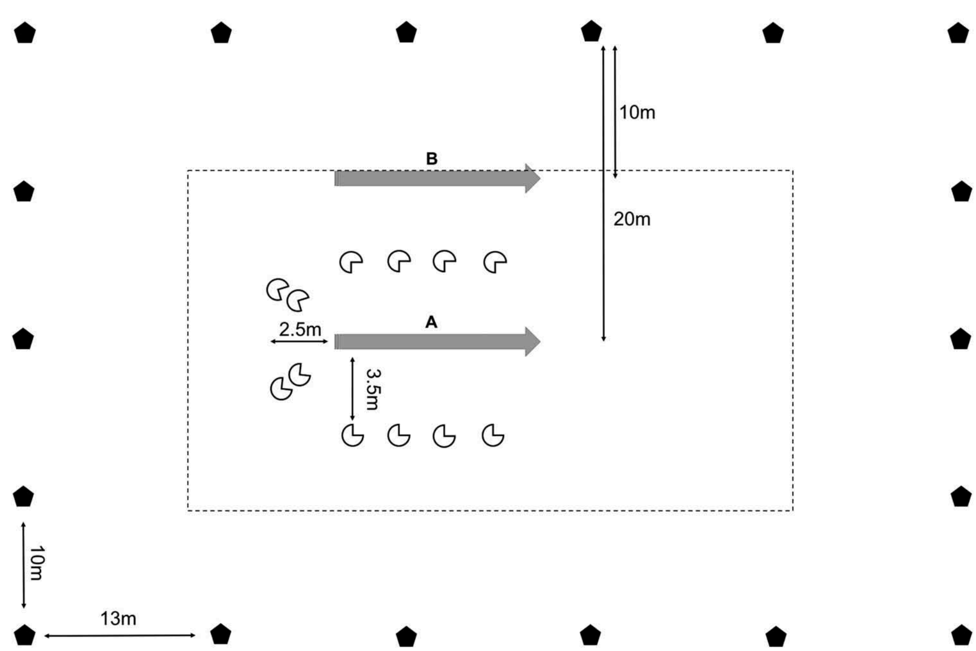

Figure 1. Schematic representation of the data collection set up (a, centre of the court; b, side of the court), with particular reference to the location of the Clearsky anchors (black pentagons) and the Vicon cameras (indented circles).

(iii) a self-paced jog over a linear course of 12 m, and
(iv) a maximal acceleration over a linear course of 12 m.

Distance, mean and peak velocity, mean and peak acceleration, and mean and peak deceleration were calculated from the raw data and utilised for the analysis.

Clearsky T6 system specifications

The set up used in this study consisted of 18 anchors positioned as presented in Figure 1. All anchors were installed at a height of 4.8 m from the ground. The laptop used for data processing was connected to the master anchor via Ethernet cabling. Data was collected at 10 Hz and processed via Openfield™ console software version 1.13.4 (Beta release, Catapult Sports, Melbourne, Australia). The system is based on ultra-wideband technology in the frequency range of 3.1–10.6 GHz as regulated by the local communications authority. The location of the receiver tags within the surveyed space is computed by a hybrid algorithm based on a combination of different methods such as Time Difference of Arrival (TDOA), Two-Way Ranging (TWR) and Angle of Arrival (AoA). To simulate a true indoor sport situation, in which multiple tags send data packages to the receiving anchors at the same time, four additional tags were placed statically on the court at a height of approximately 1.5m form the ground during each trial. Hence, five tags were active at all times during data collection.

Vicon system specifications

A 12-camera Vicon motion analysis system (Vicon Nexus T40, ©Vicon Motion Systems, Oxford Metrics, UK) was set up as presented in Figure 1 and data collected at 100 Hz. Two 14-mm reflective markers (B&L Engineering, Santa Ana, USA) were placed on the outside of the pouch containing the receiver tag, in correspondence of the top-right and bottom-left corners of the tag. The data obtained from the two-dimensional position of the two markers was then averaged for further analysis. Marker dropout was handled automatically via Vicon 3D software and managed as follows: i) if only one marker dropped out, the trajectory of the marker was determined based on the position of the other available marker at each time point; ii) if both markers dropped out, their trajectory was estimated based on the position of the markers before and after the drop out. When both markers occasionally dropped out at the very end of the data collection course (between 11 and 12 m on the linear drills), the data was excluded from further comparison analysis.

The average Vicon calibration errors (Image and World Error, respectively) for the two testing sessions were 0.124 and 0.247 mm for the session in the centre of the court, and 0.118 and 0.250 mm for the session on the side of the court.

Data filtering

Vicon raw data was filtered and smoothed using two different approaches. In the first instance, the raw data were smoothed using a Butterworth 4th order recursive digital filter with a cut-off of 5 Hz. The choice of this cut-off was initially based on results from residual analysis, spectral analysis, observation of effect on parameters for different cut-offs and visual inspection of the raw and smoothed displacement and velocity curves, which indicated a cut-off of between 5 and 9 Hz would be appropriate. However, as the sample rate of the Clearsky system was 10 Hz and frequencies above 5 Hz could not be detected, the lower frequency was chosen for smoothing the data. This approach is the standard approach utilised in our laboratory. For the second approach, the raw data was filtered with a proprietary combination of Butterworth and moving average filters, equal to the ones applied to Clearsky, which details are protected by a non-disclosure agreement.

Statistical analysis

The original Vicon datasets obtained from the filtering process was reduced from 100 to 10 Hz to allow for comparisons with Clearsky. Each pair of Clearsky and Vicon datasets for each repetition of the activities was visually inspected to ensure that a common starting and end point could be established. The performance of two systems was compared via:

(i) Percentage least-square means difference (Clearsky-Vicon) with 90% confidence interval and qualitative magnitude-based inference. The magnitude of changes was interpreted as follows: <0.20 trivial, 0.20–0.59 small, 0.60–1.19 moderate, 1.20–1.99 large, 2.0–3.9 very large, >4.0 extra-large (Hopkins, Marshall, Batterham, & Hanin, 2009). Also, the likelihood of an effect being greater than the smallest important difference was reported and classified as possibly (25–75 %), likely (>75 %), very likely (>95 %), and most likely (>99.5 %) substantial difference. Similarly, the likelihood of an effect being trivial was classified as possibly, likely, very likely and most likely trivial (Hopkins et al., 2009).
(ii) Typical error (free of device error), expressed as percentage within-subject SD.

Additionally, for each activity the residual technical error of both systems and the between-subject standard deviation were reported.

Results

The comparison between Clearsky and Vicon filtered with the same combination of Clearsky filters is presented in Table 1.

Discussion

Comparison of linear locomotor activities between systems

The comparison of the different linear locomotor activities (i.e., walk, jog, and sprint) between Clearsky and Vicon returned predominantly trivial-to-moderate mean differences for all variables, with the exception of mean deceleration. In the case of total distance, the mean bias obtained in this study ranged from 0.2 to 2.3%, which is in line with values of <3.5% reported by previous investigations utilising UWB systems

Table 1. Comparison of mean and peak speed, mean and peak acceleration and deceleration, and distance between Clearsky and Vicon (smoothed with the same filters as applied to Clearsky) during four different locomotion activities performed in the centre and on the side of an indoor court.

		Subject Means						Subject SDs (%)		Device SDs (%)	
		Court centre			Court side						
		Clearsky	Vicon	Clearsky-Vicon (%) (mean ± CI; inference)	Clearsky	Vicon	Clearsky-Vicon (%) (mean ± CI; inference)	Between (mean, ±CI)	Within (mean, ±CI)	Clearsky (mean ±CI)	Vicon (mean, ±CI)
Walk	mean speed	1.03 m.s^{-1}	0.99 m.s^{-1}	4.4, ± 1.2; small****	1.05 m.s^{-1}	1.03 m.s^{-1}	2.1, ± 1.2; small*	6.5, ± 6.3	3.3, ± 0.8	3.9, ± 0.9	2.8, ± 1.1
	peak speed	1.73 m.s^{-1}	1.61 m.s^{-1}	7.5, ± 0.8; small****	1.72 m.s^{-1}	1.64 m.s^{-1}	5.4, ± 0.8; small****	11, ± 6.3	2.8, ± 0.5	2.6, ± 0.5	1.5, ± 0.8
	mean acc.	0.35 m.s^{-2}	0.30 m.s^{-2}	15, ± 6.3; mod****	0.35 m.s^{-2}	0.34 m.s^{-2}	2.8, ± 5.6; trivial°	20, ± 12	6.1, ± 7.0	11, ± 3.7	22, ± 3.5
	peak acc.	1.29 m.s^{-2}	1.20 m.s^{-2}	7.5, ± 3.2; small***	1.32 m.s^{-2}	1.24 m.s^{-2}	6.3, ± 3.1; small**	17, ± 9.2	5.2, ± 2.1	13, ± 1.9	2.4, ± n.a.
	mean dec.	0.18 m.s^{-2}	0.10 m.s^{-2}	84, ± 20; large****	0.32 m.s^{-2}	0.26 m.s^{-2}	21, ± 2.8; small***	31, ± 28	15, ± 13	21, ± 7.9	49, ± 8.3
	peak dec.	0.59 m.s^{-2}	0.42 m.s^{-2}	41, ± 16; mod****	1.10 m.s^{-2}	1.03 m.s^{-2}	6.6, ± 12; trivial°	37, ± 37	17, ± 11	24, ± 8.2	50, ± 8.7
	distance	12.1 m	12.4 m	−2.3, ± 0.5; mod****	12.4 m	12.6 m	−1.8, ± 0.5; mod****	1.9, ± 0.8	1.7, ± 0.4	1.4, ± 0.4	1.6, ± 0.4
Jog	mean speed	1.93 m.s^{-1}	2.07 m.s^{-1}	−6.5, ± 1.3; small****	2.20 m.s^{-1}	2.21 m.s^{-1}	−0.5, ± 1.3; trivial°°°	10, ± 2.7	4.4, ± 1.0	5.7, ± 0.9	0.1, ± 2.5
	peak speed	3.71 m.s^{-1}	3.61 m.s^{-1}	2.8, ± 0.7; trivial°°°°	3.70 m.s^{-1}	3.64 m.s^{-1}	1.9, ± 0.7; trivial°°°°	19, ± 11	4.7, ± 0.8	2.3, ± 0.8	1.6, ± 1.3
	mean acc.	1.11 m.s^{-2}	1.17 m.s^{-2}	−5.3, ± 3.7; trivial°°	1.22 m.s^{-2}	1.23 m.s^{-2}	−1.1, ± 3.7; trivial°°°	34, ± 20	9.3, ± 2.7	16, ± 2.6	5.0, ± 8.7
	peak acc.	2.42 m.s^{-2}	2.35 m.s^{-2}	2.9, ± 3.0; trivial°°	2.58 m.s^{-2}	2.30 m.s^{-2}	12, ± 3.1; small****	25, ± 14	7.9, ± 1.9	12, ± 1.8	3.7, ± 5.8
	mean dec.	0.81 m.s^{-2}	0.96 m.s^{-2}	−16, ± 4.6; small***	1.00 m.s^{-2}	1.07 m.s^{-2}	−6.1, ± 4.9; trivial°°	45, ± 42	21, ± 4.2	25, ± 3.9	0.5, ± 9.8
	peak dec.	1.77 m.s^{-2}	1.79 m.s^{-2}	−1.1, ± 4.5; trivial°°°	2.17 m.s^{-2}	2.12 m.s^{-2}	2.4, ± 4.5; trivial°°°	36, ± 42	14, ± 3.2	20, ± 3.2	1.7, ± 7.1
	distance	11.8 m	12.0 m	−1.8, ± 1.4; small**	12.3 m	12.4 m	−1.1, ± 1.3; small*	4.2, ± 4.6	2.5, ± 1.1	5.2, ± 0.9	2.4, ± 1.4
Sprint	mean speed	2.08 m.s^{-1}	1.98 m.s^{-1}	5.2, ± 1.2; small*	2.57 m.s^{-1}	2.45 m.s^{-1}	5.3, ± 1.3; small*	20, ± 20	4.8, ± 1.0	2.6, ± 1.8	3.9, ± 1.1
	peak speed	5.96 m.s^{-1}	5.93 m.s^{-1}	0.5, ± 0.8; trivial°°°	6.23 m.s^{-1}	6.09 m.s^{-1}	2.4, ± 0.9; small***	5.6, ± 2.3	3.2, ± n.a.	3.1, ± n.a.	-
	mean acc.	1.60 m.s^{-2}	1.79 m.s^{-2}	−11, ± 2.5; mod****	1.83 m.s^{-2}	2.08 m.s^{-2}	−12, ± 2.7; mod****	12, ± 14	4.2, ± 3.3	8.8, ± 1.7	7.6, ± 1.7
	peak acc.	4.17 m.s^{-2}	3.90 m.s^{-2}	6.8, ± 1.5; mod****	4.40 m.s^{-2}	4.05 m.s^{-2}	8.5, ± 1.7; mod****	8.8, ± 3.8	3.5, ± 0.6	6.0, ± 0.8	0.1, ± n.a.
	mean dec.	1.48 m.s^{-2}	2.07 m.s^{-2}	−28, ± 4.2; mod****	1.95 m.s^{-2}	2.12 m.s^{-2}	−8.1, ± 6.0; small*	26, ± 8.0	18, ± 2.9	26, ± 1.5	5.2, ± 8.8
	peak dec.	3.90 m.s^{-2}	4.66 m.s^{-2}	−16, ± 9.2; mod***	4.89 m.s^{-2}	4.54 m.s^{-2}	7.8, ± 13.3; small	17, ± 9.4	10, ± 11.5	55, ± 9.4	8.7, ± 50
	distance	12.2 m	12.5 m	−2.2, ± 1.0; small***	12.5 m	12.5 m	0.2, ± 1.1; trivial	3.1, ± 4.2	1.2, ± 1.3	2.5, ± 0.6	3.3, ± 0.6
COD	mean speed	1.05 m.s^{-1}	0.92 m.s^{-1}	14, ± 2.5; mod****	1.02 m.s^{-1}	0.77 m.s^{-1}	32, ± 3.0; v.large****	8.5, ± 10	3.5, ± 1.5	8.5, ± 1.3	3.3, ± 1.7
	peak speed	3.37 m.s^{-1}	2.97 m.s^{-1}	13, ± 1.4; v.large ****	3.41 m.s^{-1}	2.93 m.s^{-1}	16, ± 1.6; v.large ****	5.0, ± 2.5	2.1, ± 1.1	3.9, ± 0.8	3.6, ± 0.8
	mean acc.	1.17 m.s^{-2}	1.17 m.s^{-2}	−0.1, ± 5.0; trivial	1.38 m.s^{-2}	1.25 m.s^{-2}	10, ± 5.7; mod***	13 ± 12	−2.2, ± 6.0	18, ± 2.9	12, ± 2.6
	peak acc.	3.12 m.s^{-2}	2.86 m.s^{-2}	8.9, ± 1.9; mod****	3.33 m.s^{-2}	2.91 m.s^{-2}	14, ± 2.1; large****	8.5, ± 3.4	5.1, ± 1.2	6.8, ± 1.1	2.4, ± 3.4
	mean dec.	1.62 m.s^{-2}	1.50 m.s^{-2}	8.3, ± 5.2; mod***	1.35 m.s^{-2}	0.99 m.s^{-2}	36, ± 6.9; large****	9.6, ± 6.1	6.2, ± 5.6	20, ± 3.1	8.6, ± 3.6
	peak dec.	3.29 m.s^{-2}	2.61 m.s^{-2}	26, ± 4.1; large****	3.37 m.s^{-2}	2.48 m.s^{-2}	36, ± 4.6; v.large****	11, ± 5.3	5.3, ± 2.8	10, ± 1.9	9.1, ± 1.8
	distance	4.9 m	4.6 m	6.3, ± 1.0; mod****	4.9 m	5.4 m	18, ± 1.1; v.large****	5.1, ± 6.3	2.2, ± n.a.	3.8, ± 0.3	0.0, ± n.a.

SDs: standard deviations; CI: 90% confidence interval; n.a., not available.
Likelihood of substantial changes: *possibly, **likely, ***very likely, ****most likely.
Likelihood of trivial changes: °possibly, °°likely, °°°very likely, °°°°most likely.

(Leser et al., 2014; Rhodes et al., 2014). Total distance is the only variable that can be compared with the existing literature, as in one study distance was the only variable assessed (Leser et al., 2014), while in the other study the absolute speed reached in the different drills was up to 2 m·s^{-1} lower than the speed reported in our work (Rhodes et al., 2014), making comparisons between studies difficult.

As a general overview, the mean differences between systems for total distance, mean and peak speed, and mean and peak accelerations were in the range of 0.2 to 12%, while the typical errors (calculated as within-subject SDs and free of device error) ranged between 1.2 and 9.3%. Errors of this magnitude compare favourably to the typical signal practitioners try to detect either when comparing between levels of competition (Aughey, 2013), finals compared to regular season matches (Aughey, 2011), or the influence of environmental factors on match running performance (Aughey, Goodman, & McKenna, 2014). Conversely, for mean and peak deceleration the differences between systems and the typical errors were as high as 84% and 21%, respectively, making detecting small important effects in these measures extremely challenging.

While the validity of Clearsky to measure distance, speed and acceleration may be considered acceptable for applications in indoor sport settings, the differences between Clearsky and Vicon for mean and peak deceleration may appear excessive at a first analysis. However, it is important to note that, from a practical perspective, practitioners may be more inclined to report acceleration and deceleration efforts either as single efforts over a longer sampling period, such as 0.2 or 0.3s (Aughey, 2011) or as average values over longer phases of a game or training session (Delaney, Cummins, Thornton, & Duthie, 2017; Delaney et al., 2016). In both cases, the error associated with these variables may be greatly reduced (Varley, Jaspers, Helsen, & Malone, 2017), making them suitable to reflect human locomotion in sport.

Comparison of COD activity between systems

Unlike the differences between systems in the linear activities, Clearsky and Vicon were substantially different when compared using an all-out, 45-degrees COD activity. The differences in the means were predominantly moderate to large when the activity was performed in the centre of the court, and increased to large/very large when the activity was performed on the side. A possible explanation for the larger differences observed in the COD activity on one side of the court may be connected to known issues in the triangulation of the signal between anchors and receiving units. As the COD activity was performed approximately 10 m from the side wall and the anchors were installed at a height of approximately 4.5 m, it is possible that during the change of direction the receiving unit may have not always been "visible" to many anchors, in turn reducing the accuracy of the position estimation. An additional factor that may have contributed to larger errors detected on the side of the courts may be the possible interferences that occur in proximity of metal structures. While UWB technology is supposed to be less susceptible to interferences from other technologies operating in similar wavelengths, large quantities of metal may provide technical challenges when position is estimated using time-difference-of-arrival (TDOA) algorithms (Liu, Darabi, Banerjee, & Liu, 2007; Ye, Redfield, & Liu, 2010). As the indoor sport complex used for the present study consisted of walls made predominantly of metal, and TDOA is one of the algorithms used by Clearsky to estimate position, such interference may have occurred.

The location of the anchors, in relation to the court sidelines and the stadium structures, must be carefully considered when interpreting positional (and derived velocity and acceleration) data during indoor sports games, as COD activities performed close to the sidelines occur regularly.

The importance of filtering and smoothing

The initial analysis in this study identified data smoothing as the main reason for differences between Vicon data (smoothed using standard motion analysis system processes) and data obtained using the filtering developed for the Clearsky system. When the Clearsky data were compared to the original Vicon data, mostly large to extra-large differences were detected, with percentage differences up to 120%. Best practice in choosing a smoothing cut-off frequency in motion analysis system data uses multiple indicators to determine the optimal level of smoothing for a given movement. These include one or more automated algorithms, spectral analyses, visual inspection of time series data, the effect on parameter values using different cut-offs and previous literature (Coventry, Ball, Parrington, Aughey, & McKenna, 2015; Parrington, Ball, & MacMahon, 2014; Peacock, Ball, & Taylor, 2017). Based on these decisions, as well as considerations around the sample rate for Clearsky, 8 Hz smoothing was chosen for the original smoothing procedure. However, 8 Hz smoothing allowed for the inclusion of step-to-step fluctuations in marker movement to be measured. While these certainly exist (the velocity of centre of mass of the body fluctuates within and between each step) this information was not evident in the Clearsky data. When the Vicon data were smoothed with a lower cut-off, the two signals aligned very closely (Figure 2). Therefore, while the loss of the step-to-step information is itself a potential issue for some metrics, in the case of a pure comparison of the two systems, the lower smoothing for Vicon was warranted and made for a more appropriate comparison.

It is worth considering the issue of step-to-step fluctuations in velocity that are not detected (or presented as these might be evident in raw signals) by Clearsky and other similar systems. The removal of this data will likely impact minimally on tactical measures. For some of the more common metrics such as area encompassed, centroid, distance from the centroid for individual players and relative phase (Goncalves, Figueira, Macas, & Sampaio, 2014), the removal of this signal will affect results minimally. However, for some of the external load measures, this is a potential problem. Given the fluctuations of the centre of mass that are removed, distances and instantaneous measures are underestimated. For example, the distance for one player/trial using the original Vicon data was 12.6 m compared to 12.3 m from Clearsky data (2.4%

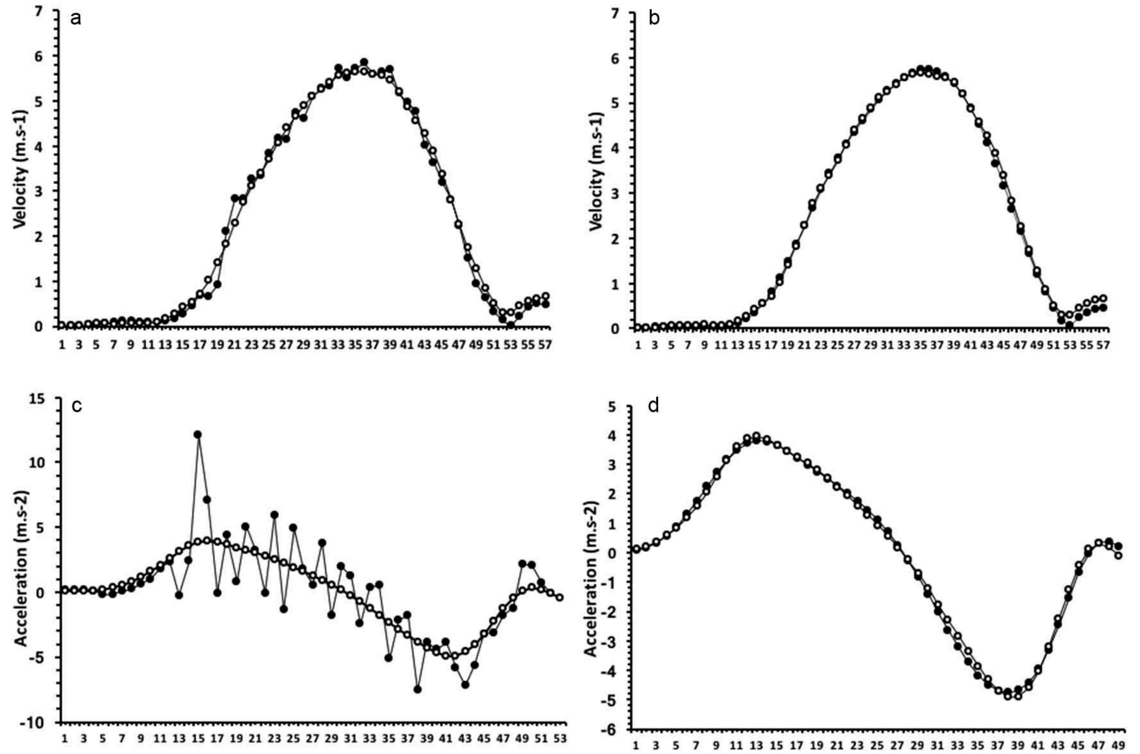

Figure 2. Example of the effect of filtering and smoothing on the Clearsky (white circles) and Vicon (black circles) velocity and acceleration data. In panels a and c, Vicon data was filtered with a Butterworth 4th order recursive digital filter with a cut-off of 5 Hz. In panels b and d, Vicon data was filtered with a proprietary combination of Butterworth and moving average filters, equal to the ones applied to Clearsky.

difference) and maximum velocity was underestimated by between 4 and 8%. Further, given variation in running efficiency exists due to excessive lateral motion or greater braking (and hence the need for greater propulsive forces) each step, this will not be detected. Whether these differences will be of practical importance will depend on the level of precision required to make appropriate decisions on load management. However, future work needs to examine the potential level of error in games due to the elimination of these fluctuations.

Limitations

The results of the present study reflect the specific set-up of the local positioning system in an indoor stadium. Therefore, validation studies should be performed before utilising the system in different environments. Also, while the number of participants involved in the data collection is limited (n = 6), the total number of observations allow for an objective comparison of Clearsky and Vicon to assess movements in indoor sports.

Conclusion

When filtered and smoothed following a similar process, the new UWB-based local positioning system had acceptable validity, compared to Vicon, to assess movements which are representative of indoor sports. The mean bias for total distance, mean and peak speed, and mean and peak accelerations in the linear drills were in the range of 0.2 to 12%, with the typical errors between 1.2 and 9.3%. Mean and peak deceleration had larger mean differences and typical errors. Differences in step-to-step fluctuations between systems may constitute an issue for some external load variables, warranting further investigation.

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No potential conflict of interest was reported by the authors.

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References

Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S., Al-Ammar, M. A., & Al-Khalifa, H. S. (2016). Ultra wideband indoor positioning technologies: Analysis and recent advances. *Sensors (Basel)*, *16*(5), 707. doi:10.3390/s16050707

Aughey, R. J. (2011). Increased high-intensity activity in elite Australian football finals matches. *International Journal of Sports Physiology and Performance*, *6*(3), 367–379. doi:10.1123/ijspp.6.3.367

Aughey, R. J. (2013). Widening margin in activity profile between elite and sub-elite Australian football: A case study. *Journal of Science and Medicine in Sport*, *16*(4), 382–386. doi:10.1016/j.jsams.2012.10

Aughey, R. J., Goodman, C. A., & McKenna, M. J. (2014). Greater chance of high core temperatures with modified pacing strategy during team sport in the heat. *Journal of Science and Medicine in Sport*, *17*(1), 113–118. doi:10.1016/j.jsams.2013.02.013

Coventry, E., Ball, K., Parrington, L., Aughey, R., & McKenna, M. (2015). Kinematic effects of a short-term fatigue protocol on punt-kicking performance. *Journal of Sports Sciences*, *33*(15), 1596–1605. doi:10.1080/02640414.2014

Delaney, J. A., Cummins, C. J., Thornton, H. R., & Duthie, G. M. (2017). Importance, reliability and usefulness of acceleration measures in team sports. *Journal of Strength and Conditioning Research*, 1. doi:10.1519/JSC.0000000000001849

Delaney, J. A., Duthie, G. M., Thornton, H. R., Scott, T. J., Gay, D., & Dascombe, B. J. (2016). Acceleration-based running intensities of professional rugby league match play. *International Journal of Sports Physiology and Performance*, *11*(6), 802–809. doi:10.1123/ijspp.2015-0424.

Goncalves, B. V., Figueira, B. E., Macas, V., & Sampaio, J. (2014). Effect of player position on movement behaviour, physical and physiological performances during an 11-a-side football game. *Journal of Sports Sciences*, *32*(2), 191–199. doi:10.1080/02640414.2013.816761

Hedley, M., Mackintosh, C., Shuttleworth, R., Humphrey, D., Sathyan, T., & Ho, P. (2010). Wireless tracking system for sports training indoors and outdoors. *Procedia Engineering*, *2*, 2999–3004. doi:10.1016/j.proeng.2010.04.101

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–13. doi:10.1249/MSS

Leser, R., Schleindlhuber, A., Lyons, K., & Baca, A. (2014). Accuracy of an UWB-based position tracking system used for time-motion analyses in game sports. *European Journal Sport Sciences*, *14*(7), 635–642. doi:10.1080/17461391.2014.884167

Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2007). Survey of wireless indoor positioning techniques and systems. *IEEE Transactions Systems Manual Cybern Particle C Applications Reviews*, *37*, 1067–1080. doi:10.1109/TSMCC.2007.905750

Malone, J. J., Lovell, R., Varley, M. C., & Coutts, A. J. (2016). Unpacking the black box: Applications and considerations for using GPS devices in sport. *International Journal of Sports Physiology and Performance*, 1–30. doi:10.1123/ijspp.2016-0236

Mautz, R. (2012). *Indoor Positioning Technologies* (Habilitation Thesis). ETH, Zurich.

Ogris, G., Leser, R., Horsak, B., Kornfeind, P., Heller, M., & Baca, A. (2012). Accuracy of the LPM tracking system considering dynamic position changes. *Journal of Sports Sciences*, *30*(14), 1503–1511. doi:10.1080/02640414.2012

Parrington, L., Ball, K., & MacMahon, C. (2014). Biomechanical characteristics of handballing maximally in Australian football. *Sports Biomechanics*, *13*(4), 307–319. doi:10.1080/14763141.2014.981201

Peacock, J., Ball, K., & Taylor, S. (2017). The impact phase of drop punt kicking for maximal distance and accuracy. *Journal of Sports Sciences*, *35*, 2289–2296. Epub ahead of print. doi:10.1080/02640414.2016.1266015

Rhodes, J., Mason, B., Perrat, B., Smith, M., & Goosey-Tolfrey, V. (2014). The validity and reliability of a novel indoor player tracking system for use within wheelchair court sports. *Journal of Sports Sciences*, *32*(17), 1639–1647. doi:10.1080/02640414.2014.910608

Sathyan, T., Shuttleworth, R., Hedley, M., & Davids, K. (2012). Validity and reliability of a radio positioning system for tracking athletes in indoor and outdoor team sports. *Behavior Research Methods*, *44*(4), 1108–1114. doi:10.3758/s13428-012-0192-2

Scott, M. T., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: A brief review. *Journal of Strength and Conditioning Research*, *30*(5), 1470–1490. doi:10.1519/JSC.0000000000001221

Sweeting, A. J., Aughey, R. J., Cormack, S. J., & Morgan, S. (2017). Discovering frequently recurring movement sequences in team-sport athlete spatiotemporal data. *Journal of Sports Sciences*, 1–7. doi:10.1080/02640414.2016.1273536

Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences*, *30*(2), 121–127. doi:10.1080/02640414.2011.627941

Varley, M. C., Jaspers, A., Helsen, W. F., & Malone, J. J. (2017). Methodological considerations when quantifying high-intensity efforts in team sport using global positioning system technology. *International Journal of Sports Physiology and Performance*, 1–25. doi:10.1123/ijspp.2016-0534

Ye, R., Redfield, S., & Liu, H. (2010). *High-precision indoor UWB localization: Technical challenges and method*. Paper presented at the 2010 IEEE International Conference on Ultra-Wideband (ICUWB), Nanjing, China.