



VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

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

This is the Accepted version of the following publication

Serpiello, Fabio, Hopkins, William, Barnes, S, Tavrou, J, Duthie, Grant, Aughey, Robert and Ball, Kevin (2017) Validity of an ultra-wideband local positioning system to measure locomotion in indoor sports. *Journal of Sports Sciences*. ISSN 0264-0414

The publisher's official version can be found at
<http://www.tandfonline.com/doi/full/10.1080/02640414.2017.1411867>
Note that access to this version may require subscription.

Downloaded from VU Research Repository <https://vuir.vu.edu.au/35059/>

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

Serpiello, F.R.¹, Hopkins W.G.^{1,2}, Barnes S.¹, Tavrou J.¹, Duthie G.M.^{1,3}, Aughey R.J.¹, Ball K.¹.

¹ Institute of Sport, Exercise and Active Living (ISEAL), College of Sport and Exercise Science, Victoria University, PO BOX 14428 Melbourne 8001, Australia

² Defence Institute, Oslo, Norway

³ School of Exercise Science, Australian Catholic University, Strathfield, Australia

Word count: 3457

Running title: Validity of a local positioning system for indoor sports

Keywords: ultra-wideband; LPS; validity; tracking; Clearsky

ACCEPTED

1 **ABSTRACT**

2 The validity of an Ultra-wideband (UWB) positioning system was investigated during
3 linear and change-of-direction (COD) running drills. Six recreationally-active men
4 performed ten repetitions of four activities (walking, jogging, maximal acceleration, and
5 45° COD) on an indoor court. Activities were repeated twice, in the centre of the court
6 and on the side. Participants wore a receiver tag (Clearsky T6, Catapult Sports) and two
7 reflective markers placed on the tag to allow for comparisons with the criterion system
8 (Vicon). Distance, mean and peak velocity, acceleration, and deceleration were
9 assessed. Validity was assessed via percentage least-square means difference (Clearsky-
10 Vicon) with 90% confidence interval and magnitude-based inference; typical error was
11 expressed as within-subject standard deviation. The mean differences for distance,
12 mean/peak speed, and mean/peak accelerations in the linear drills were in the range of
13 0.2-12%, with typical errors between 1.2 and 9.3%. Mean and peak deceleration had
14 larger differences and errors between systems. In the COD drill, moderate-to-large
15 differences were detected for the activity performed in the centre of the court, increasing
16 to large/very large on the side. When filtered and smoothed following a similar process,
17 the UWB-based positioning system had acceptable validity, compared to Vicon, to
18 assess movements representative of indoor sports.

19
20
21
22
23
24
25
26

27 INTRODUCTION

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

31 The technological advancement of tracking devices in the last two decades has resulted
32 in both an increased scientific research activity and a wider adoption of this technology
33 by sporting clubs and associations. In particular, there has been an exponential increase
34 in the number of research studies investigating different applications and
35 methodological aspects of commercial global positioning system (GPS) devices used
36 for outdoor sports (Malone, Lovell, Varley, & Coutts, 2016). As a result of the
37 significant body of knowledge with respect to GPS in sport, it is now well
38 acknowledged that this technology has acceptable validity and reliability to measure
39 locomotion in athletes when the sampling rate is at least 10 Hz (Scott, Scott, & Kelly,
40 2016; Varley, Fairweather, & Aughey, 2012).

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

52 Radio Frequency Identification has been the main technology adopted by companies to
53 provide the possibility to track athletes in indoor settings. This technology usually
54 employs proximity as the main principle to detect position and it operates on a
55 bandwidth up to 930 MHz (Mautz, 2012). The validity of RFID systems, such as
56 Inmotiotec (Inmotiotec GmbH, Austria) and the Wireless Ad hoc System for
57 Positioning (WASP, Commonwealth Scientific and Industrial Research Organisation,
58 Australia (Hedley et al., 2010)) has been previously assessed (Ogris et al., 2012;
59 Sathyan, Shuttleworth, Hedley, & Davids, 2012; Sweeting, Aughey, Cormack, &
60 Morgan, 2017). These studies found an absolute error for positioning estimation
61 between 11.9 ± 4.9 and 23.4 ± 20.7 cm (Ogris, et al., 2012; Sathyan, et al., 2012), a
62 mean error for distance across different locomotion drills of 1.26 – 3.87 % (Sathyan, et
63 al., 2012), and a mean error for average and maximal velocity up to 3.54 % and 13.15
64 %, respectively (Ogris, et al., 2012). While the results of these studies show an
65 acceptable level of accuracy, RFID suffers from signal instability and is susceptible to
66 interference (Alarifi, et al., 2016).

67 A more recent technology, UWB, may overcome limitations of RFID related to signal
68 instability and interference, and therefore have applications in indoor sport settings
69 (Alarifi, et al., 2016). Ultra-wideband is defined as a radiofrequency signal that has a
70 fractional bandwidth ≥ 0.20 than the centre frequency, or has a bandwidth ≥ 500 MHz
71 irrespective of the fractional bandwidth (FCC; Mautz, 2012). Despite the high cost of
72 UWB equipment, this technology offers the advantage of high precision, a signal that is
73 capable of penetrating most materials, and less susceptibility to interference (Alarifi, et
74 al., 2016).

75 To the best of our knowledge, two studies have investigated the accuracy, validity and
76 reliability of a UWB-based tracking system in indoor settings (Leser, Schleindlhuber,
77 Lyons, & Baca, 2014; Rhodes, Mason, Perrat, Smith, & Goosey-Tolfrey, 2014). One

78 study assessed validity of one system (Ubisense Ltd., UK) during basketball-specific
79 drills, and reported a relative error of 3.45 ± 1.99 % for distance (Leser, et al., 2014).
80 However, a trundle wheel was used as a criterion measure, distance was the only
81 variable assessed, and the receiver tags were placed on the participant's head, therefore
82 limiting the applicability of the results to real sporting settings. A more comprehensive
83 study assessed the accuracy, validity and reliability of the same system for use in
84 wheelchair sports (Rhodes, et al., 2014). The results presented an absolute positioning
85 error of 19-32 cm depending on the sampling rate, a relative error <1 % for distance and
86 mean speed, and <2 % for peak speed during linear drills, with errors being as low as
87 0.3 % for multidirectional drills (Rhodes, et al., 2014). The coefficient of variation
88 assessing intra-tag reliability was <2 % in all conditions when sampling at 8 Hz or
89 higher. However, due to the nature of the activity, only peak speeds of ~ 4 m.s⁻¹ were
90 achieved, perhaps limiting the generalisability of the findings.
91 Therefore, the aim of the present study was to assess the criterion validity of a new
92 UWB positioning system during linear and change-of-direction drills for general
93 application to indoor sports.

94 **METHODS**

95 **Participants and experimental overview**

96 Six recreationally-active men (29.2 ± 4.1 years old, 179.0 ± 8.2 cm, 75.9 ± 7.3 kg)
97 volunteered to take part in this study, which was approved by the investigators'
98 university Human Research Ethics Committee. Participants were asked to attend two
99 testing sessions separated by one week. In the first session, participants performed ten
100 repetitions of four different locomotion activities (self-paced walking, jogging, maximal
101 acceleration, and 45° change of direction) over a course located in the middle of an
102 indoor, parquet-floor court. During the second session, participants repeated the exact
103

104 same protocol with the activities performed on one side of the court, with the aim of
105 investigating possible differences due to the location of the tags on the court in relation
106 to the position of the anchors (Fig 1). During all trials participants wore a receiver tag
107 (Clearsky T6, Catapult Sports, Australia) placed inside a vest between the scapulae, and
108 two passive reflective markers were placed on the pouch containing the receiver tag to
109 allow for comparisons with the positioning derived from the criterion system (Vicon).
110 The two testing sessions were undertaken in separate days due to the length of the data
111 collection process and to try minimise differences in the light, which could have
112 occurred if data were collected in different moments of the day and could have affected
113 the VICON setup.

114
115 **** Figure 1 near here ****
116

117 **Locomotion activities**

118 Participants performed four different activities in the following order:

- 119 i) a maximal change of direction at 45° either left or right (COD45) over a total
120 distance of approximately 5.5 m,
- 121 ii) a self-paced walk over a linear course of 12 m,
- 122 iii) a self-paced jog over a linear course of 12 m, and
- 123 iv) a maximal acceleration over a linear course of 12 m.

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

126 **Clearsky T6 system specifications**

127 The set up used in this study consisted of 18 anchors positioned as presented in Figure
128 1. All anchors were installed at a height of 4.8 m from the ground. The laptop used for
129 data processing was connected to the master anchor via Ethernet cabling. Data was

130 collected at 10 Hz and processed via Openfield™ console software version 1.13.4 (Beta
131 release, Catapult Sports, Melbourne, Australia). The system is based on ultra-wideband
132 technology in the frequency range of 3.1-10.6 GHz as regulated by the local
133 communications authority. The location of the receiver tags within the surveyed space is
134 computed by a hybrid algorithm based on a combination of different methods such as
135 Time Difference of Arrival (TDOA), Two-Way Ranging (TWR) and Angle of Arrival
136 (AoA). To simulate a true indoor sport situation, in which multiple tags send data
137 packages to the receiving anchors at the same time, four additional tags were placed
138 statically on the court at a height of approximately 1.5m from the ground during each
139 trial. Hence, five tags were active at all times during data collection.

140 **Vicon system specifications**

141 A 12-camera Vicon motion analysis system (Vicon Nexus T40, ©Vicon Motion
142 Systems, Oxford Metrics, UK) was set up as presented in Figure 1 and data collected at
143 100 Hz. Two 14-mm reflective markers (B&L Engineering, Santa Ana, USA) were
144 placed on the outside of the pouch containing the receiver tag, in correspondence of the
145 top-right and bottom-left corners of the tag. The data obtained from the two-
146 dimensional position of the two markers was then averaged for further analysis. Marker
147 dropout was handled automatically via Vicon 3D software and managed as follows: i) if
148 only one marker dropped out, the trajectory of the marker was determined based on the
149 position of the other available marker at each time point; ii) if both markers dropped
150 out, their trajectory was estimated based on the position of the markers before and after
151 the drop out. When both markers occasionally dropped out at the very end of the data
152 collection course (between 11 and 12 m on the linear drills), the data was excluded from
153 further comparison analysis.

154 The average Vicon calibration errors (Image and World Error, respectively) for the two
155 testing sessions were 0.124 and 0.247 mm for the session in the centre of the court, and
156 0.118 and 0.250 mm for the session on the side of the court.

157 **Data filtering**

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

170 **Statistical analysis**

171 The original Vicon datasets obtained from the filtering process was reduced from 100 to
172 10 Hz to allow for comparisons with Clearsky. Each pair of Clearsky and Vicon
173 datasets for each repetition of the activities was visually inspected to ensure that a
174 common starting and end point could be established. The performance of two systems
175 was compared via:

- 176 i) Percentage least-square means difference (Clearsky-Vicon) with 90%
177 confidence interval and qualitative magnitude-based inference. The
178 magnitude of changes was interpreted as follows: <0.20 trivial, 0.20-0.59
179 small, 0.60-1.19 moderate, 1.20-1.99 large, 2.0-3.9 very large, >4.0 extra-

180 large (Hopkins, Marshall, Batterham, & Hanin, 2009). Also, the likelihood
181 of an effect being greater than the smallest important difference was reported
182 and classified as possibly (25-75 %), likely (>75 %), very likely (>95 %),
183 and most likely (>99.5 %) substantial difference. Similarly, the likelihood of
184 an effect being trivial was classified as possibly, likely, very likely and most
185 likely trivial (Hopkins, Marshall, Batterham, & Hanin, 2009).

186 ii) Typical error (free of device error), expressed as percentage within-subject
187 SD.

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

190

191 **RESULTS**

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

194

195 **** Table 1 near here ****

196

197 **DISCUSSION**

198 **Comparison of linear locomotor activities between systems**

199 The comparison of the different linear locomotor activities (i.e., walk, jog, and sprint)
200 between Clearsky and Vicon returned predominantly trivial-to-moderate mean
201 differences for all variables, with the exception of mean deceleration. In the case of total
202 distance, the mean bias obtained in this study ranged from 0.2 to 2.3%, which is in line
203 with values of <3.5% reported by previous investigations utilising UWB systems
204 (Leser, et al., 2014; Rhodes, et al., 2014). Total distance is the only variable that can be
205 compared with the existing literature, as in one study distance was the only variable

206 assessed (Leser, et al., 2014), while in the other study the absolute speed reached in the
207 different drills was up to $2 \text{ m}\cdot\text{s}^{-1}$ lower than the speed reported in our work (Rhodes, et
208 al., 2014), making comparisons between studies difficult.

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

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

229 **Comparison of COD activity between systems**

230 Unlike the differences between systems in the linear activities, Clearsky and Vicon were
231 substantially different when compared using an all-out, 45-degrees COD activity. The

232 differences in the means were predominantly moderate to large when the activity was
233 performed in the centre of the court, and increased to large/very large when the activity
234 was performed on the side. A possible explanation for the larger differences observed in
235 the COD activity on one side of the court may be connected to known issues in the
236 triangulation of the signal between anchors and receiving units. As the COD activity
237 was performed approximately 10 m from the side wall and the anchors were installed at
238 a height of approximately 4.5 m, it is possible that during the change of direction the
239 receiving unit may have not always been 'visible' to many anchors, in turn reducing the
240 accuracy of the position estimation. An additional factor that may have contributed to
241 larger errors detected on the side of the courts may be the possible interferences that
242 occur in proximity of metal structures. While UWB technology is supposed to be less
243 susceptible to interferences from other technologies operating in similar wavelengths,
244 large quantities of metal may provide technical challenges when position is estimated
245 using time-difference-of-arrival (TDOA) algorithms (Liu, Darabi, Banerjee, & Liu,
246 2007; Ye, Redfield, & Liu, 2010). As the indoor sport complex used for the present
247 study consisted of walls made predominantly of metal, and TDOA is one of the
248 algorithms used by Clearsky to estimate position, such interference may have occurred.
249 The location of the anchors, in relation to the court sidelines and the stadium structures,
250 must be carefully considered when interpreting positional (and derived velocity and
251 acceleration) data during indoor sports games, as COD activities performed close to the
252 sidelines occur regularly.

253 **The importance of filtering and smoothing**

254 The initial analysis in this study identified data smoothing as the main reason for
255 differences between Vicon data (smoothed using standard motion analysis system
256 processes) and data obtained using the filtering developed for the Clearsky system.
257 When the Clearsky data were compared to the original Vicon data, mostly large to

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

274

275 **** Figure 2 near here ****

276

277 It is worth considering the issue of step-to-step fluctuations in velocity that are not
278 detected (or presented as these might be evident in raw signals) by Clearsky and other
279 similar systems. The removal of this data will likely impact minimally on tactical
280 measures. For some of the more common metrics such as area encompassed, centroid,
281 distance from the centroid for individual players and relative phase (Goncalves,
282 Figueira, Macas, & Sampaio, 2014), the removal of this signal will affect results
283 minimally. However, for some of the external load measures, this is a potential problem.

284 Given the fluctuations of the centre of mass that are removed, distances and
285 instantaneous measures are underestimated. For example, the distance for one
286 player/trial using the original Vicon data was 12.6 m compared to 12.3 m from Clearsky
287 data (2.4% difference) and maximum velocity was underestimated by between 4 and
288 8%. Further, given variation in running efficiency exists due to excessive lateral motion
289 or greater braking (and hence the need for greater propulsive forces) each step, this will
290 not be detected. Whether these differences will be of practical importance will depend
291 on the level of precision required to make appropriate decisions on load management.
292 However, future work needs to examine the potential level of error in games due to the
293 elimination of these fluctuations.

294 **Limitations**

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

301 **CONCLUSION**

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

310

311 **ACKNOWLEDGEMENTS**

312 The authors would like to acknowledge all participants for their invaluable help making
313 data collection possible, and Susanne Ellens for her assistance with data analysis.

314

315 **DISCLOSURE OF INTEREST**

316 The authors report no conflicts of interest.

317

318

319

320

321

322

323

324

325

326

327

328

329

330

331

332

333

334

335

ACCEPTED

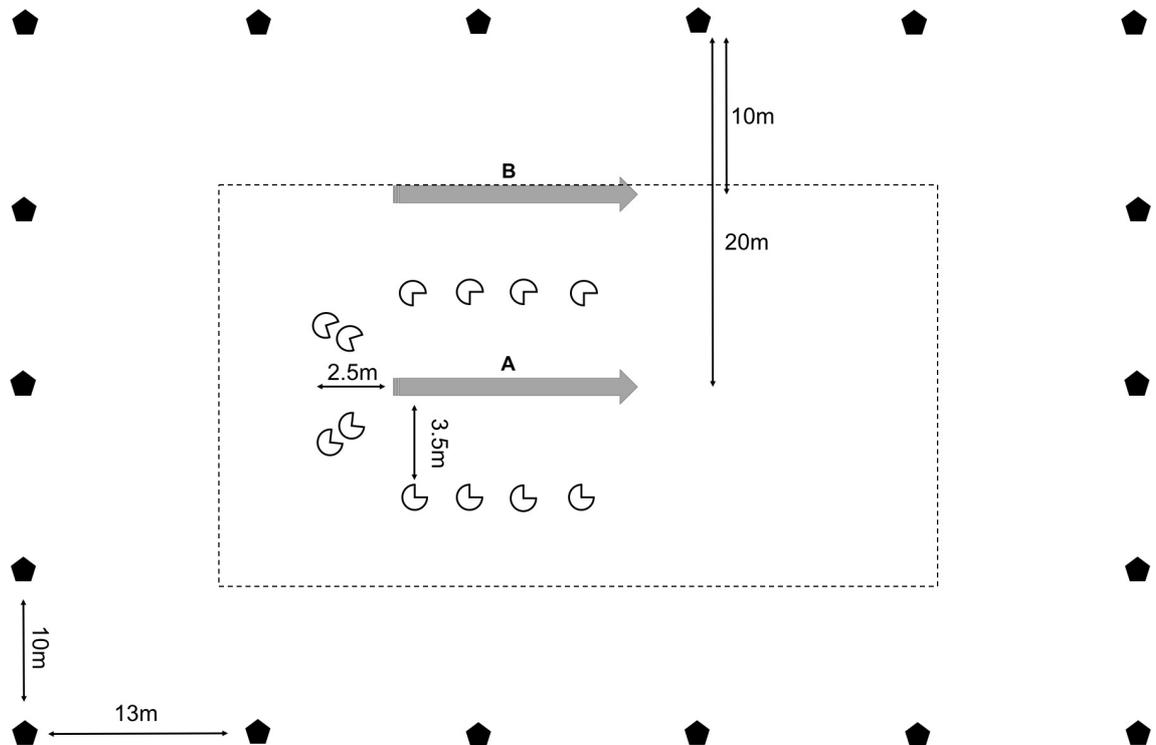
336 REFERENCES

- 337 Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S., Al-Ammar, M. A., & Al-
338 Khalifa, H. S. (2016). Ultra Wideband Indoor Positioning Technologies: Analysis and
339 Recent Advances. *Sensors (Basel)*, 16(5)doi:10.3390/s16050707 Retrieved from
340 <http://www.ncbi.nlm.nih.gov/pubmed/27196906>
- 341 Aughey, R. J. (2011). Increased high-intensity activity in elite Australian football finals matches.
342 *Int J Sports Physiol Perform*, 6(3), pp. 367-379. Retrieved from
343 <https://www.ncbi.nlm.nih.gov/pubmed/21911862>
- 344 Aughey, R. J. (2013). Widening margin in activity profile between elite and sub-elite Australian
345 football: a case study. *J Sci Med Sport*, 16(4), pp. 382-386.
346 doi:10.1016/j.jsams.2012.10.003 Retrieved from
347 <https://www.ncbi.nlm.nih.gov/pubmed/23391433>
- 348 Aughey, R. J., Goodman, C. A., & McKenna, M. J. (2014). Greater chance of high core
349 temperatures with modified pacing strategy during team sport in the heat. *J Sci Med*
350 *Sport*, 17(1), pp. 113-118. doi:10.1016/j.jsams.2013.02.013 Retrieved from
351 <https://www.ncbi.nlm.nih.gov/pubmed/23689104>
- 352 Coventry, E., Ball, K., Parrington, L., Aughey, R., & McKenna, M. (2015). Kinematic effects of a
353 short-term fatigue protocol on punt-kicking performance. *J Sports Sci*, 33(15), pp.
354 1596-1605. doi:10.1080/02640414.2014.1003582 Retrieved from
355 <https://www.ncbi.nlm.nih.gov/pubmed/25620155>
- 356 Delaney, J. A., Cummins, C. J., Thornton, H. R., & Duthie, G. M. (2017). Importance, reliability
357 and usefulness of acceleration measures in team sports. *J Strength Cond*
358 *Res*doi:10.1519/JSC.0000000000001849 Retrieved from
359 <https://www.ncbi.nlm.nih.gov/pubmed/28195980>
- 360 Delaney, J. A., Duthie, G. M., Thornton, H. R., Scott, T. J., Gay, D., & Dascombe, B. J. (2016).
361 Acceleration-Based Running Intensities of Professional Rugby League Match Play. *Int J*
362 *Sports Physiol Perform*, 11(6), pp. 802-809. doi:10.1123/ijsp.2015-0424 Retrieved
363 from <https://www.ncbi.nlm.nih.gov/pubmed/26693738>
- 364 .
- 365 Goncalves, B. V., Figueira, B. E., Macas, V., & Sampaio, J. (2014). Effect of player position on
366 movement behaviour, physical and physiological performances during an 11-a-side
367 football game. *J Sports Sci*, 32(2), pp. 191-199. doi:10.1080/02640414.2013.816761
368 Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/24016056>
- 369 Hedley, M., Mackintosh, C., Shuttleworth, R., Humphrey, D., Sathyan, T., & Ho, P. (2010).
370 Wireless tracking system for sports training indoors and outdoors. *Procedia*
371 *Engineering*, 2, pp. 2999-3004.
- 372 Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for
373 studies in sports medicine and exercise science. *Med Sci Sports Exerc*, 41(1), pp. 3-13.
374 doi:10.1249/MSS.0b013e31818cb278 Retrieved from
375 <https://www.ncbi.nlm.nih.gov/pubmed/19092709>
- 376 Leser, R., Schleindlhuber, A., Lyons, K., & Baca, A. (2014). Accuracy of an UWB-based position
377 tracking system used for time-motion analyses in game sports. *Eur J Sport Sci*, 14(7),
378 pp. 635-642. doi:10.1080/17461391.2014.884167 Retrieved from
379 <http://www.ncbi.nlm.nih.gov/pubmed/24512176>
- 380 Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2007). Survey of wireless indoor positioning
381 techniques and systems. *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.*, 37, pp. 1067-
382 1080.
- 383 Malone, J. J., Lovell, R., Varley, M. C., & Coutts, A. J. (2016). Unpacking the Black Box:
384 Applications and Considerations for Using GPS Devices in Sport. *Int J Sports Physiol*
385 *Perform*, pp. 1-30. doi:10.1123/ijsp.2016-0236 Retrieved from
386 <http://www.ncbi.nlm.nih.gov/pubmed/27736244>
- 387 Mautz, R. (2012). *Indoor Positioning Technologies* (Habilitation Thesis. ETH, Zurich).

- 388 Ogris, G., Leser, R., Horsak, B., Kornfeind, P., Heller, M., & Baca, A. (2012). Accuracy of the LPM
389 tracking system considering dynamic position changes. *J Sports Sci*, 30(14), pp. 1503-
390 1511. doi:10.1080/02640414.2012.712712 Retrieved from
391 <http://www.ncbi.nlm.nih.gov/pubmed/22906154>
- 392 Parrington, L., Ball, K., & MacMahon, C. (2014). Biomechanical characteristics of handballing
393 maximally in Australian football. *Sports Biomech*, 13(4), pp. 307-319.
394 doi:10.1080/14763141.2014.981201 Retrieved from
395 <https://www.ncbi.nlm.nih.gov/pubmed/25428519>
- 396 Peacock, J., Ball, K., & Taylor, S. (2017). The impact phase of drop punt kicking for maximal
397 distance and accuracy. *J Sports Sci, Epub ahead of*
398 *print*doi:10.1080/02640414.2016.1266015
- 399 Rhodes, J., Mason, B., Perrat, B., Smith, M., & Goosey-Tolfrey, V. (2014). The validity and
400 reliability of a novel indoor player tracking system for use within wheelchair court
401 sports. *J Sports Sci*, 32(17), pp. 1639-1647. doi:10.1080/02640414.2014.910608
402 Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/24758599>
- 403 Sathyan, T., Shuttleworth, R., Hedley, M., & Davids, K. (2012). Validity and reliability of a radio
404 positioning system for tracking athletes in indoor and outdoor team sports. *Behav Res*
405 *Methods*, 44(4), pp. 1108-1114. doi:10.3758/s13428-012-0192-2 Retrieved from
406 <http://www.ncbi.nlm.nih.gov/pubmed/22477436>
- 407 Scott, M. T., Scott, T. J., & Kelly, V. G. (2016). The Validity and Reliability of Global Positioning
408 Systems in Team Sport: A Brief Review. *J Strength Cond Res*, 30(5), pp. 1470-1490.
409 doi:10.1519/JSC.0000000000001221 Retrieved from
410 <http://www.ncbi.nlm.nih.gov/pubmed/26439776>
- 411 Sweeting, A. J., Aughey, R. J., Cormack, S. J., & Morgan, S. (2017). Discovering frequently
412 recurring movement sequences in team-sport athlete spatiotemporal data. *J Sports*
413 *Sci*, pp. 1-7. doi:10.1080/02640414.2016.1273536 Retrieved from
414 <http://www.ncbi.nlm.nih.gov/pubmed/28282752>
- 415 Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for
416 measuring instantaneous velocity during acceleration, deceleration, and constant
417 motion. *J Sports Sci*, 30(2), pp. 121-127. doi:10.1080/02640414.2011.627941 Retrieved
418 from <http://www.ncbi.nlm.nih.gov/pubmed/22122431>
- 419 Varley, M. C., Jaspers, A., Helsen, W. F., & Malone, J. J. (2017). Methodological Considerations
420 When Quantifying High-Intensity Efforts in Team Sport Using Global Positioning
421 System Technology. *Int J Sports Physiol Perform*, pp. 1-25. doi:10.1123/ijsp.2016-0534
422 Retrieved from <https://www.ncbi.nlm.nih.gov/pubmed/28051343>
- 423 Ye, R., Redfield, S., & Liu, H. (2010) *High-precision indoor UWB localization: Technical*
424 *challenges and method*. Paper presented at the 2010 IEEE International Conference on
425 Ultra-Wideband (ICUWB), Nanjing, China.
426

FIGURE LEGENDS

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).



ACCCV

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.

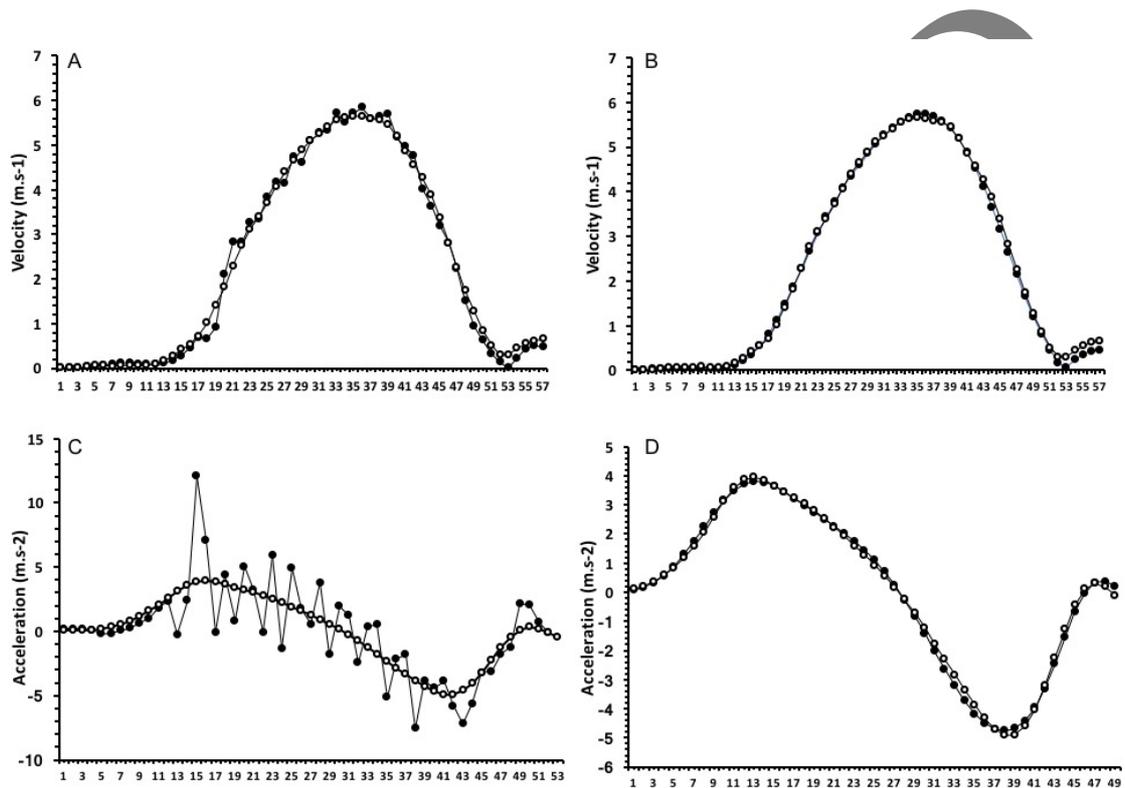


Table 1. Comparison of mean and peak speed, mean and peak acceleration and deceleration, and distance between Clearsky and Vicon (smoothed with the same filters as applied to Clearsky) during four different locomotion activities performed in the centre and on the side of an indoor court.

	Subject Means									
	Court centre			Court side			Subject SDs (%)		Device SDs (%)	
	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	14.8, ±6.3; mod.****	0.35 m·s ⁻²	0.34 m·s ⁻²	2.8, ±5.6; trivial ⁰	20, ±11.7	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	20.6, ±12.8; small***	31, ±28	15, ±13	22, ±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, ±11.8; trivial ⁰	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 ⁰⁰⁰⁰	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 ⁰⁰⁰⁰	3.70 m·s ⁻¹	3.64 m·s ⁻¹	1.9, ±0.7; trivial ⁰⁰⁰⁰	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 ⁰⁰	1.22 m·s ⁻²	1.23 m·s ⁻²	-1.1, ±3.7; trivial ⁰⁰⁰⁰	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 ⁰⁰	2.58 m·s ⁻²	2.30 m·s ⁻²	12.1, ±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	-15.9, ±4.6; small***	1.00 m·s ⁻²	1.07 m·s ⁻²	-6.1, ±4.9; trivial ⁰⁰	45, ±42	22, ±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 ⁰⁰⁰⁰	2.17 m·s ⁻²	2.12 m·s ⁻²	2.4, ±4.5; trivial ⁰⁰⁰⁰	36, ±42	15, ±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 ⁰⁰⁰	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.	0.0, ±n.a.
mean acc.	1.60 m·s ⁻²	1.79 m·s ⁻²	-10.8, ±2.5; mod.****	1.83 m·s ⁻²	2.08 m·s ⁻²	-12.3, ±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	-28.3, ±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	-16.2, ±9.2; mod.***	4.89 m·s ⁻²	4.54 m·s ⁻²	7.8, ±13.3; small	17, ±9.4	10, ±12	55, ±9.4	8.7, ±50.5
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
Change of Direction										
mean speed	1.05 m·s ⁻¹	0.92 m·s ⁻¹	14.2, ±2.5; mod.****	1.02 m·s ⁻¹	0.77 m·s ⁻¹	31.7, ±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	13.2, ±1.4; v.large****	3.41 m·s ⁻¹	2.93 m·s ⁻¹	16.4, ±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	10.3, ±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	14.4, ±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	36.4, ±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	26.0, ±4.1; large****	3.37 m·s ⁻²	2.48 m·s ⁻²	35.9, ±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	17.7, ±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: ⁰possibly, ⁰⁰likely, ⁰⁰⁰very likely, ⁰⁰⁰⁰most likely.