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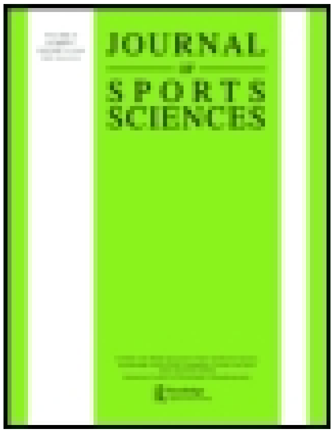

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Integrating different tracking systems in football: multiple camera semi-automatic system, local position measurement and GPS technologies

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Abstract
During the past decade substantial development of computer-aided tracking technology has occurred. Therefore, we aimed to provide calibration equations to allow the interchangeability of different tracking technologies used in soccer. Eighty-two highly trained soccer players (U14–U17) were monitored during training and one match. Player activity was collected simultaneously with a semi-automatic multiple-camera (Prozone), local position measurement (LPM) technology (Inmotio) and two global positioning systems (GPSports and VX). Data were analysed with respect to three different field dimensions (small, <30 m^2 to full-pitch, match). Variables provided by the systems were compared, and calibration equations (linear regression models) between each system were calculated for each field dimension. Most metrics differed between the 4 systems with the magnitude of the differences dependant on both pitch size and the variable of interest. Trivial-to-small between-system differences in total distance were noted. However, high-intensity running distance (>14.4 km · h^{-1}) was slightly-to-moderately greater when tracked with Prozone, and accelerations, small-to-very largely greater with LPM. For most of the equations, the typical error of the estimate was of a moderate magnitude. Interchangeability of the different tracking systems is possible with the provided equations, but care is required given their moderate typical error of the estimate.

Keywords: *soccer, tracking system, match analysis, training load, agreement, calibration equations*

Introduction

Monitoring players' physical activity during both matches and training is today a common practice in professional soccer (Carling, 2013). The detailed analysis of match activity demands allows individual physical performance profile to be determined, which can be used to define training orientations and/or design soccer-specific training drills (Di Salvo et al., 2007). In parallel, the quantification of training sessions physical demands is an integral part of training load management and monitoring players (Casamichana, Castellano, Calleja-Gonzalez, San Román, & Castagna, 2013; Scott, Lockie, Knight, Clark, & Janse De Jonge, 2013) permitting coaching staff to readjust training periodisation on a day-by-day basis.

During the past decade, there has been a substantial development of computer-aided tracking technology for the examination of player activity during training and match-play. Sophisticated systems such as multiple camera semi-automatic systems, local position measurement (LPM) technology and global positioning system (GPS) technology are now capable of quickly recording and processing the data of all players' physical contributions throughout an entire match or training session (Carling, Bloomfield, Nelsen, & Reilly, 2008). Most of these systems/technologies have been shown to allow accurate examination of players' activity on the field, with the faster and/or less linear the movements, the poorer the accuracy and the reliability (Di Salvo, Collins, Macneill, & Cardinale, 2006; Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Frencken, Lemmink, & Delleman, 2010; Ogris et al., 2012; Portas, Harley, Barnes, & Rush, 2010; Varley, Fairweather, & Aughey, 2012).

Despite their growing use in elite football, limited attempt to date has been made to comprehensively evaluate the agreement between these different systems/technologies (Harley, Lovell, Barnes, Portas, & Weston, 2011; Randers et al., 2010). Results from

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these studies have shown that multiple camera semi-automatic systems tend to report slightly-to-moderately (Harley et al., 2011) and moderately-to-largely (Randers et al., 2010) greater distance covered at high intensity (i.e., >~18 km · h^{-1}) than GPS technology. With the exception of one study comparing the accuracy of position detection between LPM and an image-based system (1 single camera) (Siegle, Stevens, & Lames, 2013), there is however, to our knowledge, no comparison between LPM technology and traditional tracking systems (i.e., multiple camera semi-automatic systems and GPS). Importantly also, the latter comparisons have been limited to match activities in a limited number of players (i.e., 6 (Harley et al., 2011) and 13–20 (Randers et al., 2010)); consequently, solutions to use these systems interchangeably are still missing. Systems interchangeability is an important point for practitioners in professional clubs, who often use two different systems throughout the week, i.e., GPS technology during training sessions and multiple camera semi-automatic systems during matches. In order to have an integrated approach to monitoring training/competitive load over an entire week, it is therefore relevant to quantify the agreement between different technologies/systems, and compare their validity and reliability during the same running drills. Consequently, the first objective of this study was to provide calibration equations to allow the interchangeability of three different tracking technologies used in professional soccer (i.e., semi-automatic multiple-camera, *Prozone*; LPM, *Inmotio* and GPS technology, *GPSports* and *VX*) to measure on-field running movements in highly trained young players. The second aim was to provide further information on the accuracy and reliability of the three technologies while comparing their measures with that obtained at the same time with timing gates used as gold standards.

Methods

Participants

Eighty-two highly trained soccer players representative of U14 to U17 teams from an elite soccer academy, and 14 athletes from the same academy track and field group (U16–U18) were studied. All soccer players participated on average in ~14 h of combined soccer-specific training and competitive play per week (6–8 soccer training sessions, 1 strength training session, 1–2 conditioning sessions, 1 domestic match per week and 2 international club matches every 3 weeks). All players had a minimum of 3 years prior soccer-specific training. Physical characteristics and match running performance of the players have been reported elsewhere (Buchheit, Mendez-Villanueva, Simpson, & Bourdon, 2010). The track and field athletes had on average in ~14 h of combined strength and speed training per week and were familiar with all the different sprints tests. These data arose as a condition of player monitoring in which player activities are routinely measured over the course of the competitive season. Therefore, usual appropriate ethics committee clearance was not required (Winter & Maughan, 2009). Nevertheless, to ensure team and player confidentiality, all physical performance data were anonymised before analysis, and the study followed the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Experimental overview

A summary of the different test protocols, variables measured and analyses conducted are presented in Table I. The 4 systems examined/compared in the present study were representative of three different technologies currently used in elite football: LPM technology (Inmotio Object tracking v2.6.9.545, 45 Hz, Amsterdam, the Netherlands), semi-automatic multiple-camera (Prozone 10 Hz, Leeds, UK) and GPS technology (GPSports, SPI Pro XII, 5 Hz, GPSport, chip version 2.6.4, Canberra, Australia, and VX, VX340a, chip version

Table I. Description of the different test protocols, variables measured and analyses conducted.

	Agreement between the systems	Validity	Reliability
Activity	Four training sessions and a friendly match	A generic sprint session (all tests repeated twice) 1. Runs on an oval 200-m course • 7.2 km · h^{-1} • 14.4 km · h^{-1} • 19.8 km · h^{-1} 2. Standardised sprints • 40-m sprint • L-shaped sprint • Zigzag-shaped sprint	
Measures	Distance into speed zones and number of accelerations	1. Distance into speed zones during the runs 2. Peak speed and acceleration (4 systems) and sprint times (timing gates and Inmotio)	
Analysis	Standardised between-system differences and calibration equations with TEE and correlation coefficients	Standardised bias compared with timing gates, TEE and correlation coefficients	Standardised CV and ICC using data from the repeated trials within each system

Note: TEE: typical error of the estimate; CV: coefficient of variation, ICC: intraclass correlation coefficient.

VXLogFW_V147–02_04Feb13, 4 Hz, Lower Hutt, New Zealand). Data were collected within 4 days in an open roof stadium (pitch: 105 × 70 m, natural grass), over 4 training sessions (2 with the U15 and 2 with the U17 team), a generic sprint session (no ball, with the track and field group) and a 20-min friendly match (combination of U14 and U15). During all sessions, players/athletes wore Inmotio, GPSports and VX sensors simultaneously (there is no need for a sensor for Prozone). The data collected with the 4 systems were processed within a month after the study by independent technicians/researchers, which were blinded to all other results.

To provide solutions to allow the interchangeability between the different systems, the variables provided by the 4 systems during the same training and matches were compared, and we provided calibration equations between each system (to predict the measures that could be expected with a given system from the data collected with another system).

In order to provide additional information on the validity of the 4 systems, we compared the measures provided by each of the 4 systems during standardised drills with running distance/times collected with timing gates (gold standard). Distance covered during different constant-velocity runs, peak velocity (V_{peak}) and peak acceleration (Acc_{peak}) were obtained from each system. The distance covered during the sprinting drill (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010a; Waldron, Worsfold, Twist, & Lamb, 2011) was not examined. The following runs were examined (Figure 1): (1) Runs at 7.2, 14.4 and 19.8 km · h^{-1} on an oval 200-m course drawn on the soccer pitch (Gray, Jenkins, Andrews, Taaffe, & Glover, 2010), (2) 2 × 40-m sprints, (3) 2 × L-shaped sprints (10 m + 10 m, 90° change of direction) and (4) 2 × Zigzag-shaped sprints (5 m + 5 m + 5 m + 5 m, 90° changes of direction). It is worth noting, however, that the variables measured by the different systems are not all strictly comparable to the criterion measures. For instance, while V_{peak} could be measured by all 4 tracking systems (as the maximal velocity reached over a 0.8-s window) and the gates using the best 10-m split, Acc_{peak} (as the maximal changes in velocity reached over a 0.8-s window) could not be assessed with the gates; the criterion measure for acceleration was actually the average acceleration over the first 10 m. Similarly while we examined Acc_{peak} and V_{peak} during the change of direction speed drills, the criterion measure was the time over the course. At present, only Inmotio can easily provide estimated distance and time for set distances (which is a feature of the LPM method).

To examine the reliability of each system, all the above-mentioned drills were repeated twice within a few minutes.

The number of satellites for GPS was satisfactory during all sessions: range: 7–12, average 9.5 ± 2 for GPSports and range: 7–14, average 9.5 ± 2 for VX. The horizontal dilution of position (HDOP), which is a reflection of the geometrical arrangement of satellites and is related to both the accuracy and quality of the signal was not collected, which is a limitation. Data processing for GPS systems was achieved while using the software provided by each manufacturer/company (AMS R1–2012.9 for GPSports, 3.88.0.0 for VX, Inmotio Object tracking v2.6.9.545).

The Prozone system is configured for match situations which feature quantifiable team shape/formations as previously described (Di Salvo et al., 2006, 2009). The standard system is not configured for monitoring training sessions and although best efforts were made to control the environment in this study, multiple player ID issues were experienced during data collection due to test participants leaving the playing field in an ad hoc manner or entering covered areas with no visibility to the Prozone tracking

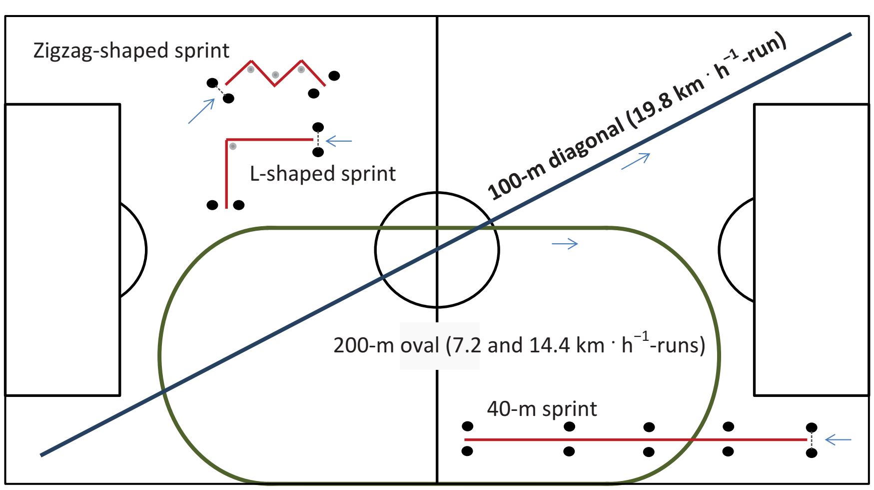

Figure 1. Illustration of the different test protocols. Arrows show tests start and running direction. Black circles refer to timing gates locations. Grey circles refer to cones.

sensors. In addition, for standard operational match situations, the Prozone system utilises a separate outside broadcasting camera feed to continually validate trajectory player ID and cross reference with eventing data concerning player actions in matches. However, this function was not available or employed for the duration of the data capture in this study, nor were any ball "events" captured. Considerable care and attention was given in order to ensure that the Prozone data provided were as accurate as possible, however, it is unlikely to achieve the same quality standard as a normal match situation. To assess the level of reproducibility of this particular procedure, all data were processed twice by two independent Prozone teams. The differences and the coefficient of variation (CV) between the two analyses were all non-substantial (standardised difference <0.2), the CV and intraclass correlation coefficient (ICC) for the reliability analysis were comparable between the two sets of data analysis, and the comparisons with the other systems were similar (i.e., the magnitude of the between-system differences, the biases and the correlations coefficients were of similar magnitude). Therefore, only data from the first analysis were used for the study.

Finally, the Inmotio system was installed, calibrated and used by three qualified technicians from the Inmotio Company during all sessions. Players wore an LPM vest containing a transponder on the back and antennas on both shoulders, ensuring optimal line of fight to the base stations (Stevens et al., 2014). A fourth qualified technician then processed the data as previously described (Stevens et al., 2014) using the dedicated software (Inmotio Object tracking v2.6.9.545, 45 Hz, Amsterdam, the Netherlands).

Data analysis

Data in text and figure are presented as mean with 90% confidence limits (CL) and confidence intervals (CI). All data were first log-transformed to reduce bias arising from non-uniformity error. Only complete player data sets were analysed (e.g., including data from all the 4 systems). Validity analysis included comparison of the different metrics with the reference measures (bias, but only when the metrics were similar, e.g., distance vs. distance or speed vs. speed), the typical error of the estimate (both in % and in standardised units) and the magnitude of the correlations between the systems. Data from all repeated trials (e.g., two runs at 19.8 $km \cdot h^{-1}$ on the 200-m oval, two 40-m sprints or two Zigzag-shaped sprints) were used to calculate for each system (1) the typical error of measurement, expressed as a CV (% absolute reliability) and (2) the ICC (relative reliability). To assess the agreement between the different systems, all analyses were performed with respect to three different field dimensions (i.e., small, <30 × 30 m; medium, <50 × 50 m; and full pitch, match). Between-system standardised differences were calculated using pooled standard deviations. Uncertainty in each effect was expressed as 90% CL and as probabilities that the true effect was substantially positive and negative. These probabilities were used to make a qualitative probabilistic mechanistic inference about the true effect: if the probabilities of the effect being substantially positive and negative were both >5%, the effect was reported as unclear; the effect was otherwise clear and reported as the magnitude of the observed value. The scale was as follows: 25−75%, possible; 75−95%, likely; 95−99%, very likely; >99%, almost certain. Additionally, we provided calibration (linear) equations to predict the measures that could be expected with a given system from the data collected with another system. The typical error of the estimate (TEE, %) and the magnitude of the correlations between the systems were also calculated. When using the data from all training sessions/matches and speed zones pooled together, the TEEs for the calibration equations were consistently very large, irrespective of the model used (e.g., linear, log-linear, log-log). Different calibration equations were therefore provided for the same three pitch dimensions as for between-system differences, i.e., within the box area (<30 × 30 m), half a pitch (<50 × 50 m) and full pitch (match), and for different speed zones. This procedure substantially decreased the magnitude of the errors within each pitch dimension/speed zone. A linear model was retained for all calibration equations since using other models didn't decrease the TEEs. Threshold values for standardised differences, typical error and typical error of the estimate were >0.2 (small), >0.6 (moderate), >1.2 (large) and very large (>2) (Hopkins, Marshall, Batterham, & Hanin, 2009). The magnitude of the ICC was assessed using the following thresholds: >0.99, extremely high; 0.99–0.90, very high; 0.90–0.75, high; 0.75–0.50, moderate; 0.50–0.20, low; <0.20, very low (WG Hopkins, unpublished observations). Finally, the following criteria were adopted to interpret the magnitude of the correlation: ≤0.1, trivial; >0.1–0.3, small; >0.3–0.5, moderate; >0.5–0.7, large; >0.7–0.9, very large; and >0.9–1.0, almost perfect. If the 90% CI overlapped small positive and negative values, the magnitude was deemed unclear; otherwise that magnitude was deemed to be the observed magnitude (Hopkins et al., 2009).

Results

There was no loss of data with Prozone and Inmotio. With the GPS systems, 4 (<2%, GPSsports) and 1

(<1%, VX) files could not be analysed due to technical issues (no more battery and/or poor GPS signal).

Agreement

Most of the metrics collected during either training sequences over different pitch sizes or during a friendly match on the full pitch differed between the 4 systems, and the magnitude of the between-system differences was related to both pitch size and the variable of interest. Overall, while there were small between-system differences in total distance, Prozone tended to report largely greater distance at high speed than the 3 other systems across all pitch sizes (Figure 2). Tables II, III and IV show selected calibration equations that can be used, at the team level, to predict the measures that could be expected with a given system from the data collected with another system. It is worth noting that the typical error of estimate was often of small-to-moderate magnitude.

Validity

Distance ran at different speeds. When comparing the distance recorded during the three runs at three different running speeds with the reference distance (200 m), Inmotio tended to largely and moderately underestimate the distance ran at 7.2 and $14.4\ km \cdot h^{-1}$ (e.g., +47 m), respectively. Prozone and GPSports tended to moderately (e.g., +47 m at $14.4\ km \cdot h^{-1}$) and largely (e.g., +50 m at $14.4\ km \cdot h^{-1}$) overestimate the distance ran at all intensities (Figure 3). VX showed values within a small range of variation at $14.4\ km \cdot h^{-1}$ (+37 m) but slightly underestimated and overestimated the distance ran at 7.2 and $19.8\ km \cdot h^{-1}$, respectively. In overall, while VX showed the lower bias in overall, Prozone provided the most consistent distance output across all speed intensities (i.e., the magnitude of overestimation was constant).

Linear speed and acceleration. The data are presented in Table V. The accuracy to measure V_{peak} was good for all systems. V_{peak} measures from all systems were

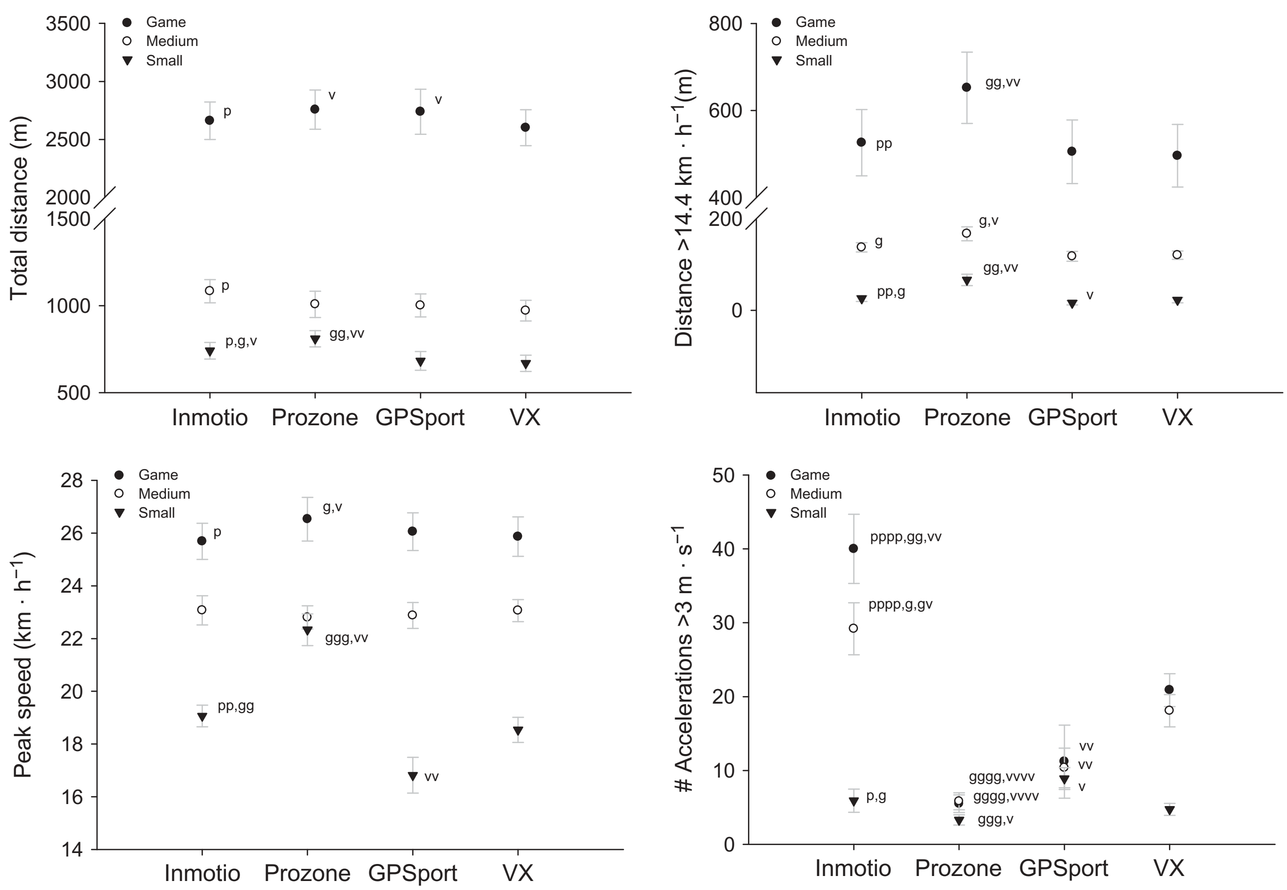

Figure 2. Mean total distance, distance ran above $14.4\ km \cdot h^{-1}$, peak speed and the number of accelerations above $3\ m \cdot s^{-2}$ (90% CIs) measured by each tracking system during a friendly match played on the full pitch, and training sequences over medium or small pitch areas. The letters refer to substantial difference compared with the other system with "p", "g" and "v" referring to Prozone, GPSport and VX, respectively. The number of letters indicates small, moderate, large or very large differences, respectively. n = 16, 205 and 163 for full (match), medium or small pitch areas, respectively. Only clear (at least possible) differences are reported.

Table II. Calibration equations between the three different technologies during training within a small area (<20–30 m^2) for total distance covered and distance ran above 14.4 km · h^{-1}. Given the good agreement between GPSports and VX measures, and the higher number of files available for GPSports, GPSports data were used as a generic measure for GPs technology.

		Inmotio	Prozone
TD	Prozone	P = (0.64 In) + 318 m TEE: 34.8% (31.5;39.0) ## *r*: 0.55 (0.45;0.64) ** In = (0.61 P + 261 m TEE: 45.5% (41.0;51.1) ## *r*: 0.55 (0.45;0.64) **	
	GPSports	G = (1.02 In) – 103 m TEE: 26.4% (23.9;29.4) # *r*: 0.94 (0.92;0.95) ***** In = (0.82 G) + 207 m TEE: 16.4% (15.0;18.3) # *r*: 0.94 (0.92;0.95)*****	G = (0.64 P) + 142 m TEE: 81.7% (72.9;93.0) ## *r*: 0.50 (0.40;0.59) ** P = (0.54 G) + 437 m TEE: 36.4% (32.9;40.7) ## *r*: 0.50 (0.40;0.59) **
D > 14.4 km · h^{-1}	Prozone	P = (1.11 In) + 37 m TEE: 200.0% (183.6;220.7) ## *r*: 0.54 (0.44;0.62) ** In = (0.26 P) + 12 m TEE: 41.1% (37.6;54.2) ## *r*: 0.54 (0.44;0.62) **	
	GPSports	G = (0.50 In) – 2 m TEE: 61.6% (56.4;67.9) ## *r*: 0.68 (0.61;0.75) *** In = (0.94 G) + 14 m TEE: 151.5% (138.9;167.0) ## *r*: 0.68 (0.61;0.75) ***	G = (−1.4 P) + 754 m TEE: 381.1% (349.3;420.0) ## *r*: −0.35 (−0.46;−0.23) * P = (−0.09 G) + 128 m TEE: 10.2% (9.3;11.2) ## *r*: −0.35 (−0.46;−0.23) *

Notes: TD: total distance, D > 14.4 km · h^{-1}: distance covered above 14.4 km · h^{-1}. In the equations, P, In and G refer to Prozone, Inmotio and GPSports, respectively. The number of "#" symbols stands for small, moderate, large and very large standardised typical error of the estimate, respectively. The number of "*" symbols refers to small, moderate, large, very large and almost perfect correlations between the two systems, respectively. n = 162.

very largely correlated with gate V_{peak}. There was no substantial bias for Inmotio and GPSports, while Prozone (moderate) and VX (small) tended to overestimate and underestimate V_{peak}, respectively. The accuracy to measure acceleration (based on 10-m sprint time) was poor-to-moderate for all 4 systems (at least moderate bias and all $r < 0.90$).

Change of direction speed and acceleration. The accuracy to measure change of direction speed (based on L-shaped and Zigzag-shaped runs sprint time) was poor-to-moderate for all 4 systems (at least moderate bias and all $r < 0.90$).

Reliability

Linear speed and acceleration. The CV data are presented in Figure 4 and ICC results in Table VI. The CVs for V_{peak} during the 40-m sprint were good for all systems (1–3%). The CVs for Acc_{peak} during the 40-m sprint were lower for Inmotio (5%) than for the 3 other systems (17–23%).

Change of direction speed and acceleration. The CVs for V_{peak} during L-shaped runs were moderate for all systems, and tended to be lower for Inmotio and VX. The CVs for V_{peak} during the Zigzag-shaped run were moderate and similar for all systems. The CVs for Acc_{peak} during the both change of direction speed tests were large and similar for all systems. Finally, the CVs for the high-intensity run were small and comparable for all systems.

Discussion

In this study, we collected simultaneously for the time data from three different tracking technologies used in professional soccer (i.e., semi-automatic multiple-camera, *Prozone*; LPM, *Inmotio* and GPS technology, *GPSports* and *VX*). We were therefore able to provide for the first time some calibration equations to allow the interchangeability of the 3 systems to measure on-field running movements in highly trained young players. We also provided further assessment of the validity and reliability of all technologies. The main results are as follow: (1) metrics collected during either training (different pitch sizes) or a friendly match (full pitch) differed between the 4 systems, and the magnitude of these differences was related to both pitch size and the variable of interest; (2) most of the calibration equations calculated were still associated with small-to-moderate typical error of the estimate; (3) all systems tended to

Table III. Calibration equations between the three different technologies during training within a medium area (<50 m^2) for total distance covered, distance ran above 14.4 and 19.8 km · h^{-1}. Given the good agreement between GPSports and VX measures, and the higher number of files available for GPSports, GPSports data were used as a generic measure for GPs technology.

		Inmotio	Prozone
TD	Prozone	P = (0.90 In) + 64 m TEE: 72.6% (65.7;81.3) ## *r*: 0.67 (0.60;0.73) *** In = (0.73 P) + 348 m TEE: 43.3% (39.5;48.0) ## *r*: 0.67 (0.60;0.73) ***	
	GPSports	G = (0.97 In) – 67 m TEE: 14.3% (13.1;15.7) # *r*: 0.97 (0.96;0.97) ***** In = (0.98 G) + 122 m TEE: 12.8% (11.8;14.0) # *r*: 0.97 (0.96;0.97) *****	G = (0.73 P) + 257 m TEE: 51.1% (46.5;56.8) ## *r*: 0.63 (0.56;0.70) *** P = (0.90 G) + 155 m TEE: 76.5% (69.1;85.7) ## *r*: 0.63 (0.56;0.70) ***
D > 14.4 km · h^{-1}	Prozone	P = (0.93 In) + 48 m TEE: 68.0% (62.9;74.1) ## *r*: 0.70 (0.63;0.75) **** In = (0.52 P) + 51 m TEE: 48.0% (37.7;44.4) ## *r*: 0.70 (0.63;0.75) ****	
	GPSports	G = (0.87 In) – 9 m TEE: 26.0% (24.1;28.4) # *r*: 0.92 (0.90;0.94) ***** In = (0.98 G) + 31 m TEE: 34.2% (31.6;37.3) # *r*: 0.92 (0.90;0.94) *****	G = (0.46 P) + 34 m TEE: 40.6% (37.6;44.3) ## *r*: 0.65 (0.58;0.71) *** P = (0.92 G) + 75 m TEE: 88.8% (82.2;96.8) ## *r*: 0.65 (0.58;0.71) ***
D > 19.8 km · h^{-1}	Prozone	P = (0.84 In) + 51 m TEE: 109.8% (101.6;119.7) ## *r*: 0.60 (0.52;0.67) *** In = 0.43 P + 13 m TEE: 54.5% (50.4;59.4) ## *r*: 0.60 (0.52;0.67) ***	
	GPSports	G = 0.74 In + 0 m TEE: 41.8% (38.7;45.6) ## *r*: 0.87 (0.84;0.89) **** In = 1.01 G + 9 m TEE: 66.1% (61.2;72.1) ## *r*: 0.87 (0.84;0.89) ****	G = 0.32 P + 7 m TEE: 49.7% (45.9;54.1) ## *r*: 0.52 (0.43;0.60) *** P = 0.86 G + 28 m TEE: 158.2% (146.3;172.4) ## *r*: 0.52 (0.43;0.60) ***

Notes: TD: total distance, D > 14.4 km · h^{-1}: distance covered above 14.4 km · h^{-1}, D > 19.8 km · h^{-1}: distance covered above 19.8 km · h^{-1}. The number of "#" symbols stands for small, moderate, large and very large standardised typical error of the estimate, respectively. The number of "*" symbols refers to small, moderate, large, very large and almost perfect correlations between the two systems, respectively. n = 205.

either overestimate or underestimate the distance covered at different speed (linear runs), with the magnitude of error being speed- and technology-dependent; (4) while the validity of the 4 systems was good to measure speed over 30–40 m, the level of accuracy was only moderate for shorter distances with/without changes of direction; (5) the correlations between peak acceleration 10-m sprint times were moderate-to-low; and (6) the CV for intra-day test-retest was low for peak speed, but increased for measures of acceleration and changes of direction speed.

Agreement and interchangeability

In the present study, we found that during the same training sessions and the same match, the different metrics collected by the 4 systems differed, and that the magnitude of these differences was related the variable of interest (Figure 2). To date, the agreement between multiple camera semi-automatic systems and GPS had only been examined twice; distance covered at high-intensity (i.e., >~18 km · h^{-1}) was slightly-to-moderately (Harley et al., 2011) and moderately-to-largely (Randers et al., 2010) greater with the camera systems than with GPS technology. Present results (Figure 4) are in alignment with these latter findings, but show in addition that the magnitude of the differences is also likely related to pitch size. These findings could actually be expected, since (i) pitch size directly affects the distance ran at high speed (Hill-Haas, Dawson, Impellizzeri, & Coutts, 2011) and (ii) we observed speed-related differences in accuracy (see

Table IV. Calibration equations between the three different technologies during match-play for total distance covered, distance ran above 14.4 and 19.8 km · h^{-1}. Given the good agreement between GPSports and VX measures, and the higher number of files available for GPSports, GPSports data were used as a generic measure for GPs technology.

		Inmotio	Prozone
TD	Prozone	P = (1.03 In) + 14 m TEE: 3.0% (2.4;4.0) *r*: 0.99 (0.97;0.99) ***** In = (0.94 P) + 62 m TEE: 2.9% (2.3;4.0) *r*: 0.99 (0.97;0.99) *****	
	GPSports	G = (1.06 In) – 99 m TEE: 3.0% (2.4;4.0) # *r*: 0.97 (0.93;0.98) ***** In = (0.89 G) + 263 m TEE: 4.8% (3.8;6.6) # *r*: 0.97 (0.93;0.98) *****	G = (1.01 P) −70 m TEE: 5.4% (4.2;7.3) # *r*: 0.96 (0.92;0.98) ***** P = (0.92 G) + 250 m TEE: 4.8% (3.8;6.6) *r*: 0.96 (0.92;0.98) *****
D > 14.4 km · h^{-1}	Prozone	P = (0.98 In) + 167 m TEE: 11.3% (8.9;15.7) # *r*: 0.91 (0.82;0.96) ***** In = (0.87 P) – 68 m TEE: 13.9% (11.0;14.4) # *r*: 0.91 (0.82;0.96) *****	
	GPSports	G = (0.81 In) + 77 m TEE: 23.2% (18.1;32.8) # *r*: 0.80 (0.62;0.90) **** In = (0.89 G) + 86 m TEE: 20.6% (16.1;29.0) # *r*: 0.80 (0.62;0.90) ****	G = (0.75 P) −12 m TEE: 23.5% (14.8;33.2) ## *r*: 0.80 (0.61;0.90) **** P = (0.94 G) + 220 m TEE: 16.8% (13.2;23.5) ## *r*: 0.80 (0.61;0.90) ****
D > 19.8 km · h^{-1}	Prozone	P = (1.05 In) + 77 m TEE: 17.0% (13.3;23.7) *r*: 0.91 (0.81;0.95) ****** In = (0.81 P) – 42 m TEE: 27.2% (21.2;38.6) *r*: 0.91 (0.81;0.95) ******	
	GPSports	G = (0.67 In) + 29 m TEE: 37.9% (29.2;54.7) *r*: 0.82 (0.65;0.91) ***** In = (0.96 G) + 23 m TEE: 38.9% (30.0;56.2) *r*: 0.82 (0.65;0.91) *****	G = (0.58 P) – 7 m TEE: 42.3% (32.5;61.5) ## *r*: 0.77 (0.57;0.89) **** P = (1.06 G) + 94 m TEE: 26.5% (20.6;37.6) ## *r*: 0.77 (0.57;0.89) ****

Notes: TD: total distance, D > 14.4 km · h^{-1}: distance covered above 14.4 km · h^{-1}, D > 19.8 km · h^{-1}: distance covered above 19.8 km · h^{-1}. The number of "#" symbols stands for small, moderate, large and very large standardised typical error of the estimate, respectively. The number of "*" symbols refers to small, moderate, large, very large and almost perfect correlations between the two systems, respectively. n = 22.

Table V and Figure 3). Taken together, these data suggest that pitch size should be considered when calculating calibration equations (Tables II, III and IV). While matches are obviously played over the entire pitch, this is rarely the case during training sessions. It is worth noting that while GPS and LPM technologies are well suited to both match and training monitoring, Prozone is designed to track players' activity during matches only. Therefore, despite the adjustments made specifically for the present study (see the "Methods" section), data collection and proceeding with Prozone during the training are unlikely to have matched the standard applied to the match situation. Based on both statistical and practical considerations, we therefore provided three levels of equations, i.e., for playing sequences within the box area (<30 × 30 m), half a pitch (<550 × 50 m) and full pitch (match). This is to our knowledge the first time that such equations have been offered, so comparisons with the literature are difficult. In practice, sports scientists willing to convert match running distances collected with Prozone into GPS-expected distances can use the equation provided in Table IV (i.e., GPS = 1.01 Prozone – 70 m). If we take the example of a player who covered 9500 m in total during a match (using Prozone), a total distance of 9525 m may have been measured if he had worn one of the GPSports units examined in the present study. Similarly, during a training sequence organised within the box area (Table II), a distance of 150 m > 14.4 km · h^{-1} measured with Inmotio may be equivalent to 77 m when measured with a GPSports unit (GPS = 0.5 Inmotio – 2 m). While we trust that the actual sample size (n = 163, 205 and 22 for small, medium and fill

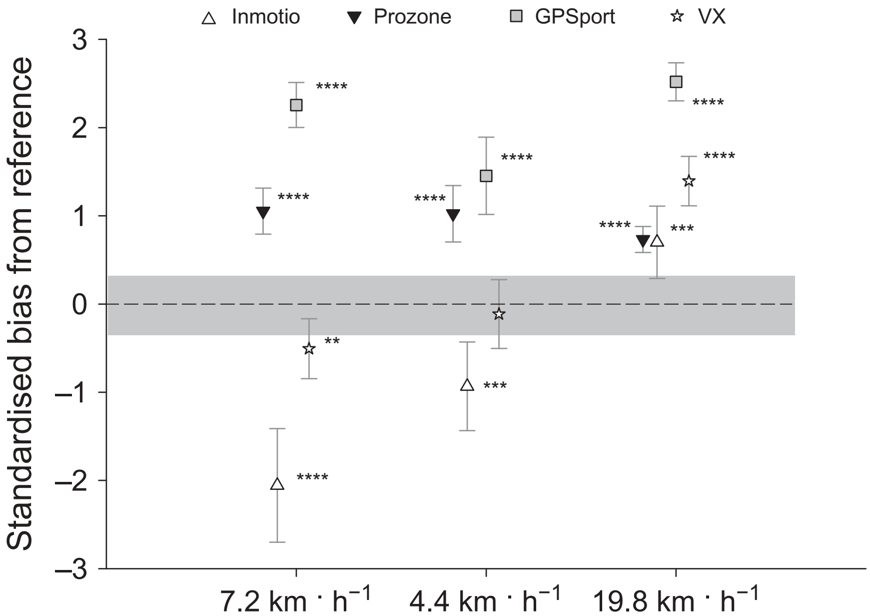

Figure 3. Standardised bias (90% CIs) in distance covered at three different set speeds for each tracking system. The number of "*" symbols indicates possible, likely, very likely and almost certain differences from the criterion measure, respectively. The grey area represents trivial difference (0.2 × pooled between-player *s*). n = 14 for runs at 7.2 and 14.4 km · h^{-1}, and n = 28 for run at 19.8 km · h^{-1}.

area, respectively) was large enough to obtain accurate equations, further cross-validation studies with external data collected during similar training/matches are required to examine the level of accuracy and precision of each equation. In fact, there were only a few equations with a non-substantial TEE (Tables II, III and IV); the conversion is therefore unfortunately not perfect, and small-to-moderate error will remain. The reasons for this source of error remain unknown, but it might be related, among others, to possible differences in transmitter movements on players' back, variations in postural sway affecting differently the different systems, and likely the difference in accuracy (Table V and Figure 3) and reliability (Table VI and Figure 4) between different systems. While averaging repeated measures is an attractive option to reduce the noise related to matches (Gregson, Drust, Atkinson, & Salvo, 2010) and training (Hill-Haas, Rowsell, Coutts, & Dawson, 2008) variations in activity patterns, the TEE as calculated here is related to the inconsistent differences between the different measurement systems. Repeating the measure might therefore not affect the magnitude of the between-subject error. Another important question to practitioners is whether the TEE for a given equation is of importance clinically (Carling, 2013). The standardisation of the error as presented in Tables II, III and IV is a first approach to try to answer this question; all errors at least small or moderate might have practical implications in terms of actual workload on the field. It is, however, worth noting that whether small standardised differences should actually be considered as the smallest practical effect with respect to matches and training activity is still unknown. The relationship between match physical activity and success is unclear (Carling, 2013) and the impact that running performance during matches and training may have on players fatigue (Nedelec et al., 2012, 2014) and fitness (Rollo, Impellizzeri, Zago, & Iaia, 2014) is likely mediated by a myriad of external factors (e.g., weekly periodisation and content of the other sessions, the use of recovery strategies), which make their relationship difficult to examine. Finally, the latest versions of the GPS systems (e.g., GPsports SPI HPU), which were not available at the time of the data recording, have been anecdotally shown to provide more accurate measures of acceleration (unpublished data). The effect of changes in hardware (e.g., new GPS units) and/or software (e.g., update) and the validity of the provided equations should be the matter of further research (Buchheit et al., 2014). Finally, between-brand comparisons within a similar type of technology (e.g., GPS Catapult vs. Statsports vs. GPSports and VX, Inmotio vs. ClearSky Catapult, or Amisco vs. Prozone) should also be the matter of future research (Johnston, Watsford, Kelly, Pine, & Spurrs, 2014; Petersen, Pyne, Portus, & Dawson, 2009).

Validity

The validity of the 4 systems was examined at different levels, i.e., distance covered at set speeds, and maximal acceleration and velocity reached during standardised drills. With respect to distance covered

Table V. Validity of the 4 tracking systems as compared with timing gates.

	Inmotio			Prozone		GPSport		VX	
Criterion (Gates)	Time	Acc_{peak}	V_{peak}	Acc_{peak}	V_{peak}	Acc_{peak}	V_{peak}	Acc_{peak}	V_{peak}
10-m time	B: −3.2% (−4.2;−3.2)## TEE: 3.1% (2.5;4.1)## *r*: 0.53 (0.23;0.74)***	TEE: 3.2% (2.6;4.3)## *r*: −0.49 (−0.71; −0.18)**	–	TEE: 3.6% (2.9;4.8)## *r*: −0.19 (−0.50;0.16)	–	TEE: 3.7% (3.0;4.9)## *r*: −0.06 (−0.39;0.29)	–	TEE: 3.7% (2.9;4.9)## *r*: 0.11 (−0.23;0.43)	–
30-m time	**B: −0.7% (−1.2;−0.2) TEE: 1.4% (1.2;1.9)# *r*: 0.93 (0.86; 0.96)*******	–	–	–	–	–	–	–	–
V_{peak} (40-m sprint)	–	–	**B: 0.4 % (0.0;0.9) TEE: 1.2% (1.0;1.6)# *r*: 0.98 (0.95;0.99)*******	–	B: 5.2 % (4.0;6.4)## TEE: 3.3% (2.6;4.4)# *r*: 0.82 (0.66;0.90)****	–	B: 0.3 % (−0.9;1.5) TEE: 3.3% (2.7;4.5)# *r*: 0.82 (0.65;0.91)****	–	B: 1.2% (0.1;2.4)# TEE: 3.4% (2.7;4.5)# *r*: 0.80 (0.64;0.90)****
L-shaped time	B: −1.9% (−2.4;−1.4)## TEE: 1.6% (1.3;2.1)# *r*: 0.82 (0.67;0.91)****	TEE: 2.7% (2.2;3.5)## *r*: −0.29 (−0.56;0.05)	TEE: 1.9% (1.5;2.5)## *r*: −0.73 (−0.85; −0.53)****	TEE: 2.7% (2.2;3.5)## *r*: −0.29 (−0.57;0.04)	TEE: 2.7% (2.2;3.5)## *r*: −0.29 (−0.56;0.05)	TEE: 2.6% (2.1;3.5)## *r*: −0.35 (−0.61;−0.02)**	TEE: 2.1% (1.7;2.7)## *r*: −0.67 (−0.82; −0.43)**	TEE: 2.9% (2.3;3.8)## *r*: −0.16 (−0.48;0.20)	TEE: 2.6% (2.1;3.5)## *r*: −0.43 (−0.68; −0.10)**
Zizag-shaped time	B: −0.1% (−0.9;−0.8) TEE: 2.6% (2.1;3.4)## *r*: 0.43 (0.11;0.64)**	TEE: 2.8% (2.2;3.8)## *r*: −0.20 (−0.51;0.16)	TEE: 2.8% (2.2;3.8)## *r*: 0.18 (−0.18;0.49)	TEE: 2.8% (2.3;3.8)## *r*: 0.05 (−0.30;0.38)	TEE: 2.8% (2.3;3.8)## *r*: −0.11 (−0.44;0.24)	TEE: 2.8% (2.3;3.8)## *r*: −0.12 (−0.45;0.23)	TEE: 2.9% (2.3;3.8)## *r*: 0.02 (−0.33;0.36)	TEE: 2.8% (2.3;3.8)## *r*: −0.09 (−0.43;0.26)	TEE: 2.8% (2.3;3.7)## *r*: 0.24 (−0.12;0.54)

Notes: V_{peak}: peak velocity reached during the test; Acc_{peak}: peak acceleration; B: mean bias (90% CLs); TEE: typical error of the estimate (90% CLs); *r*: correlation coefficient (90% CLs). The number of "#" symbols stands for small, moderate, large and very large standardised bias and TEE, respectively. For *r* values, the number of "*" symbols refers to small, moderate, large, very large and almost perfect correlations, respectively. In bold are the measures deemed to be clearly valid, i.e., non-substantial bias, small TEE and $r > 0.90$.

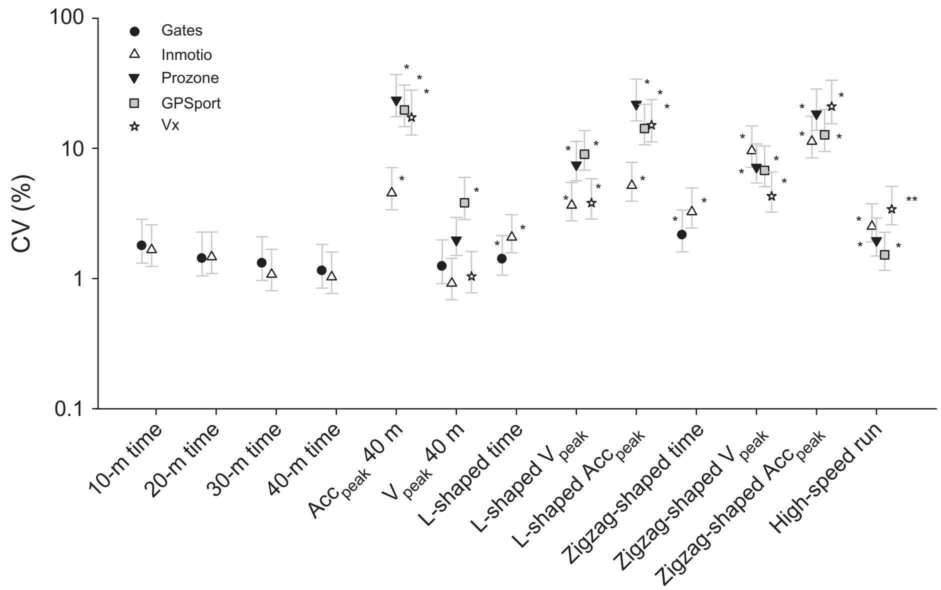

Figure 4. Coefficients of variation (90% CIs) for test-retest of different speed-related performance measures with each tracking system. Acc_{peak}: peak acceleration reached during the test; V_{peak}: peak velocity reached during the test; High-speed run refers to the distance covered within 16 s at 19.8 km · h^{-1}. Note that all measures were not available for all systems, i.e., sprint times can only be computed with timing gates and Inmotio, and peak acceleration was not computed with timing gates (since based on a fixed time window with the 4 other systems). The number of "*" symbols stands for small and moderate typical error, respectively.

Table VI. Relative reliability for timing gates and the 4 tracking systems.

	Timing gates	Inmotio	Prozone	GPSport	VX
10 m time	0.81 (0.48;0.93)***	0.70 (0.33;0.88)**			
20 m time	0.87 (0.65;0.96)***	0.80 (0.53;0.93)***			
30 m time	0.91 (0.73;0.97)****	0.91 (0.73;0.97)****			
40 m time	0.94 (0.83;0.98)****	0.94 (0.83;0.98)****			
Acc_{peak}		0.49 (0.02;0.78)*	−0.17 (−0.57;0.30)	−0.07 (−0.50;0.38)	0.04 (−0.38;0.50)
V_{peak}	0.97 (0.90;0.99)****	0.97 (0.90;0.99)****	0.88 (0.54;0.96)***	0.92 (0.86;0.92)****	0.97 (0.91;0.99)****
L-shaped time	0.60 (0.17;0.84)**	0.65 (0.30;0.85)**			
L-shaped Acc_{peak}		0.38 (−0.08;0.70)*	0.24 (−0.23;0.61)*	0.27 (−0.20;0.63)*	−0.05 (−0.50;0.42)
L-shaped V_{peak}		0.32 (−0.14;0.62)*	0.45 (0.01;0.74)*	0.07 (−0.38;0.50)	0.66 (0.29;0.86)**
Zigzag-shaped time	0.48 (−0.03;0.79)*	0.28 (−0.20;0.66)*			
Zigzag-shaped Acc_{peak}		0.21 (−0.27;0.61)*	0.43 (−0.02;0.73)*	0.36 (−0.12;0.70)*	−0.07 (−0.50;0.38)
Zigzag-shaped V_{peak}		−0.09 (−0.53;0.38)	0.30 (−0.16;0.65)*	0.61 (0.22;0.84)**	0.41 (−0.05;0.73)*
High-speed run distance		0.28 (−0.18;0.64)*	−0.47 (−0.76;0.04)*	0.20 (−0.26;0.59)*	−0.31 (−0.66;0.15)*

Notes: Intraclass correlation coefficient (90% CIs) for test-retest of different speed-related performance measures with each tracking system. Acc_{peak}: peak acceleration reached during the test; V_{peak}: peak velocity reached during the test; High-speed run refers to the distance covered within 16 s at 19.8 km · h^{-1}. ICC rating: *: low, **: moderate, ***: high, ****: very high.

during linear runs over the 200-m oval, Prozone and GPSsports tended to moderately and largely-to-very-largely overestimate the distance covered at all speeds, respectively, while the direction and magnitude of the error was speed-dependent with Inmotio and VX (Figure 2). While there is no comparable data for Prozone or VX in the literature, large overestimations (+1.5%) of distance covered over a 200-m course were also reported with 1-Hz GPSports units at 18 km · h^{-1} (Gray et al., 2010). In contrast, at the same speed on a 400- track, 5-Hz GPSports units were shown to moderately underestimate running distance by 1% to 3% (Petersen et al., 2009). Differences within (Buchheit et al., 2014; Johnston et al., 2014; Varley et al., 2012) and between (Johnston et al., 2014; Petersen et al., 2009) different GPS brands have already been

Table VII. Practical considerations when using the 4 systems.

	Equipment	Possible location(s)	Use	Data	Time to get reports	Database	Miscellaneous
Inmotio	Vest	Home training ground (outdoor and indoor)	Training + Friendly matches	Physical	~2–3 h	None	Sampling frequency related to player # Metrics likely affected by software/unit update
Prozone	None	Stadium(s) (outdoor and indoor)	Official matches	Physical + Match technical events	24 h	Extended	Players cannot leave the pitch
GPSports	Vest	Anywhere (outdoor)	Training + Friendly matches	Physical	~30 min	Extended	Metrics affected by software/unit update
VX	Vest	Anywhere (outdoor)	Training + Friendly matches	Physical	~30 min	Extended	Metrics affected by software/unit update

reported and might be related to several factors within the GPS itself or differences in data filtering and analysis within the associated software (Buchheit et al., 2014). The measurement error with GPS technology was also shown to be moderately correlated with the number of satellites to which each unit was connected (Gray et al., 2010). In the present study, however, since we wanted the data to be analysed in a real life scenario, where coaches and practitioners have to deal with the actual set of data collected (with a perfectly clear sky at least), the number of satellites was not considered in the analysis. Finally, the moderate-to-large underestimation of running distance with Inmotio is consistent with previous results with the same system (Frencken et al., 2010; Stevens et al., 2014); however, because of the large differences in running protocols (e.g., running speed, runs including changes of direction or not), results cannot be directly compared.

With respect to the standardised sprinting drills, despite some small (VX) and moderate (Prozone) bias, the validity of the 4 systems was acceptable to measure V_{peak} over 30–40 m (all $r > 0.80$ and small TEE, Table II). The validity was, however, only moderate for all systems when examining shorter distances with/without changes of direction (r: unclear to 0.7, moderate TEE, Table II). It is, however, important to mention that in the present study we focused our analysis on the V_{peak} and Acc_{peak} detected by each system, rather than the average speed over the set distances (see the "Methods" section). This is probably a reason for some of the poorer correlations coefficients and/or TEE compared with the literature. For example, Di Salvo reported almost perfect correlations for Prozone versus timing gates average speed over different sprinting distances (Di Salvo et al., 2006). In this latter study, the authors also reported summary correlation (including different sprint distances), which increases the magnitude of the correlation. With these data pooled and the limited number of data sets (i.e., $n = 3$ per distance (Di Salvo et al., 2006)), examining the specific acceleration results (or at least time/speed over a short distance) is limited. A further analysis (Di Salvo et al., 2009) of the same data (Di Salvo et al., 2006) reported a mean bias (compared with timing gates) in average velocity for all runs pooled together of 0.4%. This lower bias compared with these reported in the present study (2.7% to 5.2%, Table V) may also be related to the simultaneous analysis of all runs pooled together, in comparison with the more practical within-run analysis of the present study. The low TEE (2–3%) for V_{peak} during the sprinting drills measured with Inmotio (Table V) is similar to the data reported by Frencken et al. (2010), who used average speed during both linear and change of direction sprints. The correlation coefficient for the majority of the drills were, however, lower that those reported in this latter study (Frencken et al., 2010); this could be explained by the fact that instantaneous speed (as V_{peak} measured here) is far less reliable than average velocity (Ogris et al., 2012). Acceleration measures collected with Inmotio have been recently compared with data obtained with high-speed cameras (i.e., Vicon system), which allow a continuous monitoring of players' movements (Stevens et al., 2014). Results showed that the validity of Inmotio to measure accelerations was protocol-dependent. Peak acceleration was underestimated by 9% during runs involving 180° changes of direction, but overestimated up to 16% during movements with 90° changes of direction. Standard errors of the estimate ranged between 5% and 15% for average and peak accelerations, which tends to be greater than what we reported in the present study (i.e., <5%, Table V). However, as discussed earlier for V_{peak}, care should be taken when comparing different methods of assessment, i.e., average acceleration with timing gates versus peak acceleration with cameras. Finally, the GPS results are in agreement with recent studies showing a better accuracy of GPS for linear versus change of direction speed (Gray et al., 2010; Jennings et al., 2010a; Vickery et al., 2014). This is likely related to the fact that GPS might underestimate distance during non-linear movement due to an insufficient update rate and lean angle (standardised difference >3 to 5 when using 1-Hz GPS) (Gray et al., 2010). The poor correlations and moderate TEE when comparing GPS-derived Acc_{peak} (in $m \cdot s^{-2}$) and 10-m sprint time (Table V) are consistent with the results from previous studies comparing GPS with timing gates (Waldron et al., 2011) or speed radar (Varley et al., 2012). Recent studies have also highlighted large between-unit variations in the different metrics, which is an indirect evidence of limited accuracy (Buchheit et al., 2014; Jennings, Cormack, Coutts, Boyd, & Aughey, 2010b; Johnston et al., 2014; Petersen et al., 2009). The reasons for these sources of between-unit variations remain unclear.

Reliability

When examining the repeated high-speed ($18\ km \cdot h^{-1}$) run, the CVs and ICC were small-to-moderate and low, respectively (Figure 4 and Table VI). To our knowledge, similar test-retest analyses have not been reported for Inmotio or Prozone, but the present GPS CVs (1.5% for GPSports, 3.3% for VX) are within the 1–3% range of these reported with 1- and 5-Hz devices (Petersen et al., 2009). The greater CV for speed during the sprinting drills measured by Prozone in the present study (2% and 7% for V_{peak} and Acc_{peak}, respectively) compared with those in the Di Salvo study (~1%) (Di Salvo et al., 2006) is likely related to their use of instantaneous velocity data (Ogris et al., 2012). We could not locate any study on the reliability of the LPM technology. Present sprint data confirm that, irrespective of the measurement system, V_{peak} tends to be more reproducible than 10-m sprint time and change of direction speed. Present results also confirm that acceleration measures based on average speed (i.e., 10-m time, <2%) are more reliable than instantaneous velocity data (Ogris et al., 2012): except for Inmotio (~5%), the CV for Acc_{peak} with Prozone and the GPS ranged between 16% and 25%. These data are in line with the large CV and low ICC reported for acceleration measures during short sprints and various racquet- and team sport-specific movement patterns (Vickery et al., 2014). In previous studies where acceleration-derived variables showed lower CVs, the peak speed reached in the drills was used instead as a proxy of acceleration (<3% (Waldron et al., 2011)), and/or instantaneous GPS data were compared with instantaneous speed radar data (<5% (Varley et al., 2012)). Together with the limited validity of acceleration measures (see above), these data question the use of Acc_{peak} as provided routinely by the different systems (Buchheit et al., 2014; Stevens et al., 2014; Waldron et al., 2011).

Conclusion

In practice, all systems are of interest to monitor players' activity in the field, and each has advantages and disadvantages (Table VII). The metrics collected during different training sessions on different pitch sizes or during a friendly match on the full pitch differ between the 4 systems, and the magnitude of the between-system differences is related to both pitch size and the variable of interest. These between-system differences in running distance at set speeds can nevertheless be partially accounted for at the team level, using the calibration equations provided in this document. Because of the remaining small-to-moderate typical errors of the estimate in these equations, caution is still required when comparing/interpreting training/match activities measured by different systems. Whether the small-to-large between-system differences both in accuracy and running performance during matches/training have practical implications still remain to be determined. An important limitation of Inmotio and Prozone systems compared with GPS technology is that they can only be used on the football fields where they have been previously installed. Conversely, they can eventually be installed and used indoor and within stadiums where the use of GPS is limited (Table VII). The great interest of Prozone is that it can be used during matches, allows the collection of additional technical variables and does not require any equipment to be worn by the players. Finally, today GPS represents the most time-efficient technology with respect to data management and reports. Between GPS unit variability, within-unit chipset changes and software updates can have a substantial impact on the different metrics (Buchheit et al., 2014). It is therefore paramount to consider these factors when monitoring players over the time.

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