SCIENCE AND MEDICINE IN FOOTBALL
https://doi.org/10.1080/24733938.2023.2237493

Concurrent validity and between-unit reliability of a foot-mounted inertial measurement unit to measure velocity during team sport activity

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ABSTRACT

The concurrent validity and between-unit reliability of a foot-mounted inertial measurement unit (F-IMU) was investigated during linear and change of direction running drills. Sixteen individuals performed four repetitions of two drills (maximal acceleration and flying 10 m sprint) and five repetitions of a multi-directional movement protocol. Participants wore two F-IMUs (Playermaker) and 10 retro-reflective markers to allow for comparisons to the criterion system (Qualisys). Validity of the F-IMU derived velocity was assessed via root-mean-square error (RMSE), 95% limits of agreement (LoA) and mean difference with 95% confidence interval (CI). Between-unit reliability was assessed via intraclass correlation (ICC) with 90% CI and 95% LoA. The mean difference for instantaneous velocity for all participants and drills combined was -0.048 ± 0.581 m · s^{-1}, the LoA were from −1.09 to −1.186 m · s^{-1} and RMSE was 0.583 m · s^{-1}. The ICC ranged from 0.84 to 1, with LoA from −7.412 to 2.924 m · s^{-1}. Differences were dependent on the reference speed, with the greatest absolute difference (−0.66 m · s^{-1}) found at velocities above 7 m · s^{-1}. Between-unit reliability of the F-IMU ranges from good to excellent for all locomotor characteristics. Playermaker has good agreement with 3D motion capture for velocity and good to excellent between-unit reliability.

ARTICLE HISTORY
Accepted 7 July 2023

KEYWORDS
Inertial measurement unit; validity; reliability; locomotor activities

Introduction

In team sports, wearable sensors such as global positioning systems (GPS) and inertial measurement units (IMU) are worn at varying locations (e.g., thorax, foot) and are increasingly used to measure kinematic variables (e.g., distance, speed, acceleration) to inform the training process (Marris et al. 2021; Towlson et al. 2021; Myhill et al. 2022; Lewis et al. 2022; Jeffries et al. 2022). Practitioners should have awareness of the concurrent validity for any technology they use and the importance of this is shown by FIFA's initiatives to validate electronic performance tracking systems (FIFA 2022).

Traditionally, global navigation satellite systems (GNSS) have been predominant tools implemented in professional sport. However, for high-speed and high accelerative tasks, GNSS-derived measures may not provide sufficient spatial resolution or sampling rate to effectively accomplish this task. A recent review found a reduction in GNSS validity at higher velocities and when a frequent change of direction is involved for 1-, 5- and 10-Hz GNSS devices (Crang et al. 2021). For example, Linke et al. (2018) compared the measurement accuracy of a 15 Hz (5 Hz linearly interpolated to 15 Hz) GNSS device (GPSports) to 3D motion capture system, finding that the magnitude of error increased as speed increased with *large* standardised differences for very high-speed running during a sport-specific course (root-mean-square error [RMSE]: 9.46 m, RMSE%: 51.12%) and *moderate* standardised differences for high speed running during a small-sided game (RMSE: 4.01 m, RMSE%: 97.44%).

IMUs are an alternative method to GNSS and derive kinematic measures via a different technological and mathematical approach. They are typically attached to specific body landmarks (e.g., foot, tibia or hip) to track the acceleration of a specific body segment (Boddy et al. 2019) and comprise high-frequency sensors: accelerometers, gyroscopes and in some cases, magnetometers. IMUs can be used indoors and outdoors and have fewer potential sources of measurement error than GNSS (e.g., lack of reliance on satellites, higher sampling frequency) (Van Der Kruk and Reijne 2018). Furthermore, other measures can be derived from IMUs including spatiotemporal features of running gait (Kenneally-Dabrowski et al. 2018), peak ground reaction force (Wundersitz et al. 2013) and vertical stiffness (Buchheit et al. 2015). A recent meta-analysis reported a lack of difference between foot-mounted IMU (F-IMU)-derived measures (i.e., contact time, step frequency, flight time) and the criterion measures used (Horsley et al. 2021), highlighting the potential for gait analysis in the field. Despite this, there have been limited studies comparing IMU-derived velocity to a 3D motion capture reference system. Punchihewa et al. (2020) assessed the concurrent validity of 1000 Hz IMU-derived angular velocity during a baseball swing, finding mean absolute error percentages of 7.18% and 8.68% for hand velocity at peak and impact, respectively. This suggests the potential of IMUs for measuring velocity, but there is a lack of studies

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investigating this during running based activities and at other body landmarks.

Recently, an F-IMU designed to be worn whilst playing soccer has been used for capturing technical data (Marris et al. 2021; Towlson et al. 2021; Lewis et al. 2022), locomotor data (Myhill et al. 2022; Emmonds et al. 2022) and energy expenditure of soccer players (Dasa et al. 2022). However, the validity of the F-IMU (Playermaker, London, UK) to measure kinematic variables has yet to be fully established. Waldron et al. (2021) investigated concurrent agreement between Playermaker F-IMUs and three GNSS systems (sample rates = 18 Hz, 10 Hz, 10 Hz) during a soccer-specific, multi-directional intermittent movement protocol (SAFT90) (Waldron et al. 2021). The F-IMU recorded greater distances while changing velocity, with the total error for total distance ranging from ~25 to 50 m (Waldron et al. 2021). However, given the previously stated limitations of GNSS, their use as a criterion measurement is limited and the agreement between validity of displacement measures determined by an F-IMU system (Playermaker) should be assessed with comparison to a 3D motion capture reference system. 3D motion capture systems are considered a more appropriate criterion measure as they can measure position to sub-millimetre accuracy within a calibrated volume (Topley and Richards 2020) and can capture multi-directional movements (Van Der Kruk and Reijne 2018). Therefore, the aims of this study were firstly to investigate the concurrent validity of velocity derived from an F-IMU (Playermaker) against a 3D motion capture system (Qualisys). Secondly, to identify the between-unit reliability of the F-IMUs to determine their potential application for human motion tracking in sports.

Materials and methods

Participants and experimental overview

Sixteen individuals (4 females [age: 27 ± 2 yrs; mass: 67.8 ± 6.8 kg; height: 164.6 ± 3.9 cm], 12 males [age: 25 ± 2 yrs; mass: 82.6 ± 14.1 kg; height: 180.4 ± 12.2 cm]) participated in the concurrent validity study. According to Bujang and Baharum (2016), a sample size of 11 is required for a power of 90% and a correlation coefficient of at least 0.8. Participants completed two testing sessions, the first involved completing a 40 m sprint test to measure peak speed using timing gates (Witty, Microgate, USA) for the inclusion criteria and to complete two repetitions of 1 min 10 s of a soccer-specific, multi-directional intermittent movement protocol (SAFT90) for familiarisation. Participants were excluded if their 40 m peak speed was lower than 5.29 m · s^{-1} during familiarisation ($n = 0$). This was chosen as it is a common threshold used for very high-speed running in women's soccer (Park et al. 2019; Doyle et al. 2021; Romero-Moraleda et al. 2021) to ensure that participants would reach this speed during the SAFT90. During the second session, participants completed the full testing protocol. Ethical approval was provided for this study by Leeds Beckett Ethics Committee (REF: 84089), according to the Declaration of Helsinki, and written informed consent was received from each participant prior to participation.

Participants were fitted with an F-IMU (Playermaker, Tel Aviv, Israel) sensor on each foot over the shoe, placed above the lateral aspect of the calcanei and secured with a silicone strap, according to manufacturer instructions. A second F-IMU sensor was placed directly on top of the first sensors (Figure 1) to facilitate between-unit reliability analysis. A 9 mm retroreflective marker was placed on each participant to represent centre of mass at the T8 landmark (Figure 1) for the 3D motion capture

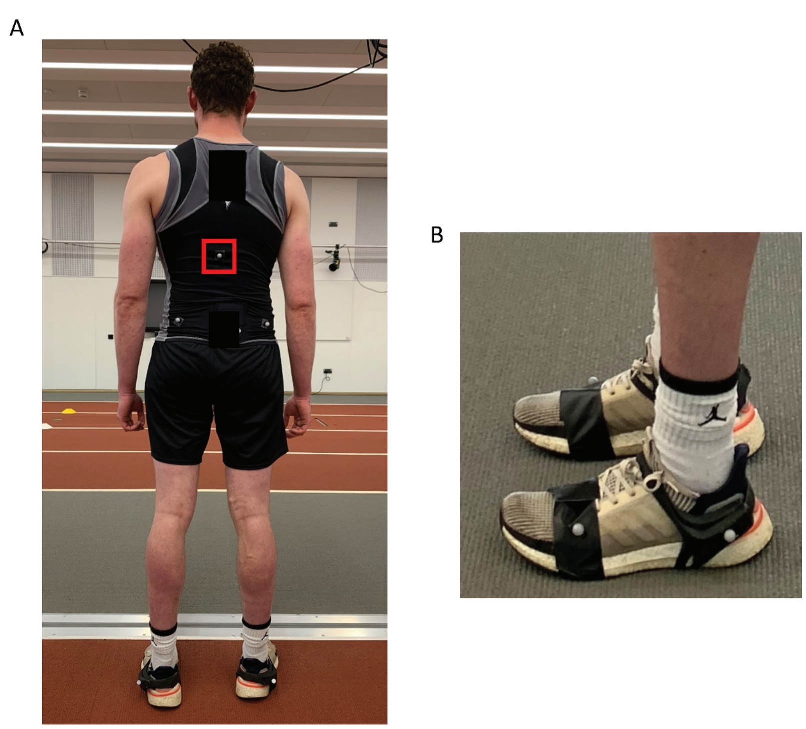

Figure 1. Equipment set-up. A) Retroreflective marker placement. *Red box highlights T8 marker*. B) Playermaker IMU placement.

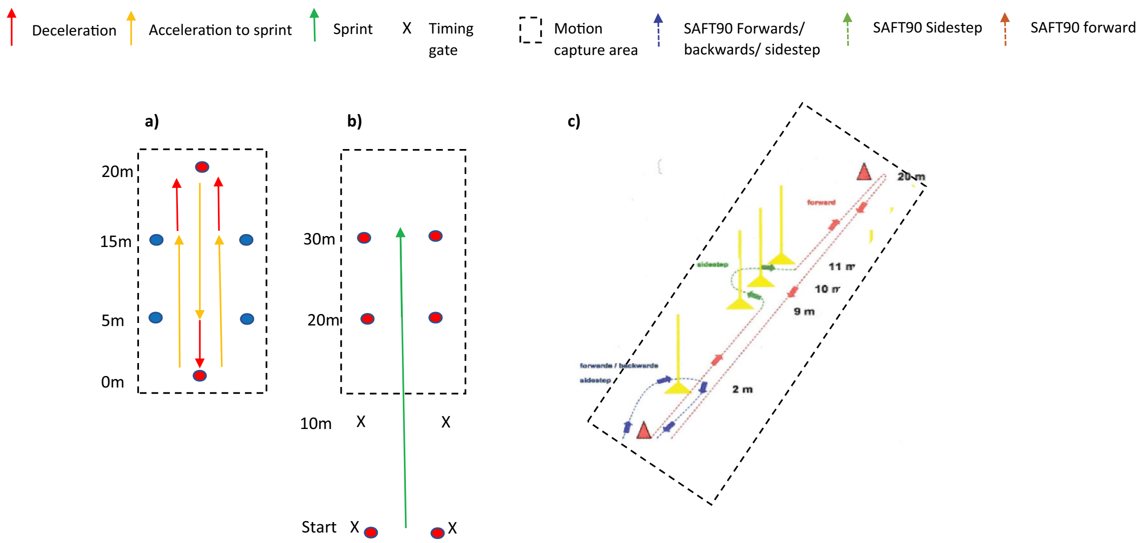

Figure 2. Overview of a) maximal acceleration drill, b) flying 10 m sprint and c) SAFT90 protocol and set-up. *1 min rest between reps and 2 min rest between drill types*: a) MAD protocol (×4): start at 0 m cone with acceleration to sprint to 15 m, deceleration to 20 m, followed by a 180° change of direction (CoD) and sprint back to the 5 m cone, decelerate to 0 m, CoD to sprint to 15 m, deceleration to 20 m followed by CoD and sprint to 15 m cone. b) Flying 10 m sprint (×4): Begin at start cone and sprint maximally through 20 m and 30 m cones. *2 min rest between reps and 2 min rest between*: c) SAFT90 protocol (×5): participants completed 1 min 10 s of activity directed by pre-recorded audio instructions. This consisted of 2 × 20 m jog interspersed with side-step cutting at 9, 10 and 11 m, 2 × 2 m back pedal, 2 × 2 m side stepping, a 20 m stride interspersed with side-step cutting at 9, 10 and 11 m, 2 × 20 m walk and 1 × 20 m maximal sprint.

reference system (Qualisys, Gothenburg, Sweden) to concurrently measure instantaneous velocity during a maximal acceleration shuttle drill, a flying 10 m and a team sport simulation shuttle course (SAFT90 (Lovell et al. 2008; Small et al. 2010; Barrett et al. 2016)) (Figure 1).

Locomotor activities

Prior to data collection, participants completed a 10 min standardised ramp warm-up. After a 5 min rest period, participants completed a maximal acceleration drill (MAD; 4 repetitions) followed by flying 10 m sprints (4 repetitions) and a soccer-specific, multi-directional movement protocol (SAFT90; 5 × 1 min 10 s); the SAFT90 duration was chosen to include each movement type at least once and to reduce the volume of captured data (Lovell et al. 2008; Small et al. 2010; Barrett et al. 2016)) (Figure 2). A total of 64 trials were captured for the maximal acceleration shuttle drill (MAD) and flying 10 m sprint conditions and 80 trials for the SAFT90, resulting in 848 samples across all measures (Total distance [m] – 144 samples; Peak velocity [m · s^{-1}] – 64 samples; mean velocity [m · s^{-1}] – 144 samples, High Speed Running (HSR) [m; >5.29 m · s^{-1}] – 144 samples, Sprint distance [m; >6.26 m · s^{-1}] – 64 samples, Acceleration distance [m; >3 m · s^{-2}] – 144 samples, Deceleration distance [m; <-3 m · s^{-2}] – 144 samples) (Figure 2). To assist data synchronisation, participants performed three pogo jumps prior to each trial. The SAFT90 is a fixed intensity shuttle running simulation around an agility course where pace and activities are dictated via pre-recorded audio instructions. The SAFT90 was designed to replicate the movement demands of English men's Championship level soccer based on time-motion analysis of match-play (Lovell et al. 2008) and it simulates the physiological responses of match play (Lovell et al. 2008).

Qualisys system specifications

Three-dimensional marker positions were measured at 250 Hz using a multi-camera motion analysis system (Qualisys, Gothenburg, Sweden) as the criterion displacement measure. 24 Oqus 700+ series infrared cameras (Qualisys, Gothenburg, Sweden) were positioned around the 22 m × 5 m test area. The reference system was spatially calibrated according to the manufacturer's recommendations. The average calibration wand residual across sessions was 2.06 ± 1.02 mm.

Playermaker F-IMU specifications

The Playermaker sensors were activated 5 min prior to the warm-up and no user calibration was required. The Playermaker sensor is an F-IMU that incorporates two components from the MPU-9150 multi-chip motion tracking module (InvenSense, California, USA), being a 16 g triaxial accelerometer and a 2000° · s^{-1} triaxial gyroscope, for measurement of accelerations and angular velocity of each foot during gait, with a sampling rate of 250 Hz. The Playermaker system calculates whole-body velocity-based metrics using data generated by the on-board microelectromechanical system, which uses a combination of proprietary gait tracking and foot-based event detection algorithms. The soccer-specific gait-tracking algorithm allows detection of the orientation and translation of the individual's limbs during gait cycles; the event detection algorithm identifies key events during gait (heel strike, toe off, zero-velocity, zero height, non-gait pattern). The microprocessor receives accelerometer and gyroscope data, from which orientation, velocity and position vectors are determined using a Kalman filter.

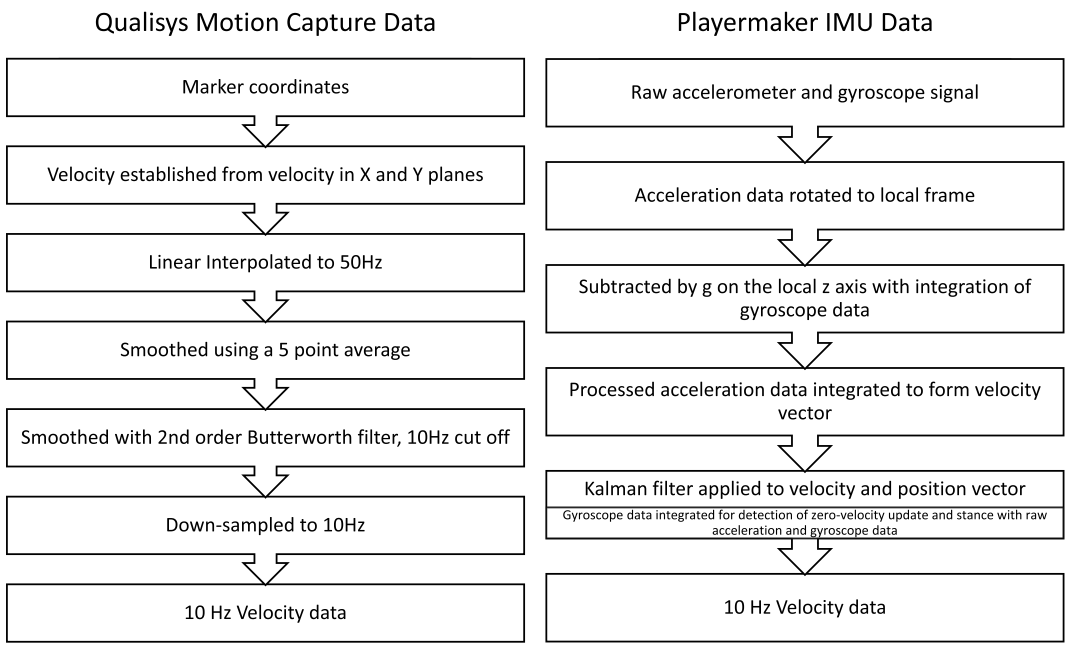

Figure 3. Data workflow from raw signal to velocity.

Data filtering

Markers were labelled and small trajectory gaps were filled using polynomial interpolation (maximum gap length filled = 157 frames). Raw position (vertical and horizontal coordinates) and velocity data for the T8 marker were exported into individual participant and drill trial files to represent centre of mass. The vertical and horizontal displacement and velocity data were linear interpolated to 50 Hz, smoothed using a 5-point moving average, and smoothed using a second-order, low-pass Butterworth filter. To represent body movement for comparison to the F-IMU velocity data, the velocity of the T8 marker was calculated from position data for each trial. Velocity plots with a range of cut-off frequencies (0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz, 15 Hz, 20 Hz) were visually inspected to determine which cut-off frequency best reduced noise while not reducing signal. A cut-off frequency of 10 Hz was selected. Data were then down-sampled to 10 Hz to allow comparison to F-IMU velocity data which were sampled at 10 Hz. The data processing workflow is shown in Figure 3.

F-IMU raw velocity files were downloaded and exported and resampled at 10 Hz using linear interpolation to ensure exact synchronisation with motion capture data. Raw velocity traces of both F-IMU and 3D kinematics were visually checked to verify temporal similarity using the pogo jumps as indication of the initiating movement allowing synchronisation. Motion capture velocity data (T8) was synchronised with F-IMU velocity data using cross correlation, and the resulting data were then trimmed and combined. The F-IMU velocity data were further synchronized with the application of a bi-directional filter, shifting forwards and backwards by 50 data points in intervals of one to find the point of maximum correlation, which was used for analysis.

Data analysis

To assess the agreement between the F-IMU and 3D motion capture displacement variables, overall mean difference with 95% confidence interval (CI), 95% limits of agreement (LoA) and the RMSE were calculated for each drill and divided into velocity bands. RMSE was reported as an overall for all drills combined and per drill type. Data were also discretised into velocity zones for all drills combined and per drill. The thresholds were chosen to align with previous female soccer research that used advanced statistical techniques to derive relevant thresholds during match play (high-speed running, 3.47–5.29 $m \cdot s^{-1}$; very high-speed running, 5.29–6.26 $m \cdot s^{-1}$; sprinting, >6.26 $m \cdot s^{-1}$) (Park et al. 2019) and also used by FIFA (FIFA 2019). Additionally, calibration (linear) equations for each drill, velocity threshold and overall velocity have been provided to predict the velocity that could be expected with 3D motion capture from data collected by Playermaker F-IMUs (see Table 1).

Between-unit reliability

To determine between-unit reliability, intraclass correlation (ICC) (3,1) (Shrout & Fleiss, 1979) with 90% CIs and 95% LoA was calculated for each time motion analysis variable measured in each drill type (MAD, flying 10 m sprint, SAFT90) using an Excel spreadsheet (Hopkins 2015). ICC values were defined as 0–0.5 *poor*, 0.5–0.75 *moderate*, 0.75–0.9 *good* and >0.9 *excellent* reliability (Koo and Li 2016).

Results

Concurrent validity

The mean difference between the F-IMU and the reference system for instantaneous velocity for all participants and drills combined was -0.048 ± 0.581 $m \cdot s^{-1}$ ($n = 65{,}552$) and RMSE

Table 1. Agreement between Playermaker F-IMUs and the reference system for instantaneous velocity.

	Average difference (m·s^{-1})	95% Confidence interval	Max difference (m·s^{-1})	95% Limits of agreement	RMSE (m·s^{-1})	Calibration equation
Overall	−0.048 ± 0.581	−0.05, −0.04	3.48	1.09, −1.186	0.583	$M = 0.039 + (1.003\ P)$
Drill type						
SAFT90	−0.003 ± 0.531	−0.008, 0.002	2.65	1.037, −1.044	0.531	$M = 0.084 + (0.958\ P)$
Flying 10 m	−0.485 ± 0.367	−0.5, −0.46	1.35	0.234, −1.203	0.607	$M = -0.74 + (1.188\ P)$
Maximal Acceleration Deceleration	−0.214 ± 0.787	−0.23, −0.19	3.48	1.328, −1.756	0.815	$M = 0.45 + (0.936\ P)$
Speed Thresholds						
<3.46 m · s^{-1}	0.044 ± 0.537	0.04, 0.05	3.48	1.097, −1.009	0.539	$M = 0.35 + (0.744\ P)$
3.46–5.29 m · s^{-1}	−0.240 ± 0.715	−0.26, −0.22	2.18	1.162, −1.641	0.754	$M = 3 + (0.312\ P)$
5.29–6.26 m · s^{-1}	−0.310 ± 0.408	−0.33, −0.29	1.17	0.488, −1.109	0.512	$M = 4.2 + (0.296\ P)$
>6.26 m · s^{-1}	−0.549 ± 0.342	−0.56, −0.53	0.77	0.12, −1.218	0.647	$M = 1.6 + (0.833\ P)$

N.B – In the calibration equations, M and P refer to motion capture and Playermaker, respectively.

was 0.583 m · s^{-1}. Mean and maximum instantaneous velocity differences, 95% CI, 95% LoA, RMSE and calibration equations are displayed in Table 1. The smallest mean difference and RMSE were reported for the SAFT90 drill (−0.003 ± 0.531 m · s^{-1}, RMSE: 0.531 m · s^{1}); the LoA were from −1.044 to 1.037 m · s^{-1}. Greater differences were reported for the MAD (−0.214 ± 0.787 m · s^{-1}, RMSE: 0.815 m · s^{-1}) and flying 10 m drills (−0.485 ± 0.367 m · s^{-1}, RMSE: 0.607 m · s^{-1}) with LoA from −1.756 to 1.328 and −1.203 to 0.234 m · s^{-1}, respectively. For speed thresholds, velocities below 3.46 m · s^{-1} reported the smallest mean difference (0.044 ± 0.537 m · s^{-1}) with LoA from −1.009 to 1.097 m · s^{-1}, and velocities above 6.26 m · s^{-1} reported the largest mean difference (−0.549 ± 0.342 m · s^{-1}) with LoA from −1.218 to 0.12 m · s^{-1}. However, the largest RMSE was found for velocities between 3.46 and 5.29 m · s^{-1} (0.754 m · s^{-1}); the LoA were from −1.641 to 1.162 m · s^{-1}. Figure 4 displays all instantaneous velocity measurements and reveals an association between mean difference and velocity above 2 m · s^{-1}, with the greatest absolute difference (−0.66 m · s^{-1}) found at velocities above 7 m · s^{-1}. Figure 5 presents the distribution of velocity differences across the three drills.

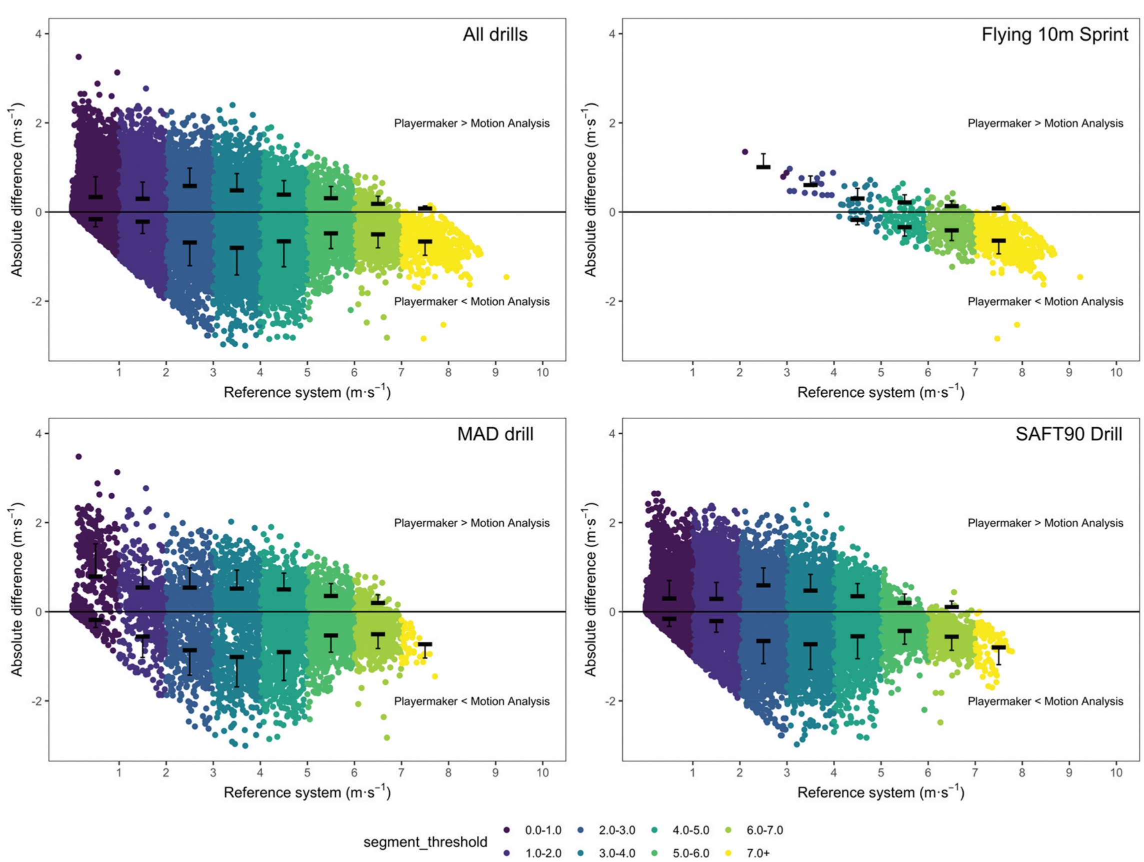

Figure 4. Differences in instantaneous velocity from the reference system, divided into speed thresholds for all drills, flying 10 m sprint, maximal acceleration deceleration drill and SAFT90 drill. Positive and negative means with error bars are presented for each velocity threshold segment.

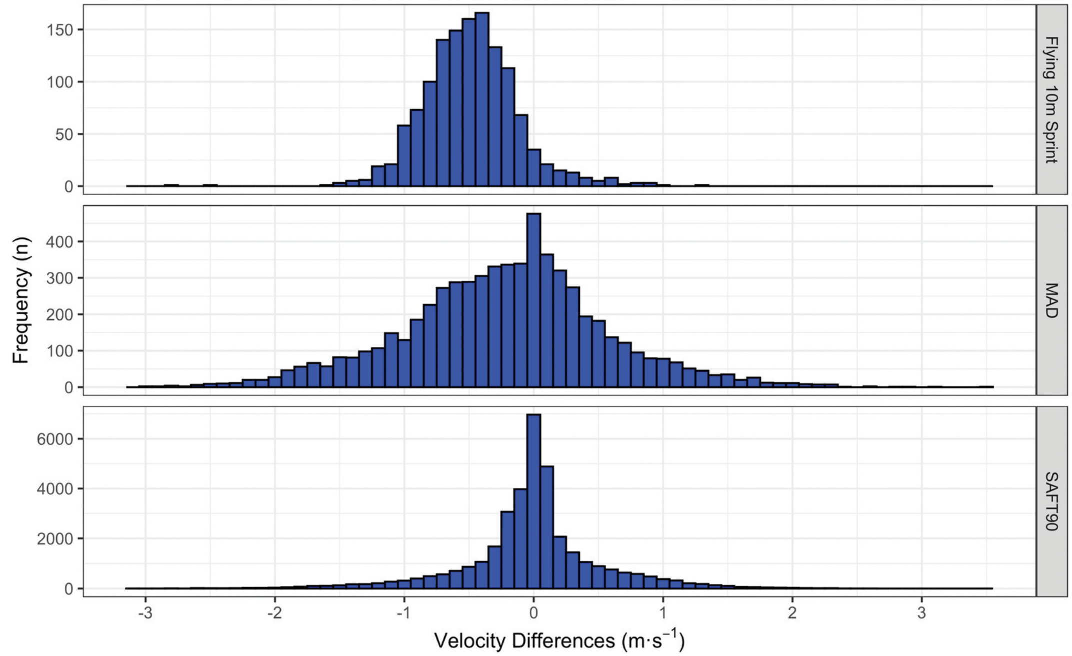

Figure 5. Velocity differences for each drill compared to the reference system.

Table 2. Between-unit reliability of playermaker F-IMUs for time motion analysis variables measured during the SAFT90, flying 10 m and MAD protocols.

Time motion analysis variable	Drill type	95% LoA	Between-unit reliability ICC (90% CI)	Reliability qualitative interpretation
Peak speed	SAFT90	0.096, −0.296	0.98 (0.97, 0.98)	*excellent*
	Flying 10 m	0.096, −0.296	0.97 (0.95, 0.98)	*excellent*
	MAD	0.096, −0.296	0.94 (0.9, 0.96)	*excellent*
Total distance	SAFT90	1.228, −5.828	0.96 (0.94, 0.97)	*excellent*
	MAD	1.444, −4.044	1 (0.99, 1)	*excellent*
HSR distance (> 5.29 m · s^{-1})	SAFT90	1.628, −5.428	0.96 (0.94, 0.97)	*excellent*
	Flying 10 m	1.244, −4.244	0.95 (0.93, 0.97)	*excellent*
	MAD	1.212, −7.412	0.96 (0.94, 0.97)	*excellent*
Sprint distance (>6.26 m · s^{-1})	SAFT90	2.24, −3.64	0.88 (0.78, 0.93)	*good*
	Flying 10 m	2.12, −5.72	0.96 (0.95, 0.98)	*excellent*
	MAD	2.80, −7.00	0.92 (0.87, 0.94)	*excellent*
Acceleration distance (>3 m · s^{-2})	SAFT90	1.752, −2.952	0.92 (0.89, 0.95)	*excellent*
	MAD	2.924, −4.524	0.84 (0.77, 0.89)	*good*
Deceleration distance (<-3 m · s^{-2})	SAFT90	1.944, −3.544	0.89 (0.84, 0.92)	*good*
	MAD	2.336, −3.936	0.88 (0.83, 0.92)	*good*

N.B LoA = limits of agreement, ICC = intraclass correlation coefficient, CI = confidence interval, MAD = maximal acceleration drill.

Between-unit reliability

Table 2 presents the between-unit reliability of the F-IMUs across displacement variables. F-IMUs report *good* to *excellent* reliability for all variables (ICC = 0.84–1) with LoA from −7.412 to 2.924 m · s^{-1}. Acceleration distance (>3 m · s^{-2}) during the MAD reported the lowest ICC value (ICC [90% CI] = 0.84 [0.89–0.77]) with the LoA from 4.524–2.924 m · s^{-2}. Total distance during the MAD reported the highest ICC value (ICC = 1.0 [0.99–1]) of all time motion analysis variables, with LoA from −4.044 to 1.444 m.

Discussion

The aims of the current study were to investigate the concurrent validity and between-unit reliability of velocity and kinematic variables derived from an F-IMU. The overall mean difference in velocity between the F-IMUs and the reference system was -0.048 ± 0.581 m · s^{-1}. The largest mean differences were reported for velocities above 6.26 m · s^{-1} (-0.55 ± 0.34 m · s^{-1}). Further, differences were dependent on the reference speed with the greatest absolute difference (−0.66 m · s^{-1}) found at velocities above 7 m · s^{-1}. The between-unit reliability of the F-IMUs ranges from *good* to *excellent* for all locomotor characteristics. Overall, the F-IMU system has good agreement with 3D motion capture for velocity and has good to excellent between-unit reliability.

GNSS and local positioning systems (LPSs) have been reported to overestimate velocity compared to a criterion (Johnston et al. 2014; Scott et al. 2016; Blauberger et al. 2021), whereas the findings of the current study suggest the F-IMUs tend to underestimate the criterion velocity at higher speeds. The distribution of velocity differences varied across drills with the flying 10 m sprint drill having a prominent shift towards negative differences to the reference system, as presented in Figure 5. It appears that the F-IMU velocity accuracy depends on the respective exercise, with the lowest RMSE found for the SAFT90 and highest error found for the MAD. There is a general increase in error with an increase in velocity, and an increase in average difference to the reference system. The average difference between the F-IMUs and the reference system for the change of direction drills (SAFT90 and MAD) is small (−0.003 to −0.214 m · s^{-1}), which is notable as previously this has been an issue for GNSS/LPS reporting moderate to large velocity differences in change of direction tasks (13–14%; 0.68 to 0.92 m · s^{-1}) (Serpiello et al. 2018; Luteberget et al. 2018). The anatomical location of the F-IMU may provide better validity of velocity during change of direction activities compared to previously reported data using GNSS. The maximum difference to the reference system (3.48 m · s^{1}) was found during a single trial of the MAD drill at velocities below 1 m · s^{-1} with the F-IMU overestimating the reference velocity, which appears as an outlier in the data as seen in Figure 4. This was similar to what was previously found when comparing trunk-mounted GPS units to F-IMU devices (Waldron et al. 2021). Practitioners will commonly refer to HSR and sprint distance when monitoring training intensity and volume in team sports, the HSR and sprint distance measured by the F-IMUs report *good* to *excellent* reliability and compared to the reference system and has an acceptable RMSE (0.51–0.65 m · s^{-1}).

No study has assessed the accuracy of instantaneous velocity as determined by an IMU over the whole range of dynamic tasks in team sports. Our study shows lower average difference in instantaneous velocity (−0.549 to −0.003 m · s^{-1}) and a smaller range of absolute difference (3.15–3.48 m · s^{-1}) than previously reported for an LPS (0.68–0.92 m · s^{-1}; −4.9 to 10.4 m · s^{-1}) (Luteberget et al. 2018). Our study reports lower velocity RMSE compared to 10 Hz GNSS (1.3 m · s^{-1}) in a previous study, and similar to reported RMSE for a lower leg IMU (0.58 m · s^{-1}) (Pillitteri et al. 2021). However, the velocity RMSE in this study across drill types (0.531–0.815 m · s^{-1}) is greater than previously shown in 15 Hz (5 Hz interpolated) GNSS (0.18–0.54 m · s^{-1}) across similar drill types, including a shuttle run and a sport specific course (Linke et al. 2018). This could be due to different filtering methods between technologies, or the interpolation of a 5 Hz GNSS signal to 15 Hz using tri-axial accelerometery, which may smooth the true signal and result in lower error. In the current study, we followed the FIFA guidelines for processing and filtering motion capture and IMU data (FIFA 2022); however, the cut-off frequency was based off a visual inspection of the raw motion capture data in the current study. Previously some studies have not disclosed the filtering and time synchronisation techniques, so it is not clear whether the differences reported are due to filtering techniques rather than the technology. Future research should detail filtering and time synchronisation techniques.

Between-unit reliability (ICC) of the F-IMU ranges from *excellent* for peak speed (range of peak speeds attained: 6.36–7.81 m · s^{-1}), total distance and HSR, to *good* to *excellent* for sprint distance, acceleration and deceleration. This was consistent across all drill types, which included activities ranging from linear running to cutting, change of direction and back-pedalling. The F-IMUs have greater between-unit reliability for measuring total distance (ICC: 0.96–1) and high magnitude (>3 m · s^{-2}) acceleration and deceleration (ICC: 0.84–0.92, *good* to *excellent*) when compared to 10 Hz GNSS systems (total distance ICC: 0.51; acceleration and deceleration: CV% 1.7–11.9%, *good* to *poor*) (Johnston et al. 2017; Thornton et al. 2019). Overall, results suggest that the F-IMU devices demonstrate acceptable between-unit reliability when quantifying distances, speed, acceleration and deceleration. This suggests practitioners can be confident when comparing velocity and displacement variables between players within a squad.

The peak velocity capabilities of participants in the current study were a limitation. Ten participants recorded maximum velocities above 8 m · s^{-1} according to the reference system, all during the flying 10 m sprint drill. Further research would benefit from participants who can achieve higher velocities, particularly maximum velocities above 9 m · s^{-1}, because based on the current data, the absolute difference to the reference system trends towards a greater difference at higher velocities, above 7 m · s^{-1}. Practitioners should consider this limitation when monitoring sprint volume of athletes with peak velocities above 9 m · s^{-1}. The lack of consistency of reliability and validity variables reported in the literature makes comparisons difficult. With the development and wearability of technologies during team sports, there is a call for greater insight into the change of direction and biomechanical demands of movement patterns in addition to displacement. Future research is warranted to examine the validity of mechanical measures derived from the F-IMU.

Practical applications

Velocity measures from the Playermaker F-IMU can be used in time motion analysis for team sports. However, caution is required when analysing movement demands performed at velocities above 6.26 m · s^{-1} as the F-IMU tends to underestimate these velocities compared to the reference system. While there is a larger RMSE for velocities measured between 3.46 and

5.29 $m \cdot s^{-1}$, the average difference is smaller, which could be due to more data captured at this velocity. For practitioners to be confident of velocity differences between players in training and competition (i.e., varied movement demands) using the F-IMUs, a difference of above 0.583 $m \cdot s^{-1}$ is required. Repeated measures of peak speed and distances covered within speed thresholds captured by Playermaker FIMUs can be used confidently in time motion analysis for team sports.

Conclusion

The F-IMUs report good agreement to the reference system for velocity (captured during flying 10 m sprint, maximal acceleration deceleration and SAFT90 drills). The findings demonstrate that the F-IMUs report similar concurrent validity compared with GNSS and LPS. Reliable measures of player movement demands are captured by Playermaker, with similar reported reliability to GNSS and LPS. Consequently, knowing the error of the F-IMUs, practitioners can make informed decisions based on the data presented in this study.

Acknowledgements

The authors would like to thank Eran Amit and Benny Gamus, current and former data scientists at the foot-mounted IMU company (Playermaker), for facilitating data synchronisation between the 3D motion capture and Playermaker IMU.

Disclosure statement

This project was part-funded by The Football Association, of which Playermaker provided sensors for. Playermaker do not provide any financial funding for the project. The fourth author of this study is employed by Playermaker, despite this, and to remove the potential for bias, the fourth author was not involved in any data processing, statistical analysis or data interpretation conducted.

Funding

The author(s) reported that there is no funding associated with the work featured in this article.

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Data availability statement

The data that support the findings of this study are available from the corresponding author [NM] upon reasonable request.

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