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ORIGINAL INVESTIGATION

Measuring Acceleration and Deceleration in Soccer-Specific Movements Using a Local Position Measurement (LPM) System

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Purpose: A local position measurement (LPM) system can accurately track the distance covered and the average speed of whole-body movements. However, for the quantification of a soccer player's workload, accelerations rather than positions or speeds are essential. The main purpose of the current study was therefore to determine the accuracy of LPM in measuring average and peak accelerations for a broad range of (maximal) soccer-specific movements. ***Methods:*** Twelve male amateur soccer players performed 8 movements (categorized in straight runs and runs involving a sudden change in direction of 90° or 180°) at 3 intensities (jog, submaximal, maximal). Position-related parameters recorded with LPM were compared with Vicon motion-analysis data sampled at 100 Hz. The differences between LPM and Vicon data were expressed as percentage of the Vicon data. ***Results:*** LPM provided reasonably accurate measurements for distance, average speed, and peak speed (differences within 2% across all movements and intensities). For average acceleration and deceleration, absolute bias and 95% limits of agreement were 0.01 ± 0.36 m/s^2 and 0.02 ± 0.38 m/s^2, respectively. On average, peak acceleration was overestimated (0.48 ± 1.27 m/s^2) by LPM, while peak deceleration was underestimated (0.32 ± 1.17 m/s^2). ***Conclusion:*** LPM accuracy appears acceptable for most measurements of average acceleration and deceleration, but for peak acceleration and deceleration accuracy is limited. However, when these error margins are kept in mind, the system may be used in practice for quantifying average accelerations and parameters such as summed accelerations or time spent in acceleration zones.

Keywords: local position measurement, performance analysis, team sports, accuracy, time-motion analysis

In recent years, computerized time–motion analysis has become the standard for measuring (external) workload during training and matches in all kinds of team sports, particularly in soccer. Improved technologies to collect 2-dimensional position data at a high sampling rate have provided sports scientists and coaches with useful information about total distances run, time spent in speed zones, and number of sprints and direction changes made.[1] These parameters can help exercise physiologists and coaches improve workload management for training and match play.

One of the most reported parameters in the literature on workload is the distance or time players spent in certain speed zones.[2,3] However, it has been argued that this way of analyzing underestimates workload, especially at lower speeds, since it does not account for additional energy spent when accelerating or decelerating.[4–7] Therefore, to establish a more valid measurement of workload, for example, high-intensity activities, more and more sports scientists have begun to include acceleration-related workload parameters[5] such as distance or time spent in acceleration and deceleration zones,[7,8] number of accelerations,[9,10] and average accelerations.[10]

The measuring systems that are used for monitoring team sports include video-based tracking systems, global positioning systems (GPS), and the more recently introduced electronic tracking systems. Many studies have shown that video-based systems and GPS provide accurate and reliable estimates of distance and average speed (both usually slightly overestimated) in linear courses at relatively low movement intensity.[11] However, accuracy of video-based and GPS tracking decreases substantially (underestimation of distance and average speed) when measuring higher speeds and shorter and/or nonlinear courses, likely because of a relatively low sampling rate.[11–13] Even newer GPS devices with higher sampling rates differ almost 10% relative to the criterion measurement when measuring instantaneous speed during acceleration and deceleration.[14] To make the next step in time–motion analysis, the inclusion of

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instantaneous speed and acceleration parameters would be necessary to achieve a better estimation of workload.[14] Therefore, potentially more accurate electronic tracking systems might be of great value.

Several studies have reported on the validity and reliability of electronic tracking systems, but most of the study protocols used were not suitable for the detection of accelerations in dynamic conditions.[15–17] Recently, Ogris et al[18] compared a local position measurement (LPM) system with Vicon, a 3-dimensional motion-capture system, under realistic, dynamic conditions. However, despite the use of a gold standard and a wide range of movement intensities and movements involving accelerations, the participants in the Ogris et al study performed neither movements at maximal acceleration and deceleration nor movements involving a 180° change of direction, as occur frequently during soccer.[19] Moreover, data on acceleration or deceleration were not reported. In discussing their study's limitations, Ogris et al[18] specifically indicated that they expect that the newer versions of the LPM system in combination with the latest filtering techniques could positively influence the estimation of the dynamics.

The main purpose of the current study was to assess the accuracy of such a state-of-the-art LPM system in measuring position, speed, acceleration, and deceleration for a wide range of (maximal) soccer-specific movements including movements involving a 90° or 180° change of direction. Furthermore, to determine the influence of movement intensity on LPM accuracy, maximal and 2 submaximal intensities were included among the experimental conditions. We hypothesized that the accuracy of the LPM system depends on the type of movement performed and that the accuracy decreases at higher movement intensities, particularly with regard to the measurement of acceleration.

Methods

Subjects

Twelve male amateur soccer players (mean ± SD age 22 ± 3 y, height 183 ± 8 cm, body mass 76 ± 7 kg) who played soccer at least 2 times a week participated in the experiment. They were informed about the experimental protocol before providing their written consent. The study was approved by the local ethics committee.

Equipment

A commercially available Inmotio LPM system (version 05.30R, Inmotiotec GmbH, Regau, Austria) with 11 base stations was set up and calibrated in the range of an artificial-turf soccer field located inside an air dome. Location of measurement was at least 10 m inside the calibrated LPM field. Players wore an LPM vest containing a transponder on the back and antennas on both shoulders, ensuring optimal line of sight to the base stations. During data collection, 6 players were equipped with a transponder. An additional 16 transponders were randomly located around the calibrated LPM field, to simulate a real match situation in terms of the number of transponders active at the same time, limiting the maximal sampling rate to 45.45 Hz (1 kHz/22 transponders).

A 10-camera Vicon motion-analysis system (Vicon MX T40S, Nexus 1.7.1, Oxford, UK), operating at 100 Hz, was used as gold standard. Reflective markers (8-mm diameter) were mounted on top of both LPM antennas. Two camera alignments were used, a runway (observation field = 30 × 2 m) for straight movements and a rectangle (15 × 6 m) for all other movements. The system was adjusted and calibrated immediately before each session. Image error (RMS distance in camera pixels) was below 0.20 for all Vicon cameras.

Procedures

The participants performed 8 soccer-specific movements[19] (Figure 1) at 3 different movement intensities: jog, submaximal, and maximal. The first 3 movements involved a 180° change of direction: forward-backward (run of 4 × 5 m; 2 × forward, 2 × backward), shuttle running while facing running direction (run of 4 × 8 m), and moving sideways (run of 4 × 5 m). Two movements involved a 90° change of direction: 2.5-m slalom with a slanting side- and forward step while facing forward and 5-m slalom. The last 3 movements consisted of straight running without change of direction: acceleration from standstill (followed by constant pace for jog and submaximal intensity), deceleration from running to standstill, and deceleration from running to standstill immediately followed by acceleration. Cones marked the start, turning points, and end of each course.

For practical reasons the participants were divided in 2 groups of 6 participants. Each group performed 2 sessions, 1 in each camera alignment. Before each session the participants performed a warm-up of at least 10 minutes. They were familiarized with the movements and performed practice runs. To standardize the start of every run, the participants started with 1 foot on and both shoulders behind the starting line.

For the movements (M) involving a 180° change of direction (M1-2-3; Figure 1) the participants were instructed to turn with at least 1 foot on the line between the cones. In the shuttle run (M2) the participants were instructed to alternate turning foot and therefore turning direction. In the 2.5-m slalom (M4) and 5-m slalom (M5) conditions, the participants had to move around the cones with both feet. Facing directions are illustrated in Figure 1 by the small dotted arrows. A starting sign was given by one of the investigators. If the participant started a run too early or performed a movement incorrectly, the participant had to execute the run again. To standardize the end of the movements (M1-2-3-7-8) the participants had to stop on the finish line for 5 seconds. Between runs, the participants had at least 3 minutes of rest.

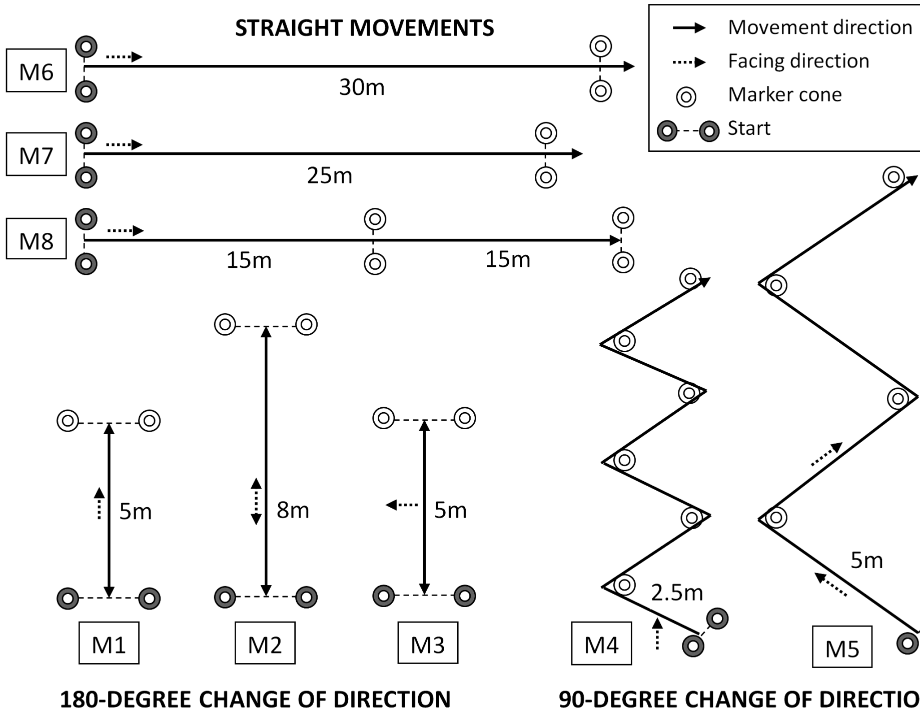

Figure 1 — Schematic representation of soccer-specific movements divided into 3 categories: 180° change of direction: M1 = forward–backward, M2 = shuttle run, M3 = sideways; 90° change of direction: M4 = 2.5-m slalom, M5 = 5-m slalom; and straight movements: M6 = acceleration from standstill (M6a) followed by constant running (M6b), M7 = deceleration from running to standstill, M8 = combined deceleration/acceleration.

Data Processing

Vicon signals (*x-y* direction) of both shoulder markers were combined to 1 signal and low-pass filtered using a fourth-order 1-Hz Butterworth filter. Position data were differentiated twice to obtain speed and acceleration. LPM data sampled at 45.45 Hz were filtered (integrated "weighted Gaussian average" filter set at 85% as recommended by the manufacturer), and this filtered signal was resampled at 100 Hz by Inmotio software (version 2.6.9, Inmotiotec GmbH, Regau, Austria).

To select a characteristic movement out of the complete run, predefined cutoff points were used to indicate the start and end of the movement. For each movement involving a change of direction, the maximum number of complete movement cycles that were captured by the Vicon system was included in the analysis. For movements with a 180° change of direction, data were selected between the first and fourth speed maximum (Figure 2), excluding the start and end of the run. The signal between the first and fifth speed maximum was used for the 2.5-m slalom (M4), and the first and third speed maximum were used for the 5-m slalom (M5). Acceleration thresholds were used for selecting the relevant part of the straight movements. Acceleration from standstill (M6a) was started when the Vicon acceleration exceeded 0.2 m/s^2 and ended when acceleration was lower than 0.2 m/s^2. The end of the acceleration from standstill movement (M6a) was the start of the movement at constant speed (M6b). The movement at constant speed ended when 30 m in the whole run (acceleration from standstill + constant) was completed. Deceleration from running to standstill (M7) and combined deceleration/acceleration (M8) started when acceleration fell below –0.2 m/s^2 and ended when acceleration exceeded –0.2 m/s^2 (M7) or fell below 0.2 m/s^2 (M8), respectively.

LPM data were synchronized using least-mean-square difference between the speed measured by Vicon and LPM. The following parameters were calculated: total distance run, average speed, peak speed, average acceleration (sum of all accelerations for Vicon or LPM divided by Vicon acceleration time; Figure 2), peak acceleration (mean of the peak values), average deceleration (sum of all decelerations for Vicon or LPM divided by Vicon deceleration time), and peak deceleration (mean of the peak values). For the constant-speed run (M6b) the mean and standard deviation (between participants) of the mean absolute acceleration peaks (within participant) was calculated to obtain an indication of the baseline acceleration noise at constant speed in LPM compared with Vicon.

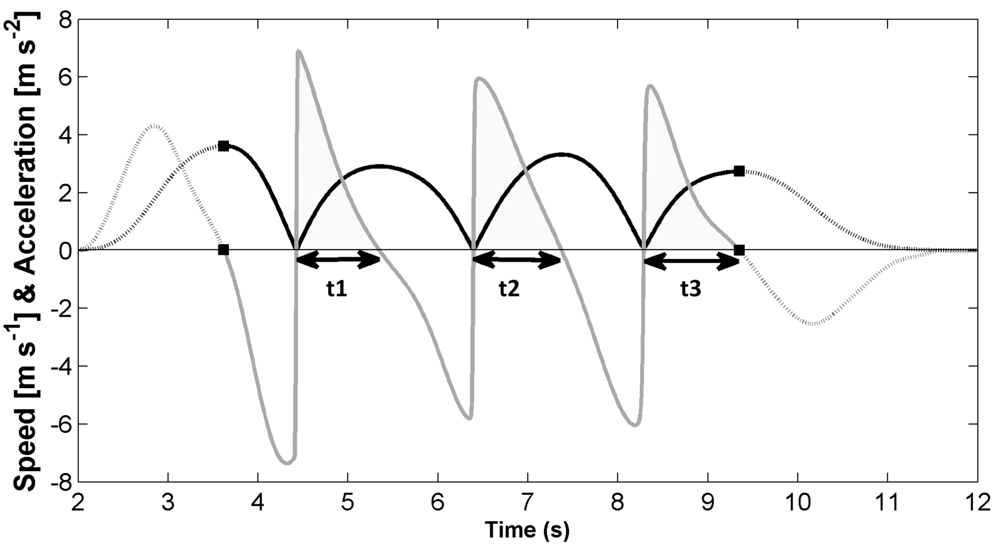

Figure 2 — Example of the selected Vicon signal, in this case for the movements involving a 180° change of direction. Cutoff points (black squares) are first and fourth speed maximum. Average acceleration was calculated by summing all positive accelerations (separate for Vicon and local position measurement) and dividing this by the total Vicon acceleration time of the selected Vicon signal (ie, t1 + t2 + t3).

Statistical Analysis

Each participant performed a single run at each movement intensity for each movement, resulting in (12 × 3 × 8) 288 runs. Descriptive statistics of the relative differences between Vicon and LPM system were calculated for all parameters. A 2-way repeated-measures ANOVA was conducted to determine the effects of movement intensity (jog, submaximal, maximal) and measurement system (Vicon and LPM), as well as their interaction (intensity × system), on all parameters. The assumption of sphericity was checked using the Mauchly test of sphericity. Statistical significance was set at $P \leq .05$. Simple linear regression[20] was performed for each parameter over the whole range of movements and intensities. Standard error of the estimate (SEE), calculated as the standard deviation of the absolute differences between systems, and Pearson product–moment correlation coefficient were determined. Finally, absolute bias and 95% limits of agreement[21] were calculated for each movement category separately and for all movements together.

Results

As intended, for all movements a main effect on movement intensity (P = .000–.001) was found for all speed and acceleration parameters. In general, LPM provided reasonably accurate measures for distance, average speed, and peak speed (Tables 1, 2, and 3). Only for movements involving a 180° change of direction, both distance and average speed were systematically underestimated (P = .000) compared with the Vicon reference (Table 1). LPM yielded a low bias for average acceleration and average deceleration (Table 3); however, accuracy decreased for movements with a 90° change of direction (Figure 3 and Table 2). LPM yielded less accurate mean measures for peak acceleration and peak deceleration (Table 3); furthermore, limits of agreement were relatively large for both peak parameters. These results are described in more detail in the following subsections.

Distance and Speed

With respect to distance and average speed, the mean differences between systems were significant (P = .000–.049; Table 1) for most movements but under 3% for all movements involving a 90° change of direction or straight running (Table 1). However, LPM underestimated distance and average speed by 2% to 7% for movements involving a 180° change of direction (P = .000). Constant running was not different between systems for both distance (P = .961) and average speed (P = .782). Peak speed (mean) differences of individual movements were 4% at most.

Acceleration and Deceleration

For movements involving a 180° change of direction, LPM in general underestimated (P = .000–.038) average acceleration and deceleration up to 9%, which was the largest mean difference found between systems (M2 at maximal intensity; Table 1), whereas for movements with a 90° change of direction, LPM overestimated average acceleration (P = .003–.009) and average deceleration

Table 1 Vicon Values and Relative Differences Between Systems (LPM – Vicon) for All Movements and All Intensities, N = 12

		Distance (m)		Mean speed (km/h)		Peak speed (km/h)		Mean acceleration (m/s²)		Mean deceleration (m/s²)		Peak acceleration (m/s²)		Peak deceleration (m/s²)	
		VIC	μ (SD), %	VIC	μ (SD), %	VIC	μ (SD), %	VIC	μ (SD), %	VIC	μ (SD), %	VIC	μ (SD), %	VIC	μ (SD), %
M1	Jog	12.5	–4.0 (2.5)^{M}	5.4	–2.3 (2.6)^{M}	7.4	1.7 (4.3)	1.3	–0.4 (5.7)^{M,I}	–1.7	0.7 (4.5)^{M,I}	3.8	–3.3 (10.1)	–4.0	–7.8 (11.1)^{M,I}
	Submax	12.1	–5.3 (2.2)	7.0	–3.6 (2.0)	10.1	–0.9 (3.6)	2.3	–4.6 (4.1)	–3.1	–4.1 (5.0)	5.5	0.0 (11.1)	–5.9	–11.8 (8.3)
	Max	12.1	–5.1 (1.4)	8.2	–2.6 (1.2)	11.9	–0.8 (1.8)	3.1	–5.3 (2.1)	–4.2	–3.6 (3.6)	7.2	–0.6 (6.7)	–7.6	–11.1 (5.9)
M2	Jog	21.1	–3.6 (0.8)^{M,I}	7.3	–2.0 (0.5)^{M,I}	9.7	2.2 (3.0)^{M,I}	1.4	5.8 (4.3)^{M,I}	–1.6	4.8 (2.8)^{M,I}	5.1	10.1 (11.5)^{M}	–5.4	–8.0 (9.7)^{M,I}
	Submax	20.6	–4.8 (0.9)	9.4	–2.8 (0.7)	12.9	–2.5 (2.2)	2.4	–5.0 (4.4)	–2.9	–3.4 (3.1)	7.0	7.5 (7.7)	–7.5	–8.2 (5.5)
	Max	20.7	–5.4 (1.1)	11.2	–3.0 (1.1)	15.9	–4.1 (1.7)	3.3	–8.5 (2.9)	–4.7	–7.0 (2.3)	8.8	3.4 (5.4)	–9.4	–9.3 (5.1)
M3	Jog	12.1	–4.0 (1.5)^{M,I}	6.0	–1.5 (1.5)^{M,I}	7.9	0.9 (2.8)	1.5	1.0 (3.9)^{M,I}	–2.1	2.2 (5.1)^{M,I}	4.9	9.3 (9.0)^{M,I}	–5.1	–4.7 (4.9)^{M,I}
	Submax	11.7	–6.8 (1.2)	7.0	–3.3 (1.0)	9.4	–0.3 (3.6)	2.1	–3.6 (5.4)	–3.2	–2.6 (5.7)	6.3	3.6 (7.6)	–6.7	–11.1 (5.4)
	Max	11.6	–6.8 (1.8)	7.8	–2.9 (1.5)	10.9	0.3 (2.7)	2.8	–3.6 (3.6)	–4.1	–3.3 (4.5)	7.3	–0.9 (7.4)	–7.8	–14.9 (4.7)
M4	Jog	10.5	–2.6 (1.0)^{M,I}	6.3	–1.0 (0.8)^{I}	7.5	2.2 (3.1)^{M}	1.1	6.9 (15.2)^{M}	–1.2	4.1 (14.2)^{M}	2.0	15.1 (16.8)^{M,I}	–2.2	–8.0 (13.3)
	Submax	10.3	–2.1 (1.1)	7.5	0.5 (1.1)	9.0	2.6 (3.1)	1.6	13.3 (19.2)	–1.7	6.1 (18.2)	2.6	27.1 (21.7)	–2.8	–2.3 (12.8)
	Max	10.5	–1.0 (1.3)	8.2	1.0 (1.0)	9.9	3.4 (1.5)	1.9	13.8 (13.5)	–2.0	11.3 (12.1)	3.0	21.5 (11.9)	–3.2	2.8 (13.8)
M5	Jog	10.0	–0.6 (0.7)^{M}	7.4	–0.2 (0.6)	8.7	2.1 (2.9)^{M}	0.7	13.8 (15.0)^{M}	–0.9	16.1 (21.8)	1.4	41.1 (38.0)^{M}	–1.8	3.4 (24.4)^{M,I}
	Submax	9.5	–0.8 (1.0)	9.7	–0.2 (1.0)	11.4	0.1 (1.8)	1.2	3.5 (11.2)	–1.5	–0.9 (10.6)	2.2	21.2 (15.6)	–2.7	–12.3 (10.8)
	Max	9.4	–1.3 (0.8)	12.0	–0.4 (0.8)	14.3	2.1 (2.5)	2.0	8.6 (12.8)	–2.2	1.9 (12.8)	3.3	15.8 (14.1)	–3.7	–11.6 (11.2)
M6a	Jog	4.7	2.0 (3.5)	6.6	2.0 (3.5)^{M}	10.0	—*	1.1	5.4 (16.6)	—	—	2.8	35.7 (31.7)^{M}	—	—
	Submax	9.5	0.7 (1.5)	11.2	0.7 (1.5)	16.9	—*	1.5	0.2 (6.3)	—	—	3.7	30.3 (22.6)	—	—
	Max	23.9	–0.1 (0.8)	20.2	0.1 (0.8)	29.7	—*	1.9	–1.6 (3.0)	—	—	5.0	22.1 (21.0)	—	—

(continued)

Table 1 (continued)

		Distance (m)		Mean speed (km/h)		Peak speed (km/h)		Mean acceleration (m/s²)		Mean deceleration (m/s²)		Peak acceleration (m/s²)		Peak deceleration (m/s²)	
		VIC	µ (SD), %	VIC	µ (SD), %	VIC	µ (SD), %	VIC	µ (SD), %	VIC	µ (SD), %	VIC	µ (SD), %	VIC	µ (SD), %
M7	Jog	3.1	–0.8 (1.7)[M]	5.5	–0.6 (1.6)[M]	10.3	—*	—	—	–1.5	2.2 (6.2)	—	—	–3.0	6.9 (19.2)
	Submax	5.3	–0.9 (1.7)	8.6	–0.8 (1.7)	16.5	—*	—	—	–2.2	0.9 (4.4)	—	—	–5.2	3.5 (9.8)
	Max	8.5	–0.3 (0.7)	13.7	–0.2 (0.6)	28.1	—*	—	—	–3.4	–1.7 (2.0)	—	—	–7.2	–0.9 (12.8)
M8	Jog	8.0	0.3 (0.9)[M]	8.2	0.6 (0.9)[M]	10.6	—*	0.6	9.8 (14.3)[I]	–0.5	10.7 (10.9)[I]	2.1	35.5 (25.1)[M]	–2.4	5.7 (22.7)
	Submax	12.2	0.5 (0.5)	13.0	0.6 (0.5)	16.7	—*	0.8	6.1 (12.4)	–0.8	4.1 (12.5)	2.9	22.4 (20.3)	–4.0	6.4 (16.1)
	Max	14.9	–0.1 (0.4)	16.9	0.2 (0.4)	23.3	—*	1.3	–0.9 (4.3)	–1.3	–3.8 (5.0)	3.6	25.0 (17.7)	–6.3	–3.5 (8.0)
M6b	Jog	25.9	0.1 (0.4)	10.1	0.2 (0.4)	10.8	—*	—	—	—	—	—	—	—	—
	Submax	20.5	–0.2 (0.4)	16.9	–0.1 (0.4)	17.5	—*	—	—	—	—	—	—	—	—

Abbreviations: LPM, local position measurement; VIC, the average Vicon data; µ (SD), mean and standard deviation of the relative differences of LPM compared with Vicon (LPM – Vicon); M1, 180° change of direction forward–backward; M2, 180° change of direction shuttle run; M3, 180° change of direction sideways; M4, 90° change of direction 2.5-m slalom; M5, 90° change of direction 5-m slalom; M6a, straight acceleration from standstill; M7, straight deceleration from running to standstill; M8, straight combined deceleration/acceleration; M6b, straight constant pace.

[M] Main effect of measurement system ($P < .05$). [I] Interaction effect between movement intensity and measurement system ($P < .05$).

*Difference between systems not indicated because no real peak speed is reached in the selected movement; peak speed is the highest speed in the selected movement.

Table 2 Absolute Bias Between Systems (LPM – Vicon) and 95% Limits of Agreement (LOA) for Each Movement Category

	180° COD			90° COD			Straight		
	df	Bias	95% LOA	df	Bias	95% LOA	df	Bias	95% LOA
Distance (m)*	107	–0.74	[–1.31;–0.17]	71	–0.14	[–0.38; 0.10]	131	0.01	[–0.21; 0.23]
Average speed (km/h)	107	–0.21	[–0.46; 0.04]	71	0.00	[–0.18; 0.18]	131	0.02	[–0.23; 0.27]
Peak speed (km/h)	107	–0.09	[–0.83; 0.66]	71	0.21	[–0.32; 0.73]	—	—	—
Average acceleration (m/s^2)	107	–0.08	[–0.34; 0.18]	71	0.14	[–0.32; 0.60]	71	0.02	[–0.17; 0.20]
Average deceleration (m/s^2)**	107	0.09	[–0.25; 0.43]	71	–0.08	[–0.56; 0.40]	71	0.00	[–0.17; 0.17]
Peak acceleration (m/s^2)	107	0.18	[–0.87; 1.24]	71	0.52	[–0.39; 1.42]	71	0.88	[–0.61; 2.36]
Peak deceleration (m/s^2)**	107	0.66	[–0.32; 1.65]	71	0.16	[–0.67; 0.98]	71	–0.04	[–1.25; 1.17]

Abbreviations: LPM, local position measurement; COD, change of direction; df, degrees of freedom.

*Only for distance, absolute bias is dependent on total distance; Vicon average distances are 14.9 m, 10.0 m, and 12.4 m for, respectively, 180°, 90°, and straight. **A positive difference for (average and peak) deceleration means that LPM is less negative than Vicon, thus underestimating the deceleration.

Table 3 Absolute Bias Between Systems (LPM – Vicon), 95% Limits of Agreement (LOA), and Regression Statistics for All Movement Categories Together

	df	Bias	95% LOA	*r*	Regression equation	SEE
Distance (m)*	311	–0.31	[–1.05; 0.48]	.998	$y = 1.02x + 0.07$	0.38
Average speed (km/h)	311	–0.06	[–0.38; 0.25]	.999	$y = 0.99x + 0.04$	0.16
Peak speed (km/h)	179	0.03	[–0.69; 0.75]	.990	$y = 1.04x – 0.14$	0.35
Average acceleration (m/s^2)	251	0.01	[–0.35; 0.37]	.973	$y = 1.04x – 0.08$	0.18
Average deceleration (m/s^2)**	251	0.02	[–0.36; 0.39]	.989	$y = 1.06x + 0.13$	0.18
Peak acceleration (m/s^2)	251	0.48	[–0.80; 1.75]	.952	$y = 0.98x – 0.40$	0.65
Peak deceleration (m/s^2)**	251	0.32	[–0.86; 1.49]	.966	$y = 1.08x + 0.05$	0.58

Abbreviations: LPM, local position measurement; df, degrees of freedom; *r*, Pearson correlation coefficient; SEE, standard error of the estimate; *y*, predicted Vicon reference value; *x*, local position measurement value.

*Only for distance, absolute bias is dependent on total distance; Vicon average distance is 12.7 m. **A positive difference for (average and peak) deceleration means that LPM is less negative compared with Vicon, thus underestimating the deceleration.

(P = .039; M4) up to 16% (M5 at jog intensity; Table 1). In straight runs, average acceleration or deceleration did not significantly differ between the 2 systems (P = .079–.679).

LPM overestimated (P = .001–.049) peak acceleration (up to about 10%) for 2 of the 3 movements involving a 180° change of direction (M2-3), whereas a greater overestimation (15–41%; P = .000) of peak acceleration was shown in the other movement categories (Table 1). In addition, Table 2 shows a broader range in the 95% limits of agreement for movements with a 90° change of direction and straight movements, compared with movements with a 180° change of direction. Peak deceleration was underestimated (P = .000) by LPM for movements with a 180° change of direction (average of 10%; Table 1). Regarding movements with a 90° change of direction, only the 5-m slalom (M5) showed a significant underestimation (P = .004) of peak deceleration by LPM.

Interaction Effects

Several significant interactions between movement intensity and measurement system were found, yet without an unequivocal direction. In some movement conditions, differences between systems decreased with increasing movement intensity (eg, average acceleration in the combined deceleration/acceleration movement; M8; Table 1), whereas in other movement conditions differences between systems increased with increasing movement intensity (eg, peak deceleration in the sideways movement; M3).

Baseline Acceleration Noise at Constant Speed

At constant speed (M6b), when accelerations were low, the absolute acceleration peaks were significantly higher (P = .000) for LPM compared with Vicon reference values, probably due to measurement noise. These peaks

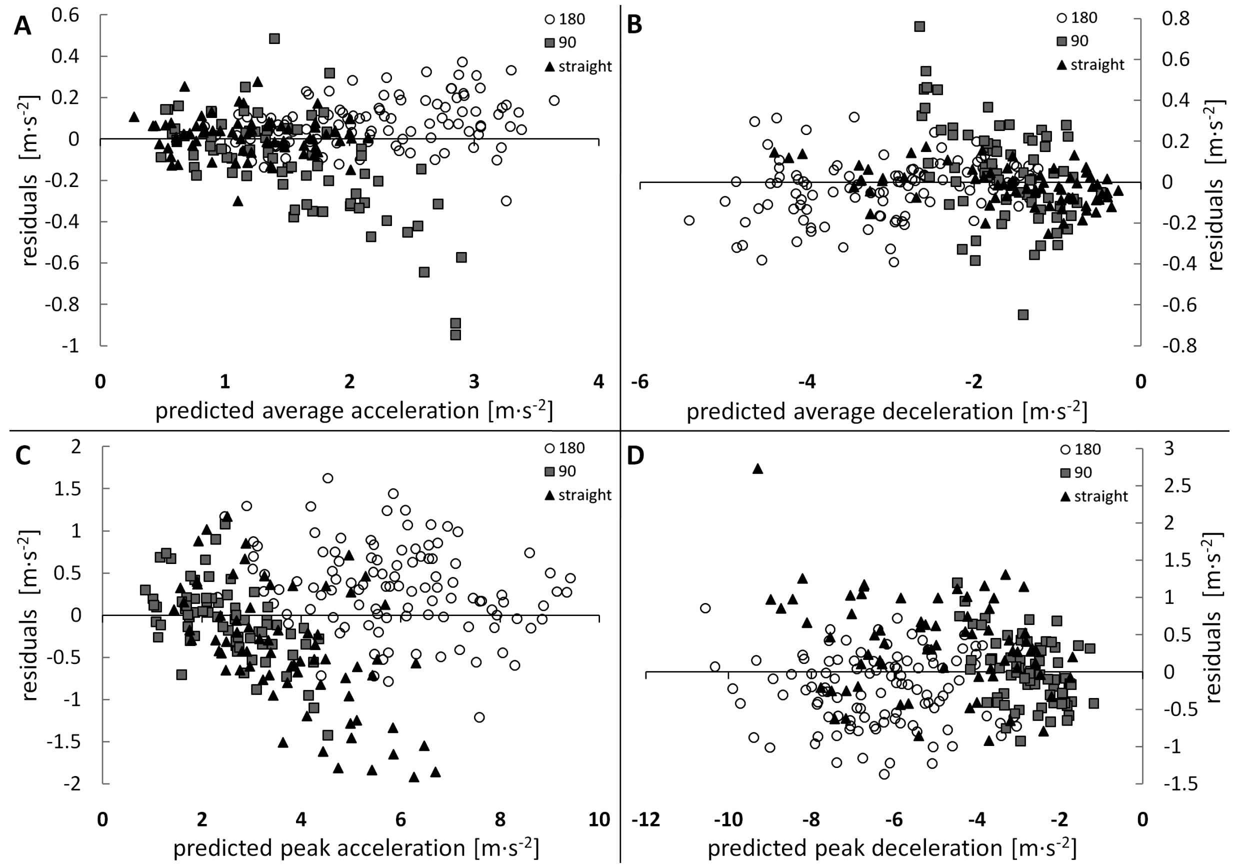

Figure 3 — Residuals (Vicon-predicted local position measurement [LPM]) versus predicted (predicted LPM) plots for (A) average acceleration, (B) average deceleration, (C) peak acceleration, and (D) peak deceleration plotted against Vicon acceleration values. Note: For acceleration (A + C) a negative residual means that predicted LPM overestimates Vicon acceleration, while for deceleration (B + D) a negative residual means that predicted LPM underestimates Vicon deceleration.

were similar for jog and submaximal intensity, with acceleration peaks of 0.8 ± 0.5 m/s^2 (mean ± SD) for LPM and 0.2 ± 0.1 m/s^2 for Vicon. Note that for maximal intensity the speed was not constant.

Discussion

The current study was designed to validate the Inmotio LPM system for the measurement of position, speed, acceleration, and deceleration in soccer-specific movements including maximal movement intensities and turning. Our findings demonstrate that the LPM system provides—even in maximal-intensity soccer-specific exercises—accurate position, average speed, and peak speed measurements; however, when measuring (average and peak) acceleration and (average and peak) deceleration, it depends on the purpose of analyses whether the error margins are acceptable. The comparison of single peak accelerations between players or within players in a repeated-sprint test is not possible due to the large variation. Even across all movements and intensities, Pearson correlation coefficients were below the value of .98 assumed to be minimally needed to track a smallest worthwhile change.[22] On the other hand, counting accelerations with minimal time and acceleration thresholds during longer periods of play may result in useful data. Furthermore, we found that the accuracy depends on type of movement and movement intensity; however, whether increased movement intensity leads to a decrease or increase of accuracy is movement specific.

Our results showed that LPM underestimated distance by –2.0% on average (for all movements and intensities) and by –6.8% at most. Frencken et al[15] found a lower underestimation of distance (–1.6% at most); however, comparable runs (90° change of direction on maximal or sprint intensity) between our study and the study of Frencken et al[15] yielded a similar underestimation of distance, –1.3 and –1.6%, respectively. In the current study, LPM underestimated average speed with –0.8% on average (for all movements and intensities) and –3.6% at most (180° change of direction). Frencken et al[15] found a similar maximal relative underestimation

(–3.9%), yet their study did not include a 180° change of direction. Considering only the straight and 90° change-of-direction movements, the average and maximal errors of LPM average speed in our study (0.1% and 2.0%, respectively) were less than in the study of Frencken et al[15] (–2.8% and –3.9%, respectively). Furthermore, our results indicated that peak speed estimation of LPM differed between –4% and 3% (0.6% on average) from the gold standard, which is considerably less than the average relative difference of 10% found by Ogris et al.[18]

One of the reasons for the lower average- and peak-speed error estimation of LPM in our study compared with other studies, apart from differences in protocol, can be the newer version of the LPM system used in the current study. As already indicated by Ogris et al,[18] this newer version has improved filter algorithms, including Kalman filtering, which probably reduces position-estimation error, thereby improving the tracking of the dynamics. A Kalman filter is an algorithm that predicts data based on a weighting of the dynamics of previous data combined with the current measurement. It is often used for the purpose of navigation and has the advantage that it can measure in real time, as is necessary when providing instant feedback in team sports.

Our results demonstrated that especially the straight movements, including acceleration from standstill, showed a high overestimation of peak acceleration (0.88 m/s^2 bias). When standing still, no useful information of future movement direction is available as input for the Kalman filter, and a sudden acceleration from standstill will be detected only after a certain delay. To “catch up” with the actual position of the transponder, the LPM signal shows a higher acceleration than took place in reality (Figure 4). This delay can also explain the underestimation of distance in the 180° change-of-direction movements. Because of the fast sequence of direction changes, the estimated position is delayed relative to the actual position. The actual position is already moving in the opposite direction, passing the estimated position before the estimated position has a chance to arrive at the actual turning point. Possibly the Kalman filter can also partly explain the (low but unexpected) accelerations that occurred during constant running. Figure 4 shows an LPM acceleration signal that fluctuates around the smooth Vicon signal. This fluctuation also occurred during running at constant speed. These baseline fluctuations in LPM acceleration signals indicate that accelerations below ~1.5 m/s^2 cannot be correctly measured by the LPM system, because these accelerations could also represent measurement noise when running at constant pace.

The choice of filtering method is an important issue regarding (electronic) tracking systems,[16] especially when measuring accelerations and decelerations. A state-of-the-art LPM system provides data that are not useful for kinematic analyses but are useful for time–motion analysis, as they reflect a more global representation of the movement of the athlete’s body. To make a fair comparison with LPM, we chose to filter the Vicon data with a 1-Hz Butterworth filter. Although this filter is rather strong and filters out the single steps of movement (in which we were not interested since they cannot be measured with LPM), the dynamics of the whole-body movement are clearly visible in the signal.

Not only the choice of filtering but also the location of the antennas influences the estimation of position. Whereas LPM places antennas on top of the shoulders, to ensure optimal line of sight and thereby prevent body blockage of the radio-based signal,[16] other electronic tracking systems place antennas on the back (WASP,

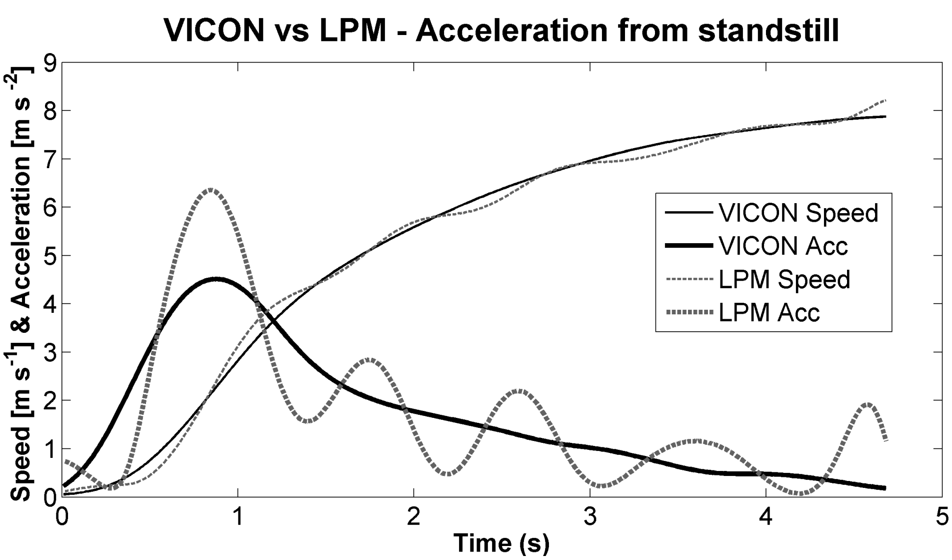

Figure 4 — Vicon and local position measurement (LPM) speed and acceleration signal. LPM shows an overestimated acceleration, probably due to the Kalman filtering.

CSIRO, Clayton South, Australia) or in a belt worn on top of the pelvis (ZXY Sport Tracking AS, Trondheim, Norway). Ideally, the antennas are placed close to the body's center of gravity, as this position best reflects the movement of the athlete's body. However, when placing antennas near the body's center of gravity the probability of covered signals and positional errors increases.[16] Future research on the influence of antenna placement on position-related parameters is needed to gain insight into the compatibility of data collected with different (electronic) tracking systems.

We chose to validate the LPM system under carefully standardized conditions, rather than during match play, in which the number of possible movements and the intensities at which they are executed is almost infinite. This would have required categorizing the movements afterward, which in turn would have increased the variability of outcome measures. Moreover, capturing an entire soccer field with Vicon cameras with players kicking balls around is difficult to accomplish. Admittedly, however, the ecological validity of the data may have been better in the latter situation.

Practical Implications

Although current LPM systems are typically more costly and less flexible than GPS and video-based tracking, LPM improves the possibilities for time–motion analysis in (elite) team sports. Where other tracking systems are often limited to measured displacements in speed zones, LPM provides meaningful data on acceleration and deceleration. Sport scientists and coaches have the ability to improve (live) monitoring of training load and, if allowed by the sport's regulations, match load. Especially in training, where relatively much time is spent on direction changes, traditional time–motion parameters (distance in speed zones) would underestimate workload.[6] New time–motion parameters such as number of accelerations or time spent in acceleration or deceleration zones can add vital knowledge to the estimation of workload of training exercises and matches. It may also provide new insights into fatigue-related changes over time.[10] In addition, more accurate metabolic power estimation is feasible, as LPM improves the input data for already developed power-estimation algorithms.[4]

Conclusions

The current study provides information on the accuracy of the newest LPM system in soccer-specific movements on a range of movement intensities. We found that the LPM system is an accurate system to track distance, average speed, and peak speed of the players. Depending on the purpose of analyses (ie, acceleration count in game play), acceleration- and deceleration-related parameters can provide valuable information, too. The accuracy of the LPM system depends on not only movement intensity but also type of movement.

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