Assessment of the accuracy of different systems for measuring football velocity and spin rate in the field

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The aim of this study was to measure the level of agreement of four portable football velocity and spin rate measurement systems (Jugs speed radar gun, 2-D high-speed video, TrackMan and adidas miCoach football) against a Vicon motion analysis system. One skilled male university football player performed 70 shots covering a wide range of ball velocities (12–30 m·s^{-1}) and spin rates (94–743 rpm). A Bland-Altman analysis was used to assess the level of agreement. For ball velocity, the 2-D high-speed video had the smallest systematic error, followed by the radar gun, TrackMan and miCoach football at 0.2, 0.4, 0.5 and 4.8 m·s^{-1}, respectively. A similar ranking was also observed for the random errors (±0.4 m·s^{-1}, ±1.5 m·s^{-1}, ±1.9 m·s^{-1} and ±6.0 m·s^{-1} 95% CIs). The first three systems all tracked ball velocity in > 90% of shots, while the miCoach football tracked slightly fewer shots (79%). For spin rate, the miCoach football had a much smaller systematic error (4 rpm vs 38 rpm) and random error (±24 rpm vs ±355 rpm 95% CIs) compared to TrackMan. The miCoach also successfully tracked spin rate in more shots than the TrackMan (79% vs 44%). These results indicate that 2-D high-speed video would be the preferred option for the field assessment of ball velocity, however, radar gun and TrackMan may also be appropriate. A minimum of ten frames of 2-D high speed video, captured close to the ball starting position, was demonstrated to be sufficient in providing a reliable measure of ball velocity. The miCoach ball is the preferred option for field assessment of ball spin rate.

Keywords: soccer; speed; miCoach; TrackMan; radar gun; high speed video; spin rate; velocity

Introduction

Conducting research in the field may be challenging due to limitations related to power supply, risk of damage or portability. For the field assessment of ball velocity and spin rate for football shooting, different portable measurement systems have been used including radar guns [1, 2] and 2-D high-speed video (HSV) [3, 4]. However, the accuracy of the ball velocity and spin rate measurements from these systems has not been assessed. Furthermore, there has been a recent growth in consumer technology to measure ball velocity and spin rate, again with little reported on the accuracy of these devices, such as the adidas miCoach SMART football.

The aim of this study was to assess the level of agreement for portable ball velocity and spin rate measurement systems compared to an automatic motion analysis system (Vicon). Previous studies have demonstrated that Vicon can track markers to sub-millimetre accuracy (e.g. 0.62 mm [5]) corresponding to an upper limit in ball velocity error of 1–3%, thereby supporting the use of Vicon as the comparison system. The systems tested included the following: radar gun; 2-D HSV; TrackMan football prototype (Doppler radar-based launch monitor); and adidas miCoach SMART football (integrated six-axis MEMS IMU to measure the ball's acceleration and rotation rate which is transferred via Bluetooth to an iOS app). All five systems measured ball velocity, whilst three systems (Vicon, TrackMan and miCoach football) measured spin rate (Table 1).

Methods

One male university football player (age 21 years, height 1.97 m, mass 88 kg) participated in the study, which received ethical clearance from the institutional ethics committee. The participant provided written informed consent in accordance with the requirements of the Helsinki Declaration for human participant research.

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Table 1. Summary of the key features of the systems assessed for football velocity and spin rate measurement.

	Jugs Radar gun [13]	2-D high-speed video	TrackMan [14]	adidas miCoach
Cost	$1,095	~$2,000 – $3,000	Not available	$200
Technology	Doppler radar-based	Image analysis	Doppler radar-based	IMU embedded in ball
Measurements	Velocity	Velocity	Velocity	Velocity
Reported	±0.5 mph	Setup dependent	Not available	Not available
Set-up				
Calibration	No	Yes	Yes	No
Recording	Manual	Manual	Automatic	Manual via
Additional		Lighting sensitive	Left/right foot	Smartphone needed
Data capture	None	1000 Hz	None	None
Post-processing	None	Digitizing and run	None	None

Test protocol

The participant was instructed to perform shots with a wide range of ball velocities (from 50% to 100% of maximum) and spin rates (from zero to maximum) to test the systems under a wide range of conditions. Shots were performed from an artificial turf run up (1.5 m long) towards a vertical target line on a wall positioned 8.2 m from the starting ball position in the direction of flight (Fig. 1). The wall was comprised of two crash pads, each 3 m long and 1.8 m high, joined at the vertical target line, as well as a ceiling hanging net positioned immediately behind the crash pads to capture any high shots. As recommended by the manufacturer for the miCoach football, only shots ≥1 m above the ground were considered to be successful. A total of 70 successful shots were recorded.

A 10-camera Vicon MX motion analysis system (Vicon Motion Systems Ltd, Oxford, UK) was set to capture at 400 Hz with the cameras evenly distributed around the indoor lab test zone on a ceiling-based rail approximately 3 m above the ground (Fig. 1). This provided a calibrated ball flight distance of 4 m in the horizontal kicking direction and 2 m vertically from the ground. The radar gun (Jugs Sport, Tualatin, OR) was held in a small gap in the target wall between crash pads at a height of approximately 1.2 m pointing to the ball starting position along the target flight path (Fig. 1). The HSV (FASTCAM ultima APX, Photron Inc, San Diego, CA) was set to capture at 1000 Hz with a shutter speed of 1/8000 s and resolution of 1024×1024 pixels. The HSV was placed on a tripod 0.5 m above ground, 2.1 m from the starting ball position in the direction of flight, set back 3.5 m perpendicular to the flight path. The HSV field of view extended 1.4 m horizontally to ensure at least 35 HSV frames (~15 Vicon frames) containing the entire ball were captured at the predicted maximum ball velocity of 30 m·s^{-1}. Additional lights (ARRI POCKET 400, Arnold & Richter Cine Technik GmbH & Co, Munich, Germany) were positioned either side of the HSV. Following the manufacturer recommendations, the TrackMan football prototype (TrackMan Golf, Vedbaek, Denmark) was placed 3 m behind and 0.5 m to the right of the starting ball position. The miCoach football (adidas, Herzogenaurach, Germany; diameter 0.22 m, mass 0.43 kg, pressure 0.9 bar) was patterned with eight hemispherical retroreflective markers (7 mm radius) for tracking by the Vicon motion analysis system. The markers were positioned approximately equidistant over the half of the ball surface facing the target in the ball starting position; thereby ensuring minimal interference to the player during kicking, good visibility to the Vicon cameras and sufficient coverage for sphere fitting. For each kick, the miCoach football was orientated as recommended by the manufacturer (valve facing the kicker; middle arrow facing towards centre

of target) and the participant was instructed to kick the ball in the valve zone, again as recommended by the manufacturer.
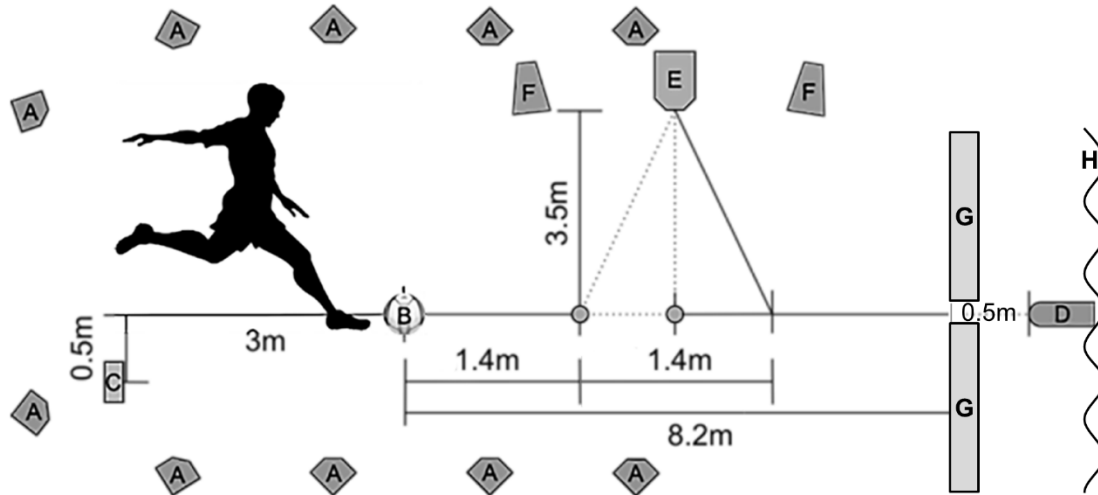

Figure 1. Aerial schematic of lab-based test set-up.
A: 10 camera Vicon motion analysis system cameras; B: adidas miCoach football; C: TrackMan Football prototype; D: Jugs speed radar gun; E: 2-D high-speed video (HSV); F: 2 × ARRISUN 12 lights; G: crash pads meeting at the target line; H: hanging net.

Data analysis

Ball velocity/spin rate from the radar gun, TrackMan and miCoach football were provided directly by the systems after each shot. Ball velocities were converted to $m \cdot s^{-1}$, while spin rates were converted to revolutions per minute (rpm).

The 2-D HSV was post processed using the digitising software Tracker (version 4.11; Open Source Physics). For each shot, 30 to 60 frames were digitised, depending on ball velocity, using six reference points around the edge of the ball. These frames were selected to match the horizontal range used to calculate the ball velocity from the Vicon system. A fixed diameter circle was fitted to the six digitised points in each frame to minimise the average root

mean square difference per frame between the digitised points and the circle on a per shot basis. Typical values for the root mean square difference across a shot were 1.0 ± 0.5 mm (mean$\pm$SD). Using the measured ball diameter (0.22 m) allowed the frame-to-frame movement of the ball centre to be determined in SI units from which numerical differentiation using first order finite differences was used to obtain frame-to-frame ball velocities. The final HSV ball velocity for each shot was calculated as the mean frame-to-frame value across all frames analysed.

The 3-D co-ordinate data representing the eight ball markers were exported from Nexus 1.8 (Vicon Motion Systems Ltd, Oxford, UK) for post processing in Matlab (The Mathworks, Natick, MA). To reduce noise in the marker trajectory data, the rigid body pose estimation method [6] was applied to the eight markers in each frame based on an initial static capture of the ball (the RMS differences were ~1 mm with all <2 mm). A fixed diameter sphere was then fitted to each frame with the diameter determined from the static trial (0.222 m). Numerical differentiation using first order finite difference method was used to obtain frame-to-frame ball velocities. Rotation matrices from frame-to-frame [7, 8] and differentiated using first order finite difference method [9] were used to obtain frame-to-frame spin rate. The Vicon frames corresponding to the section of ball flight recorded and processed from the 2-D HSV were identified and used as a basis for determining the mean ball velocity and mean spin rate from the Vicon data. Typical coefficient of variation in ball velocity and spin rate across these frames was < 1%.

No pre-filtering of the raw digitised points from the 2-D HSV or the raw marker trajectories from Vicon was performed. This was based on observation of the data resulting from the circle fitting process for the 2-D HSV and the pose estimation followed by sphere fitting for Vicon that suggested no further steps to reduce noise were necessary.

Statistical analysis

Level of agreement for ball velocity and spin rate was assessed using a Bland-Altman analysis [10] in which the results from each system were compared to those from Vicon. Assumptions of normal distribution and outliers for parametric tests were validated and hence mean difference values were compared to zero using a one-sample t-test.

Results

Ball velocities and spin rates from Vicon ranged from 11.6 to 30.4 $m \cdot s^{-1}$ and 94 to 743 rpm, respectively (Fig. 2). Measurement success rate was ≥90% for all systems except the miCoach football spin rate (79%) and TrackMan spin rate (44%) as shown in Tables 2 and 3.
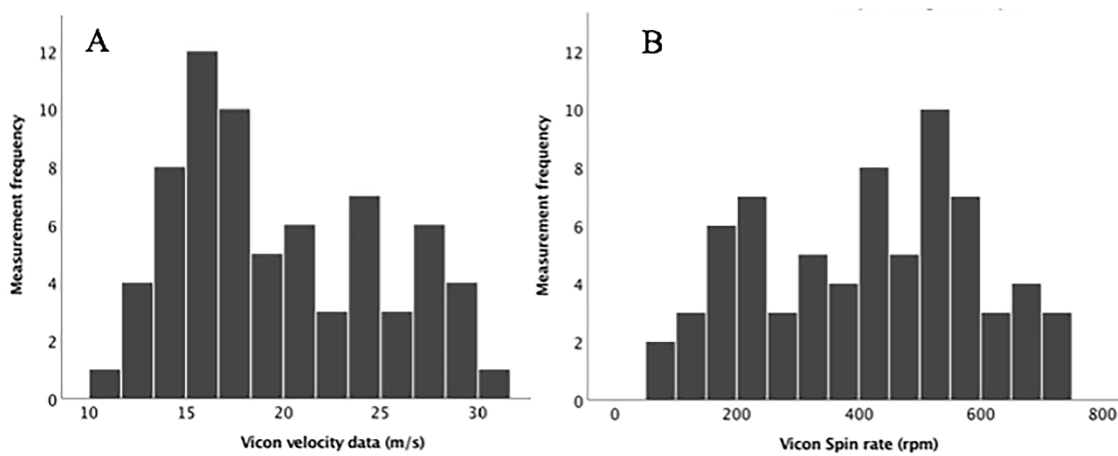

Figure 2. Histogram of Vicon: (A) ball velocities and (B) ball spin rates.
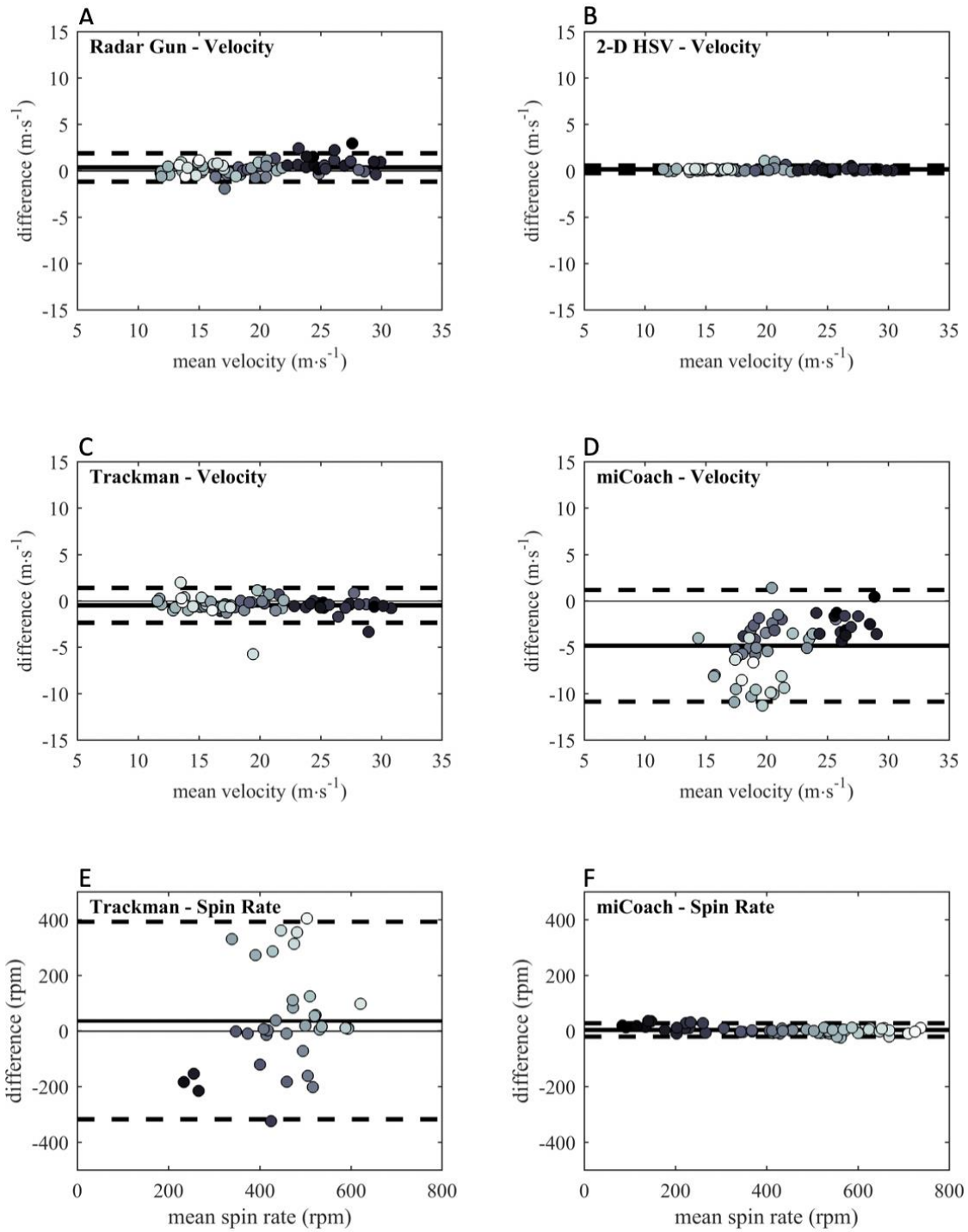
Figure 3. Bland-Altman plots for ball velocity and spin rate.
Difference = Vicon–comparison system; Thick solid line = mean difference; Thick dashed lines = 95% confidence intervals for the difference. The level of shading represents the spin rate from black (low) to white (high).

Table 2. Bland Altman results for ball velocity (each system compared to Vicon).

	N	Mean±SD (m·s^{-1})	Range (m·s^{-1})	Mean difference (m·s^{-1})	Lower LOA (m·s^{-1})	Upper LOA (m·s^{-1})
Vicon	70	19.72±5.26	11.60-30.40			
Radar Gun	69	19.41±4.98	11.94-29.72	0.37***	-1.15	1.89
2-D HSV	63	19.67±5.32	11.41-30.36	0.17***	-0.25	0.59
TrackMan	65	20.34±5.53	11.60-31.20	-0.46***	-2.34	1.42
miCoach	55	23.80±3.21	16.39-30.83	-4.82***	-10.86	1.22

N = number of shots successfully recorded; Mean difference = Vicon–comparison system; LOA = 95% limits of agreement; *** = p ≤ 0.001.

For ball velocity, the Bland-Altman analysis indicated the smallest systematic error (mean difference) and random error (95% limits of agreement) for 2-D HSV, followed by the radar gun and TrackMan (Table 2 and Fig. 3A–C). For all three systems, the systematic errors were very small (<0.5 m·s^{-1}), as were the random errors (±2.0 m·s^{-1}), particularly for the 2-D HSV, which had a random error of only ±0.4 m·s^{-1}. In contrast, the miCoach football demonstrated a relatively high systematic error (-4.8 m·s^{-1}) and random error (±6.04 m·s^{-1}) as shown in Table 2 and Fig. 3D. However, for the miCoach ball, the systematic error appears to depend on spin rate; higher spin rates led to a greater over-estimation of ball velocity (Fig. 3D).

For spin rate measures, the Bland-Altman analysis indicated a small systematic error and random error for the miCoach football of 4 rpm and ±24 rpm, respectively (Table 3 and Fig. 3F). For shots with a spin rate <300 rpm, the miCoach football tended to consistently give spin rates smaller than the Vicon values (Fig. 3F). In contrast, TrackMan demonstrated much larger systematic and random errors of 38 rpm and ±355 rpm, respectively (Table 3 and Fig. 3E).

Table 3. Bland Altman results for ball spin rate (each system compared to Vicon).

	N	Mean±SD (rpm)	Range (rpm)	Mean difference (rpm)	Lower LOA (rpm)	Upper LOA (rpm)
Vicon	66	406±179	94-743			
TrackMan	31	442±114	173-617	38***	-317	393
miCoach	55	421±186	74-732	4***	-20	28

N = number of shots successfully recorded; Mean difference = Vicon–comparison system; LOA = 95% limits of agreement; *** = p ≤ 0.001.

Discussion

This study assessed the level of agreement of four football velocity and spin rate measurement systems in comparison to a Vicon automatic motion capture system.

The 2-D HSV demonstrated the strongest level of agreement for ball velocity, whilst the radar gun and TrackMan systems followed closely behind. In contrast, the miCoach football demonstrated a much poorer level of agreement, particularly at high spin rates. The strong agreement for 2-D HSV is unsurprising given this was the only system where the measurement trajectory range could be controlled and matched to the Vicon range; the small differences are likely the result of ball out-of-plane movement. For all other systems, the measurement range along the ball trajectory was not as well defined and may have contributed to the increased errors. For the miCoach football, there were additional errors associated with the ball velocity being calculated from the sensor data rather than directly measured. For ball spin rate, miCoach football directly measures this variable and demonstrated a much stronger level of agreement. In contrast, the level of agreement for ball spin rate was much poorer for TrackMan as was the tracking success of this variable.

From these results, recommendations can be made for the appropriate measurement system to be used for different applications. Using ball velocity accuracy thresholds of ± 0.5 m·s^{-1} and ± 1 m·s^{-1} for research and coaching applications, respectively, 2-D HSV is the most reliable and accurate option. However, radar gun and TrackMan also meet these criteria and are less expensive alternatives that are easier to set-up and analyse data (Table 1). Using ball spin rate accuracy thresholds of ± 10 rpm and ± 25 rpm for research and coaching applications, respectively, the miCoach football meets both these criteria and is low cost and easy to set-up and analyse.

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A limitation of this study was the distance of the 2-D HSV perpendicular to the target flight path. It is recommended that future studies use a distance greater than the 3.5 m utilised here (constrained by the lab dimensions) to reduce the effect of ball out-of-plane movement and further improve the performance of this measurement system. Also, although 30 to 60 HSV frames were digitised per trial to allow the horizontal measurement range between the 2-D HSV and Vicon systems to be matched, further analysis of this data revealed that only ten frames of the 2-D HSV were needed to generate velocity values statistically the same as those obtained using all frames.

Since both ball velocity and spin rate reach a maximum very rapidly post-kick before slowly decreasing over the remainder of flight, the system comparisons may have been confounded by the different parts of the flight path used by the various measurement systems. For Vicon and 2-D HSV, the measurement zone was selected close to the ball starting position, such that velocity and spin rate were close to their maximum values (within 5%) [11, 12]. For the other systems, the radar gun reports maximum velocity [13]. Assuming TrackMan football uses principles similar to TrackMan for golf, then velocity and spin rate are measured immediately following the kick [14] and, therefore, should also be very close to the maximum values. Whilst there is little technical information available for the miCoach football, the logical assumption is that from the continuous IMU data, the maximum for velocity and spin rate are extracted and reported. On this basis, the 2-D HSV and Vicon data are directly comparable, while for the remaining systems, the measurements may be expected to be up to 5% greater than Vicon due to differences in location along the flight path where measurements were taken. Although these expected differences are small and do not affect the key outcomes of this study, they are reinforced by the mean difference results for all systems, except the radar gun velocity (Tables 2–3). Furthermore, they also highlight the importance of measurement zone selection

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when using 2-D HSV and the recommendation to use a very early section of the flight path (i.e. within the first 2–3 m) to gain a velocity value close to the maximum.

Conclusion

Of the systems tested, 2-D HSV provided the best method for measuring ball velocity in field-based research on football shooting performance, while radar gun and Trackman represented viable alternatives. Furthermore, a minimum of ten frames of 2-D HSV captured close to the ball starting position was demonstrated to be sufficient to provide a reliable measure of ball velocity. Only the miCoach football provided a viable means of measuring ball spin rate. This study is the first to offer researchers objective data to support the selection of a portable measurement systems for ball velocity and spin rate.

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