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The penalty kick accuracy in soccer: A new biomechanical approach

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ABSTRACT

The purpose of this study was to present a practical novel method to calculate the penalty kick accuracy in football. The mathematical advantage considered the ratio of the rectangle goal dimension (1:3) and equalized between horizontal axis as it longer 3 times than the vertical axis. Twelve male soccer players 16 (3) years)), height 174.7 (4.5) cm)), body mass 67.6 (5.5) kg)) volunteered to participate in this study. The players were asked to do penalty kicks where the ball is aimed at the farthest point from the centre of the target portion for shooting. The soccer goal was split into quarters at three different velocities (low, medium, and high) the calculation was conducted two times by height to width ratio (HWR) and the most common method radial error. Kinovea Software 0.8.27. were used for digitizing. The ICC demonstrated high reliability ($r = .99$) for digitization at the moment the ball crossed the goal line for the inter and intra-ratter reliability. There was a significant relationship between some kinematics variables of the ball and the accuracy outcome of the HWR method in the four sections of the goal ($p < .05$).

Keywords: Height to width ratio (HWR); Perspective grid; Kicking accuracy; VAR.

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INTRODUCTION

Soccer is the most popular sport in the world (Lees & Nolan, 1998) and impacts positively upon the economy. At the last FIFA World Cup in Russia in 2018, video technology (Video Assistant Referee [VAR]) helped the referees to make correct decisions pertaining to goals scored, awarding of penalty kicks and red card dismissals. A penalty kick is a unique opportunity for an attacking player to score a goal, whilst presenting a difficult task for a goalkeeper to prevent a goal with limited time to decide how to save the ball. Penalty kick takers will strike the ball away from the goalkeeper with pace and accuracy.

Kicking accuracy has been defined as the ability to direct the ball to a specific area (Finnoff, Newcomer, & Laskowski, 2002). Accuracy is a key element of the penalty kick for scoring success, therefore, improving the shooting technique is a basic objective to develop the performance of soccer players (Finnoff et al., 2002). The combination of accuracy and velocity are key elements that contribute to successful shots (Lees & Nolan, 1998; Markovic, Dizdar, & Jaric, 2006; Mirkov, Nedeljkovic, Kukolj, Ugarkovic, & Jaric, 2008; Vieira et al., 2018).

There are several common methods to measure soccer accuracy such as the Loughborough soccer Shooting Test (LSST), Loughborough soccer Passing Test (LSPT) (Ali et al., 2007) and the 356 soccer Shooting Test (356-SST) (Radman et al., 2016). Some tests measure ball velocity, whether the ball hits a specific target, others count the frequency of shots during a game or the number of passes completed between two targets, with often time to complete the test recorded and reported (Ali et al., 2007; Finnoff et al., 2002; McLean & Tumilty, 1993; Nagasawa, Demura, Demura, Matsuda, & Uchida, 2011; Radman et al., 2016). Previous examples of tests used for accuracy include shooting into the four corners of the goal equally with both the dominant and non-dominant leg with points scored for accuracy (Nagasawa et al., 2011) and shooting into marked scoring zones again with a point scoring system (Loughborough soccer Shooting Test) , (Ali et al., 2007) However, recent research has discussed the shortcomings of these methods and stated that low validity and sensitivity make these methods not suitable for measuring accuracy (Bacvarevic et al., 2012; Ugur & Mehmet, 2017). Further, these accuracy tests do not take into account the different kinematics required for different shot positions, therefore making it difficult to identify the relationship between the kicking kinematics and accuracy result. Thus, there is a need to develop a new method for determining kicking accuracy more precisely.

Due to these short-comings, accuracy tests have been developed that included the metric measurement of the distance from the centre of the ball to the middle of the goal. This can be calculated in two ways. The first way is using a distance measurement tool that is found within motion analysis software (Alcock, Gilleard, Brown, Baker, & Hunter, 2012; Scurr & Hall, 2009; Sterzing, Lange, Wächtler, Müller, & Milani, 2009), but the disadvantage of this method is that it does not take into account the direction of the ball. The second way is to calculate the radial error using two dimensions (X, Y), which is the square root of the square of dimensions (X, Y) (Ferraz, van den Tillaar, Pereira, & Marques, 2017; Hancock, Butler, & Fischman, 1995; van den Tillaar & Ulvik, 2014; Vieira et al., 2018). The disadvantage of this method is that it is only valid with a circular shape with an equal radius which is not appropriate with the rectangular shape of the goal. In addition, there is the possibility to obtain the same distance measured from the middle of the ball to the middle of the goal in all directions, up and down or right and left. The preferred accuracy for shooting success, is placing the shot in the corners of the goal (Nagasawa et al., 2011). Therefore, the farther the ball is from the centre of the goal, the greater the chance of scoring and it becomes more difficult for the keeper to catch the ball. Therefore, the purpose of this study was to develop and evaluate an innovative method to calculate the penalty kick accuracy in soccer according to the ball coordinates. The new method of height to width ratio

(HWR) would overcome the shortcomings of the common methods using the radial error. By dividing the goal into four equal sections and providing a ratio to the ball coordinates that reflects the accuracy level obtained through an equation that takes into account the coordinates of the ball, accuracy could be correlated to the player's kinematic variables while performing the penalty kick. The ratio should not be replicated within one section of the goal, so that the farther the ball was from the centre of the goal, the higher was the accuracy score.

MATERIALS AND METHODS

The Novel method description

The height to width ratio (HWR) method for calculating the penalty kick accuracy takes into account the ratio of the rectangle goal dimension (1:3). This ratio is fixed between the height and width of the whole goal (h = 2.44 m, w = 7.32 m) or in the 4 sections as quarters of the goal (H = 1.22 m, w = 3.66 m). The proposed method provides a mathematical advantage to the horizontal axis as it is always 3 times longer than the vertical axis and thus the range to score is higher. During a penalty, the goalkeeper might cover the vertical area using his arms to get a unique percentage accuracy. The novel method equalized the length of both goal axes X (width) and Y (height), by dividing X values by 3 (Equation 2). This division aims to correct the measurement error and therefore enhance accuracy.

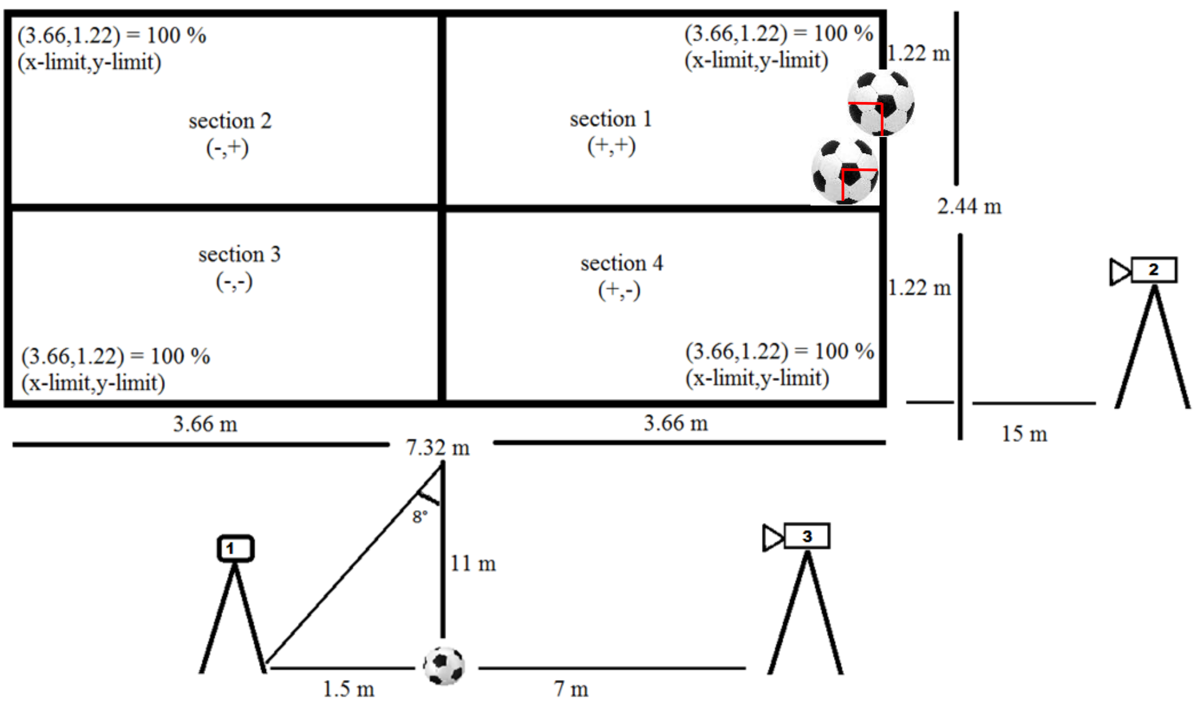

Figure 1. Goal sections using the Cartesian system and camera setting locations (r = -------).

The calculations of the accuracy using the radial error method Equation 1 and the calculations of the accuracy using HWR method Equations 2 and 3.

(1) $Radial\ error = \sqrt{(x)^2 + (y)^2}$

(2) $HWR\ index = \sqrt{(\frac{|x|}{|xlimit|})^2 + (\frac{|y|}{|ylimit|})^2} + \frac{|x|}{3}$

(3) $Accuracy\ percentage = \frac{HWR\ index}{Maximum\ HWR\ index} * 100$

$|xlimit|$ = absolute value of the maximum width for each section (3.66m- ball radius), Figure 1,
$|ylimit|$ = the absolute value of the maximum height for each section (1.22m- ball radius),
$|\ x\ |$ = absolute value of the horizontal coordinates of the ball,
$|\ y\ |$= absolute value of the vertical coordinates of the ball; 3 = width ratio to height.

Evaluation of practical applicability
The horizontal coordinates of each section range from 0.01 meters to 3.55 meters and the vertical coordinates range from 0.01 meters to 1.11 meters. These represent the minimum and maximum width and height of any section of the goal without the radius of the ball which is 0.11 meters. The coordinate matrix in each section was calculated so that the ball may cross the goal line with a change of a minimum of 1 cm in the centre of the ball on the horizontal and vertical axis using Excel (Microsoft, USA). This is considered the highest accuracy for digitization.

The total number of the possible values of the ball position was 39405. These huge numbers included in the matrix cannot be presented in the methods section. Therefore, we only present duplicate values of the accuracy percentage form the various coordinates (Table 1) of the radial error matrix.

The limitation of the radial error method
The limitation of radial error

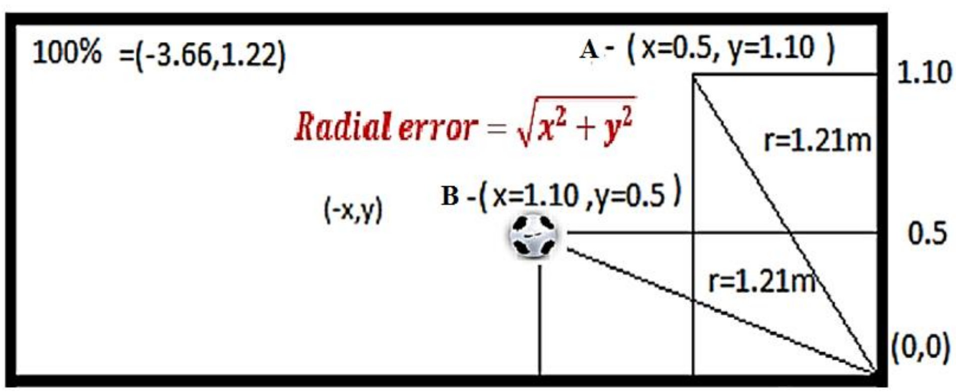

Figure 2. The method of calculating accuracy using the radial error in the second section of the goal.

In the radial error method, the distance of the ball direction is not determined because it depends on the resultant distance. Figure 2 shows the method of calculating the accuracy using the radial error in the second section of the goal. It demonstrates that various coordinates of the ball provide the same result of accuracy (1.21 m) which is the distance of the ball from the centre of the goal. In the first case (A) the coordinates were (x = 0.5 m, y = 1.10 m) and the second case (B) the coordinates were (x = 1.10 m, y = 0.5 m). therefore, it cannot discriminate between the shots. On the other hand, using the proposed HWR method, the accuracy is not calculated by meters or by distance, but it is displayed as a percentage that expresses the value of the accuracy index. In accordance with Equations 2 and 3, when we apply HWR calculation on the first case A (x = 0.5, y = 1.10), we have the accuracy percentage of 44.9%. for the second case B (x = 1.10, y = 0.5) the accuracy percentage was 35.1%. (as 0% represents the lowest accuracy which is the middle of the goal and 100% represent the highest accuracy which the ball at the farthest point from the goalkeeper (Figure 2).

Participants

Twelve male soccer players (age: 16 (3) years, height 174.7 (4.5) cm and body mass 67.6 (5.5) kg) from an Austrian regional level soccer team volunteered to participate. The code of ethics described in the Helsinki agreement was followed and each participant signed an agreement form, respectively. The players provided informed consent alongside their parents. The players participated in soccer 2 to 3 times per week during the study period.

Experiment procedure

Figure 1 shows the goal partition and the location of the cameras. Two high-speed cameras (GoPro Hero 5 black 240 Hz, USA) were used. The first camera was set to capture the ball as it crossed the line of the goal in any of the four sections. It was located 11 meters in front of the goal and 1.50 meters from the left side of the penalty spot. This allows enough space for the player to shoot without disrupting the view of camera on the goal. To adjust the slope of the camera, ensure accurate coordinates, and to obtain the camera's vertical position with respect to the goal, the perspective grid of Kinovea Software 0.8.27 (Charmant, 2018) was used (Puig-Diví et al., 2017).

The second camera was placed 15 m from the side of the goal to determine the moment the ball enters the goal. The cameras (1 and 2) were synchronized by dropping a ball and determining the moment when the ball hit the ground. The cameras determined the moment the ball crossed the goal line and determined the position of the ball (x, y). A third camera was used and placed vertically at a distance of 7 meters at the side of the ball to capture the movement of the ball during kicking.

The Cartesian coordinate system (Figure 1) was used through Kinovea Software 0.8.27 to divide the dimensions of the goal (7.32 m × 2.44 m) into four equal sections. The zero points (0,0) for the horizontal and the vertical dimensions were at the centre of the goal to get the maximum width ($xlimit$) and the maximum height ($ylimit$) for each section. Section one (3.66 m, 1.22 m), section two (-3.66 m, 1.22 m), section three (-3.66 m, -1.22 m), and section four (3.66 m, -1.22 m) are presented in Figure 1. The ratio between height and width is 1:3.

Two ratters experienced using the computer software, digitized the ball coordinates at the instant the ball crossed the goal for 10 repeated kicks (trials) (Kinovea Software 0.8.27). To calculate the reliability of the digitization process, the ratters digitalized the same 10 trials twice. An intraclass correlation was used to calculate the inter-rater and intra-ratter reliability. The error ratio of calibrating the goal dimensions was calculated using the perspective grid feature for the video resolution using the following equation:

$$\frac{\text{width in cm}}{\text{width in pixel}}\,\frac{847\text{cm}}{1280\text{ pixel}} = 0.66 \text{ cm.}$$

Kinematic analysis

The players performed a general warm-up for 10 minutes and each player performed three kicks in each section of the goal (Figure 1). Each player was asked to shoot as near as possible to the centre of each section of the goal at three speeds (low, medium, and high). All 144 implemented shots were analysed. The velocity of the ball was measured using the three cameras described above and the 2D Tracker v5 kinematics analysis software was used to track the ball path. A low pass Butterworth filter cut-off of 15 Hz was used to filter the raw data. All the kinematic parameters of the ball were calculated (vertical velocity, horizontal velocity, resultant velocity, launch angle) using MATLAB R2016a software.

Statistical analysis

The statistical analysis software SPSS v20 was used to calculate the mean and standard deviation of the kinematic variables of the ball (vertical velocity, horizontal velocity, resultant velocity, Launch angle). Intraclass correlation (ICC) was used to calculate the inter and intra-ratter reliability. The limits of agreement for consistency were calculated using Bland Altman (J. Martin Bland & Altman, 1999; Giavarina, 2015), and Pearson's correlation coefficient to determine the relationship between some kinematic variables of the ball and the resulting accuracy.

RESULTS

Table 1. A sample of the duplicated values of accuracy percentages (measurement error) in the coordinate matrix calculated by radial error. Each colour represents the same accuracy values for two other (X, Y) coordinates.

X / Y	1.11	1.1	1.09	1.08	1.07	1.06	1.05	1.04	to 0.01
3.29	3.472204	3.46902	3.465862	3.46273	3.459624	3.456545	3.453491	3.450464	
3.28	3.46273	3.459538	3.456371	3.45323	3.450116	3.447028	3.443966	3.44093	
3.27	3.453259	3.450058	3.446883	3.443733	3.44061	3.437514	3.434443	3.431399	
3.26	3.443792	3.440581	3.437397	3.434239	3.431108	3.428002	3.424923	3.421871	
3.25	3.434327	3.431108	3.427915	3.424748	3.421608	3.418494	3.415406	3.412345	
3.24	3.424865	3.421637	3.418435	3.41526	3.412111	3.408988	3.405892	3.402822	
3.23	3.415406	3.412169	3.408959	3.405775	3.402617	3.399485	3.39638	3.393302	
3.22	3.405951	3.402705	3.399485	3.396292	3.393125	3.389985	3.386872	3.383785	
3.21	3.396498	3.393243	3.390015	3.386813	3.383637	3.380488	3.377366	3.37427	
3.2	3.387049	3.383785	3.380547	3.377336	3.374152	3.370994	3.367863	3.364759	
3.19	3.377603	3.37433	3.371083	3.367863	3.364669	3.361503	3.358363	3.35525	
3.18	3.36816	3.364877	3.361622	3.358392	3.35519	3.352014	3.348865	3.345744	
3.17	3.35872	3.355428	3.352163	3.348925	3.345714	3.342529	3.339371	3.33624	
3.16	3.349284	3.345983	3.342708	3.339461	3.33624	3.333047	3.32988	3.32674	
to 0.01									

The data in Table 1 represents a sample of the potential coordinate matrix calculated by the radial error method and its measurement unit is the meter – Equation 1. The coloured values indicate the result of repeated accuracy outcomes of different coordinates (each colour represents the accuracy value but with a different coordinate output). There were many duplicates values in the matrix from different ball positions.

Table 2. Intraclass correlation coefficient at 95% confidence interval for the inter and intra-ratter reliability for the ball digitization process.

	Intraclass correlation	95% Confidence Interval	
		Lower Bound	Upper Bound
Intra-ratter x	.999	.997	1.000
Intra-ratter y	.996	.987	.999
Inter-rater x	.999	.998	1.000
Inter-rater y	.996	.988	.999

The Intraclass correlation coefficients shown in Table 2 demonstrate excellent intra- and inter-rater reliability with ICC > .99 for the ball digitization process.

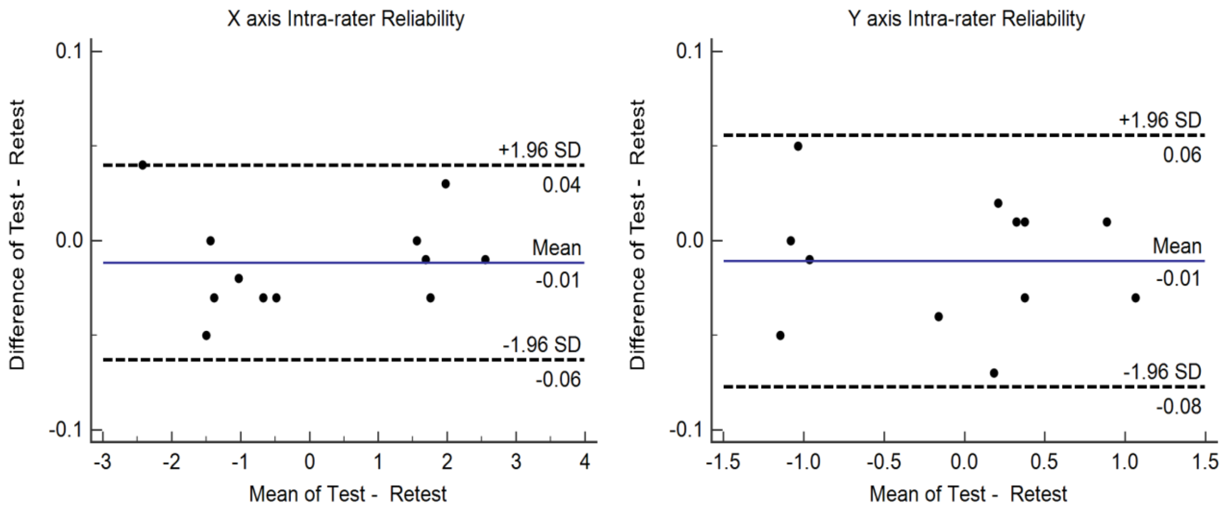

Figure 3. The limits of consistency using Bland Altman Plot method for the intra-ratter reliability for ball digitization at the centre of the ball.

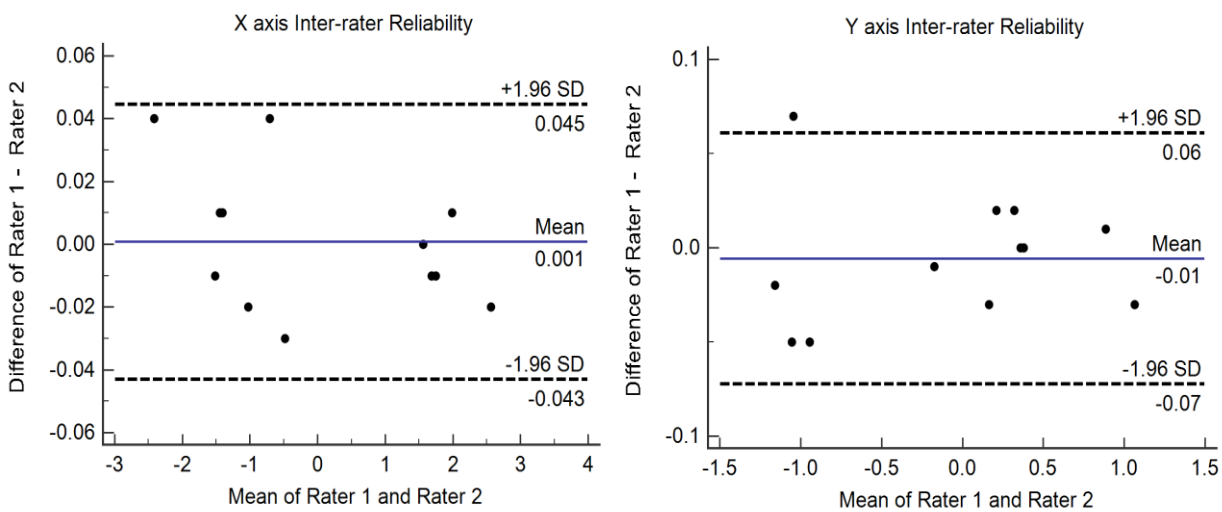

Figure 4. The limits of consistency using Bland Altman Plot method for the inter-ratter reliability for ball digitization at the centre of the ball.

To find out the limits of consistency between the ratters, the Bland Altman Plot method was used for the inter and intra-ratter reliability (Figures 3,4). The systematic bias were all ≤ -0.01 and the limits of agreement for all digitized trials were between ± 1.96 SD.

The data in Table 3 represents the mean and standard deviation of the kinematic variables of the ball at the moment of kicking and the accuracy of the HWR method in the four sections of the goal. The data in Table 4 represents the Pearson correlation coefficient between the kinematic variables of the ball at the moment of kicking and the accuracy of HWR in the four sections of the goal. Overall, the results showed high reliable digitization demonstrating the validity of the data produced by the new HWR method.

Table 3. Mean and standard deviation of the kinematics variables of the ball at the moment of kicking and the accuracy outcome between the HWR method in the four sections of the goal.

	Section 1 n = 36	**Section 2 n = 36**	**Section 3 n = 36**	**Section 4 n = 36**
HWR (%)	75.8 ± 10.04	73.9 ± 11.27	75.6 ± 12.90	73.8 ± 11.94
Horizontal velocity ($m.s^{-1}$)	21.4 ± 3.12	20.5 ± 3.11	21.0 ± 2.64	21.1 ± 4.06
Vertical velocity ($m.s^{-1}$)	5.3 ± 0.98	6.1 ± 1.08	4.0 ± 1.20	3.1 ± 1.19
Resultant velocity ($m.s^{-1}$)	22.1 ± 3.08	21.5 ± 3.14	21.4 ± 2.67	21.4 ± 4.00
Launch angle (°)	14.5 ± 3.10	17.383 ± 2.92	10.9 ± 3.13	9.0 ± 4.76

Table 4. Pearson correlation coefficient between the kinematics variables of the ball at the moment of kicking and the accuracy outcome of the HWR method in the four sections of the goal.

	HWR Section 1 n = 36	**HWR Section 2 n = 36**	**HWR Section 3 n = 36**	**HWR Section 4 n = 36**
Horizontal velocity ($m.s^{-1}$)	-0.03	0.03	-0.24	-0.32
Vertical velocity ($m.s^{-1}$)	0.41*	0.40*	-0.44**	-0.29
resultant velocity ($m.s^{-1}$)	0.01	0.07	-0.27	-0.33*
Lunch angle (°)	0.38*	0.39*	-0.33*	-0.11

*Note: **: Significant (p < .01); *: Significant (p < .05).*

DISCUSSION

The purpose of the present study was to propose a modern and accurate methodology to calculate penalty kick accuracy in soccer. The proposed HWR would enable us to overcome the shortcomings of the common methods employed to date. The results demonstrated that the HWR method was a valid and reliable method to discriminate between the players in terms of kicking accuracy. Thus, the study achieved the aim of providing an objective methodology for calculating the accuracy of the penalty kick in soccer, which will be explained below.

The outcomes of the accuracy using the radial error method (Table 1) shows that there are many values that were repeated from the different coordinates of the ball inside the sections of the goal, preventing discrimination between different shots. Each coordinate was coloured so that each colour expressed an exact coordinate, and the values reflect the distance from the centre of the goal to the centre of the ball according to the radial error calculation method (van den Tillaar & Ulvik, 2014). However, this distance ignores the direction of the ball, so it is difficult to correlate the kinematic variables of the ball and the outcome of accuracy. Otherwise, The HWR method indicates that it is not possible to repeat the accuracy values and that every possible coordinate of the sphere in the same section have a unique ratio of accuracy.

Therefore, this method is more objective and sensitive than the radial error method as we can distinguish between the players and kicks in terms of accuracy. This is a practical application for determining the most successful penalty kicks and employing these in matches.

In Table 4 the Pearson correlation coefficient explained the relationship between the kinematic variables of the ball at the moment of kicking and the accuracy outcome of the proposed HWR. Positive correlations for vertical velocity and launch angle ($p < .05$) were found for the upper right and left corners of the goal. The proposed equations that are employed in the HWR method give a greater emphasis to the horizontal axis X (3.66 m) because it represents three times the vertical axis according to the ratio of height and width 1:3 for the distance of the goal. This explains the increase in accuracy to 100%, which represents the farthest and highest point in the upper sections of the goal when increasing the vertical velocity and the kicking angle of the ball.

Reciprocally, in the lower left section, the accuracy outcome using HWR showed a negative relationship with the vertical velocity ($p < .01$) and with the kicking angle ($p < .05$). This result is the opposite for the left and right upper sections since 100% represents the farthest and lowest point for the lower left and right sections. Therefore, the lower the values of these variables, the greater the accuracy outcome was. As for the bottom right corner there was a negative relationship ($p < .05$) between the HWR method and the launch angle, while there was a moderate negative correlation between HWR and the resultant velocity. This can be explained by players kicking the ball with their instep and with an open angle, thus finding a balance between velocity and accuracy. Previous research by Nagasawa and colleagues suggested that accuracy when shooting in the upper corners were worse than the lower corners (Nagasawa et al., 2011). This is not consistent with the outcome of this study, where shooting into the bottom sections is very difficult, especially when the goalkeeper was standing in the middle of the goal.

The reliability for the ball digitization was credibility with the intraclass correlation coefficient for the inter- and intra-ratter reliability having a high correlation ($r = .99$), consistent with previous research (Finnoff et al., 2002). However, a disadvantage of the intraclass correlation coefficient is that it does not provide the difference between testing and retesting (J. M. Bland & Altman, 2003; Kottner et al., 2011). Therefore, the Bland and Altman method was employed to identify the mean difference and limits of agreement for inter and intra-ratter reliability (Chhapola, Kanwal, & Brar, 2015). The results showed an acceptable range 95% confidence interval for each of the minimum and maximum limits of agreement (± 1.96 SD) for inter-rater reliability (Figure 3) and intra-ratter reliability (Figure 4), which demonstrates clearly that the ball digitization process using the perspective grid is reliable and can be used to calculate the equations accurately.

In summary, this novel HWR method is one of several approaches that have been employed to determine penalty kicking accuracy. The objective and reliable HWR method, showed a high precision and less error compared with previous methods. In addition, the method provides a more ecologically valid alternative to those which have targets, count frequency of shots or record ball velocity only. The method allows penalty takers to complete training in a much more ecologically valid manner which is likely to lead to greater match success. Further, HWR could be combined with big data processing to determine training programs and identify training deficiencies. In addition, due to the high precision of the method, it could be employed to select penalty takers in training and potentially increase the success rate of scoring in matches.

CONCLUSION

The results showed that the HWR method is a valid and more accurate method for calculating the accuracy of the penalty kick in soccer compared to the most commonly used radial error method. There were low relationships between some kinematics variables of the ball ($p < .05$) and the HWR method in the four sections of the goal. This method does not need to employ specific goals inside the net and thus has more ecological validity for the penalty taker. The HWR equations can be included when using kinematics analysis software such as Kinovea to obtain the accuracy ratio directly. Thus, the method can be employed within the training ground to potentially improve penalty taking accuracy.

ETHICS STATEMENT

The code of ethics described in the Helsinki agreement was followed and each participant signed an agreement form, respectively. The players provided informed consent alongside their parents. The players participated in soccer 2 to 3 times per week during the study period.

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DECLARATION OF COMPETING INTEREST

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