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Original Article

MODELING THE TWO-DIMENSIONAL ACCURACY OF SOCCER KICKS

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Soccer, Penalty, Speed, Accuracy, Trade-off, Kick, Modeling

Word Count - 3512

Abstract

In many sports, athletes perform motor tasks that simultaneously require both speed and accuracy for success, such as kicking a ball. Because of the biomechanical trade-off between speed and accuracy, athletes must balance these competing demands. Modelling the optimal compromise between speed and accuracy requires one to quantify how task speed affects the dispersion around a target, a level of experimental detail not previously addressed. Using soccer penalties as a system, we measured two-dimensional kicking error over a range of speeds, target heights, and kicking techniques. Twenty experienced soccer players executed a total of 8466 kicks at two targets (high and low). Players kicked with the side of their foot or the instep at ball speeds ranging from 40% to 100% of their maximum. The inaccuracy of kicks was measured in horizontal and vertical dimensions. For both horizontal and vertical inaccuracy, variance increased as a power function of speed, whose parameter values depended on the combination of kicking technique and target height. Kicking precision was greater when aiming at a low target compared to a high target. Side-foot kicks were more accurate than instep kicks. The centre of the dispersion of shots shifted as a function of speed. An analysis of the covariance between horizontal and vertical error revealed right-footed kickers tended to miss below and to the left of the target or above and to the right, while left-footed kickers tended along the reflected axis. Our analysis provides relationships needed to model the optimal strategy for penalty kickers.

Introduction

In many sports, athletes must hit, throw, or kick a ball with power and accuracy to defeat an opponent. When doing so, athletes face a biomechanical trade-off between speed and accuracy, which forces a compromise between objectives (Andersen and Dorge, 2011; Etnyre, 1998; Freeston and Rooney, 2014). For example, soccer players must kick the ball fast enough to beat a diving goal-keeper and accurately enough to place it within the goal. Models can be used to show which strategy optimises success, but must be based on experiments that quantify the biomechanical trade-offs between speed and accuracy in not just one, but two dimensions. Mean distance from target is not enough to show biases in accuracy, which can occur in different directions. For example, if a player tends to kick more to the left of the target with increasing speed, this changes the strategy to optimise scoring success. Quantifying such biases requires experiments in which players hit, throw, or kick repeatedly over a range of speeds, while controlling for key factors such as technique, target, and environment.

Here, we tested the trade-off between speed and accuracy using penalty kicks in soccer, as a first step towards modelling the optimal strategy for success. Previous studies show that players kick at slower speeds when focusing on accuracy (Andersen and Dorge, 2011; Asami et al., 1976; Kawamoto et al., 2006; Lees and Nolan, 2002), which suggests a trade-off between speed and accuracy but is not specific enough to predict scoring success. Both speed and accuracy depend on how the kicker’s foot interacts with the ball, because this interaction determines the magnitude, direction, and position of force applied to the ball (Asai et al., 2002; Carre et al., 2002). A faster kick requires the player to use a greater range of motion (Browder, 1991; Lees and Nolan, 2002; Stoner and Ben-Sira, 1981), increasing the distance the foot travels to meet the ball. Two theories of motor control, Fitt's law (Fitts, 1954) and Impulse-Variability (Schmidt et al., 1979), predict that movement becomes less precise when a limb travels farther to its target. We should mention Fitt's law is more applicable to tasks allowing corrections during the movement, and can be violated by ballistic movements (Juras et al., 2009). Regardless, increased movement amplitude in this case should create variation in the direction and position of force applied to the ball, reducing the accuracy and precision of the kick.

Technique should also affect the relationship between kicking speed and accuracy. Players can enhance speed by striking the ball with the instep of the foot (or laces of the shoe), instead of the side of the foot (Levanon and Dapena, 1998; Nunome et al., 2002), though side-foot kicks are more accurate (Sterzing et al., 2009). Based on this, we expect instep-kicks to be less accurate at any speed than those from the side-foot. We will control for kicker's technique while repeatedly measuring the two-dimensionality of kicks relative to a target in order to estimate, for the first time, the likelihood of missing a target.

Target height should also affect the relationship between kicking speed and accuracy because it affects the probability of missing a target in the vertical dimension. A target on the ground cannot be missed below, even if the player kicks into the ground (or "tops" the ball), and gravity may reduce the magnitude of error above it. Slow shots kicked on an inaccurate upward trajectory may arc down toward the target, reducing the effect of the initial error. Conversely, shots at an above-ground target may miss above or below the target. Overall, aerial shots should have greater vertical error across all speeds compared with those on-ground. This is interesting, considering that players often aim near the top of the goal. Of 311 penalties in professional matches, 100% of penalty kicks placed in the top 3rd of the goal were successful, regardless of their position along the horizontal axis (Bar-Eli and Azar, 2009)—though it is unknown whether these kicks were aimed toward the top of the goal or landed there by mistake. If the height of the target mediates the relationship between speed and accuracy, kicking toward the top of the goal could actually be less effective.

To evaluate our predictions about the speed-accuracy trade-off, we measured the kicks of semi-professional soccer players in a controlled setting. Importantly, we surpass previous efforts to quantify this trade-off by modelling kick error across two-dimensions and a range of speeds. As predicted, variance in error (distance to target) increased as ball speed and target height increased. Variance was also greater for instep-kicks compared with side-kicks. We used these data to generate probability density functions describing where shots are likely to go, depending on shooting technique, target height, and footedness. These functions will enable scientists to develop models of optimal kicking behaviour during penalty kicks and can be adapted to other ball sports requiring speed and accuracy.

Methods

Subjects

Twenty soccer players from the University of Queensland Football Club participated in the experiment, ranging in age (17-35 years) and playing experience (10-24 years). Fifteen and five players were right-footed and left-footed, respectively. Subjects played in the Brisbane Premier League, Brisbane City League 1, Brisbane City League 3, or Brisbane Premier Under 20's. Data were collected over two consecutive years, with new kickers participating each year. Informed consent was obtained and the methods and protocols for this experiment were approved by the University of Queensland Behavioural and Social Sciences Ethical Review Committee.

Accuracy trials

Subjects were instructed to kick a soccer ball (size 5 inflated to 9 psi) at a target from a distance of 11 m, which is the standard for penalty kicks. The target (25 cm x 25 cm) was attached to a fence with its base positioned on the ground (first and second years) or with its centre positioned 1.6 m above the ground (second year only). The latter height is approximately 2/3 of the distance between the ground and the crossbar. For each kick, subjects were instructed to use either laces (instep) or side-foot and an approximate kicking speed based on a percentage of their maximal effort, ranging from 40% -100%. Subjects kicked with their dominant foot only (Vieira et al., 2016), and were allowed a self-selected run-up angle for each kick (Scurr and Hall, 2009). Each participant attended multiple sessions across separate days. The number of sessions completed and the number of days between sessions varied among participants, who completed between 178-787 kicks each in the first year and 160-402 in the second year. We observed 3384 and 3157 right-footed kicks in the first and second years, respectively, and 728 and 1197 left-footed kicks in the first and second years, respectively.

In a single session, each participant warmed up for 10 min then executed 80 kicks in 8 blocks of 10, with each block alternating between techniques (side-foot and laces). The first technique of each block also alternated across sessions. Each block of 10 kicks consisted of two sub-blocks of five kicks with different instructions (e.g., the first five kicks were 40% side-foot, but the second five kicks were 80% side-foot). This ensured that all combinations of speed and technique were performed in each session. In the second year, we added target height to the blocking schedule, so each combination of target height and kicking technique, across a range of speeds, was completed twice in each session. Ordering of speeds for each session and participant were randomized.

Analyses of video

To measure ball-speed, we used the DLTcal5 and DLTdv5 packages of MATLAB (Hedrick, 2008). High speed cameras (Casio, EX-FH25 or Panasonic Lumix DMC-TZ40) were calibrated to a three-dimensional space, then coordinates (x,y,z) were extracted from subsequent footage taken with them. To calibrate the cameras, an “imaginary” focal point was designated at 1 m in front of the ball along the ball-to-target line (i.e., 10 m from the target). An 11-point calibration box (1.5 m x 1 m x 0.6 m) was centred on the focal point, thereby filling the space through which the ball travelled. Two cameras, each on a 1 m tripod, were oriented 90 degrees from each other and facing the focal point (Fig. 1). The first camera was positioned approximately 2 m behind the ball’s starting position and 1 m to the side, so as not to impede the kicker’s approach. The second camera was placed 3 m in front of the ball’s starting position and 3 m out from the ball-to-target line. After positioning and filming the calibration box with both cameras, the box was removed. Each kick was then recorded on the cameras at identical frame rates (100 fps with Lumix, 240 fps with Casio). In MATLAB, the position of the centre of the ball was extracted from six frames. These frames spanned the first 50 ms after the foot struck the ball. Position data, along with frame rate, enabled us to calculate the speed of the ball. The accuracy of each kick was recorded with a high-speed camera (50 fps with Lumix, 120 fps with Casio) mounted on a 1.5 m tripod. The camera was positioned next to one of the cameras recording ball speed (see Fig. 1). This third camera captured the target and position of the ball as it made contact with the fence. Using the software program Kinovea (*Kinovea*, 2011), we measured error in horizontal and vertical dimensions, from the centre of the target to the centre of the ball.

Statistical modelling of accuracy

We modelled the fixed effects of speed ($m{\cdot}s^{-1}$), footedness (left vs right), target (0 m vs 1.6 m), and technique (laces vs side-foot) on the horizontal and vertical accuracies of a kick. The identity of the kicker was included as a random factor. To see whether kicks were less precise at higher speeds, we modelled the residual variation in shot location in several ways; a model in which residual variation increased as a power of speed fit the data best (see Tables 1 and 2). We also modelled the residual variance separately for different targets and techniques. Models were fit with the nlme library (Pinheiro et al., 2011) of the R Statistical Package (R Core Team, 2016). Data from the first and second years were combined for the analysis; however, kicks at speeds below 15 $m{\cdot}s^{-1}$ were excluded for being unrealistically slow.

To estimate the most likely effect of each variable on horizontal or vertical accuracy, we used multi-model inference based on information theory (Burnham & Anderson 2002). First, we estimated the parameters of a model containing every main effect and interaction, Then, we used the *MuMIn* library (Bartoń, 2013) to estimate the parameters of every sub-model, including the null model in which accuracy depends on a stochastic process described by a Gaussian distribution of error. For each model, we calculated the Akaike weight, which equals the likelihood that the model describes the data better than other models do. Finally, we averaged the values of each parameter among models, weighting each value by the likelihood of the model. We used the full-average method, in which a parameter was considered zero when the factor did not appear in a model. The resulting values of parameters were used to calculate the most likely mean for each treatment level.

Multimodel inference estimates effects more accurately than null-hypothesis testing, in which one uses a *P* value to choose between the full model and the null model. Null hypothesis testing biases estimates of effects by relying exclusively on a single model despite the that fact that other models may fit the data as well or better. Multimodel inference eliminates the need to interpret *P* values, because all models (including the null model) contributed to the most likely value of each mean. However, we have included P values in those tables that show the parameters of our statistical models (Tables 3 & 4).

Modelling Covariance of Horizontal and Vertical Accuracies

To estimate the covariance between horizontal error and vertical error, we fit a bivariate Gaussian function to the data for each combination of footedness, target, and technique. To improve the fit of this distribution, we truncated the model at a vertical position of 0.1 m to reflect the constraint imposed by the ground. These distributions were fit with the *gmm.tmvnorm* function of the *tmvtnorm* library of R (Wilhelm, 2015). After estimating parameters, we used the *dtmvnorm* function to compute the joint density function for contour plots.

Results

As predicted from biomechanical constraints, kicking speed and style influenced accuracy. Tables 3 and 4 show the parameters of our statistical models estimated by multi-model inference, which include statistical significance for each factor and interaction. These parameters let us visualize the relationship between speed and accuracy for each kick type (Figs. 2 and 3, respectively). In vertical and horizontal dimensions, a faster kick was usually less accurate. Variance in ball placement increased as a power function of speed, $\alpha \cdot \text{speed}^{(2\delta)}$, where α depended on the combination of kicking technique and target height; power functions are depicted as dashed red lines in Figs. 2 and 3. Loss of vertical accuracy with increasing speed was especially pronounced when aiming at a target on-ground—fast kicks were likely to land more than 50 cm above the ground and sometimes approached or exceeded the crossbar (Fig. 2, bottom panels). When aiming at a target in the air, even slow kicks were vertically inaccurate, landing anywhere between the ground and a meter above the crossbar (Fig. 2, top panels). Fast kicks were very likely to be inaccurate in the horizontal dimension even if they were accurate in the vertical dimension (Fig. 3).

Both speed and accuracy depended on the technique used to kick the ball. No player generated a speed above 30 $\text{m} \cdot \text{s}^{-1}$ when contacting the ball with the side-foot, but speeds as fast as 33 $\text{m} \cdot \text{s}^{-1}$ were achieved when contacting the ball with the laces. Regardless of speed, kicks initiated with laces were less accurate than those initiated with the side of the foot. This difference can be seen by comparing the parameter values of power functions shown in Figs. 2 and 3, for which the most likely estimate of α was about 50% greater for kicks with laces than for kicks with the side-foot (see Tables 3 and 4). This relationship among technique, speed, and accuracy amplifies the trade-off between speed and accuracy for a player attempting to kick at maximal speed. In other words, a player can only achieve top speed by kicking the ball with the laces, which is the less-accurate technique.

Using bivariate distributions, we detected strong covariances between horizontal and vertical accuracy. Right-footed kickers tended to miss above and to the right of the target, or below and to the left (Fig. 4). By contrast, left-footed kickers tended to miss high and left, or low and right (Fig. 4). These distributions illustrate the greater spread of the ball when kicking in the air or with the laces of the shoe.

Discussion

We show a clear speed-accuracy trade-off in soccer, with faster kicks being less accurate. Previous studies revealed that players kick more slowly when asked to focus on accuracy, though kick accuracy was not measured, or defined as hit or miss (Andersen and Dorge, 2011; Asami et al., 1976; Lees and Nolan, 2002). Kawamoto et al. (2006) found that experts and novices kicked more slowly when asked to focus on accuracy but only novices (not experts) were less accurate when asked to focus on speed. Though their study measured accuracy as the absolute error between the ball and target, each participant (8 experts and 8 novices) executed only five kicks in each condition, precluding a confident statistical assessment between conditions. Our study is the first to report accuracy of kicking across the full range of speeds used in matches and to consider accuracy in horizontal and vertical dimensions. By doing so, we show that faster kicking reduces accuracy in both dimensions.

Right- and left-footed kickers had different patterns of error. Right-footed kickers were more likely to miss above and right or below and left, creating a right-leaning distribution around the target, while left-footed kickers had a left-leaning distribution. This pattern can be explained by the swing plane of the kicking foot and the point on the ball where the foot strikes. When a player aims to strike a specific spot on the ball, the actual point where the foot strikes the ball is non-randomly distributed, likely making contact with the lower quadrant of the ball on the side closest to the kicker or in the upper quadrant furthest from them. Variation in the point of contact along this axis results in a distribution of shots that lean away from the kicker's body, so the error structures of right-footed and left-footed kickers should differ by 90°. Previous studies of the interaction between foot and ball only measured the orientation of the foot and how this orientation affects ball trajectory (Sakamoto and Asai, 2013; Shinkai et al., 2009; Tol et al., 2002). Less is known about where the foot contacts the ball during a kick. Asai et al. (2002) investigated how the location of the foot's contact point on the ball affects ball spin, but location was defined as an offset distance only in the horizontal dimension from the centre of the ball and did not consider the vertical dimension. Both kickers and goalkeepers can take advantage of predictability in mistakes to improve goal-scoring or -saving, respectively. For example, right-footed shots that go closer to the keeper than intended are likely to be close to the ground on the keeper's left or high on the keeper's right. Goalkeepers may have greater success during right-foot penalty kicks when diving low and left or up and right. Kickers should also consider this error structure when selecting a target location that maximises success, whether shooting at goal or passing to a team-mate.

Aiming at a target off the ground substantially decreases the accuracy of the kick, though variation is greater in the vertical compared with horizontal dimension. Players should consider the greater difficulty of placing the ball accurately when aiming off the ground. For example, a penalty kick aimed at the top of the goal is more likely to miss over the cross-bar or outside of the post. Taken together, the costs for kicking at targets in upper regions of the goal should be weighed against the benefits of aiming in a region that is difficult to defend. A recent study revealed that penalties kicked into the top third of the goal were never saved; however, they did not consider the loss of accuracy resulting from aiming at this part of the goal because shots that missed the goal were excluded from the analysis (Bar-Eli and Azar, 2009) .

The speed-accuracy trade-off affects the optimal speed, target, and technique for shooting or passing the ball. To appreciate this effect, consider a shot at a target on the ground, only 50 cm inside the goalpost. If one were to use the side of the foot, increasing the speed from 18 to 30 $m \cdot s^{-1}$ decreases the chance of placing the ball inside the goalpost from 90% to 76% (Fig. 5). The chance of placing the ball inside the goalpost declines because ball placement becomes less accurate and less precise at higher speeds (i.e., the central tendency and the variance of ball placement shifts with speed). When choosing a fast speed, shooters should account for the trade-off by aiming further inside the post than usual. Although players can kick faster when striking the ball with the top (laces) rather than side of the foot, the latter technique reduces the variance of ball placement when aiming at a target on the ground. Therefore, players should only use the top of the foot when kicking at speeds that cannot be attained by kicking with the side of the foot (> 30 $m \cdot s^{-1}$), making sure to aim an appropriate distance inside the post.

A goal-keeper generally moves before the shooter contacts the ball, influencing the outcome of the penalty kick. Assuming a keeper dives in the correct direction, diving earlier increases the chance of intercepting the ball, especially for fast kicks directed toward the extremes of the goal. Thus, the probability of scoring a goal depends on the target, shot speed, and kick technique, combined with the keeper's movement relative to that of the ball. A greater proportion of side-foot kicks at 18 $m\cdot s^{-1}$ would end up inside the goal than similar kicks at 30 $m\cdot s^{-1}$ (Fig. 5), but the effectiveness of this strategy depends on how far the keeper can move before the ball reaches the goal. A successful kick places the ball inside the goal and out of the keeper's reach. By modelling all combinations of speed, target, and technique interacting with a keeper's movement, the optimal goal-scoring strategy can be identified. Here, we have taken the first step toward such a model.

Previous studies in cricket, baseball, or handball either support the existence of a speed-accuracy trade-off (Freeston et al., 2007; Freeston and Rooney, 2014; Indermill and Husak, 1984), or do not (Urbin et al., 2012; Van Den Tillaar and Ettema, 2006). These mixed results likely occurred because accuracy was not assessed in both horizontal and vertical dimensions across a full range of speeds. Our approach should be replicated across sports in where speed and accuracy are required (e.g., throwing a cricket ball, baseball, handball, or an American football). Understanding the limits to throwing or kicking accuracy will help coaches assess athlete performance and develop training methods to improve it.

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Conflict of Interest Statement

There are no conflicts of interest to declare.

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Figure list and headings

Figure 1 – Graphical representation of experimental setup

Figure 2 – Raw data of effect of speed on inaccuracy of shots in the vertical dimension for side-foot and laces kicks aimed at low and high targets (right footed players only). Target is represented by dotted black line (top two panels) or y = 0 (bottom two panels) Solid black line represents height of crossbar in soccer goal. Solid red lines and dotted red lines represent mean miss and ± 1 SD respectively from statistical model.

Figure 3 – Raw data of effect of speed on inaccuracy of shots in the horizontal dimension for side-foot and laces kicks aimed at low and high targets (right footed players only). Target is represented by dotted black line. Solid black lines represent left and right goal-posts of soccer goal for target in the centre of goal. Solid red lines and dotted red lines represent mean miss and ± 1 SD respectively from statistical model.

Figure 4 – Bivariate distribution of kicks for right and left footed players shooting side-foot and laces at low and high target. Origin represents the ground and large black dots represent the target. Small dots are raw data for each condition. Contours shown are level curves of the joint density function of the best-fit truncated bivariate normal distribution, where the truncation occurs 0.1 m above the ground.

Figure 5 – Proportion of shot distributions that will miss the goal in the horizontal dimension for side-foot shots of 18 ms^{-1} and 30 ms^{-1}. Black dot represents target of 50cm inside the goal-post. Distributions generated from best-fit model.

Table List and Headings

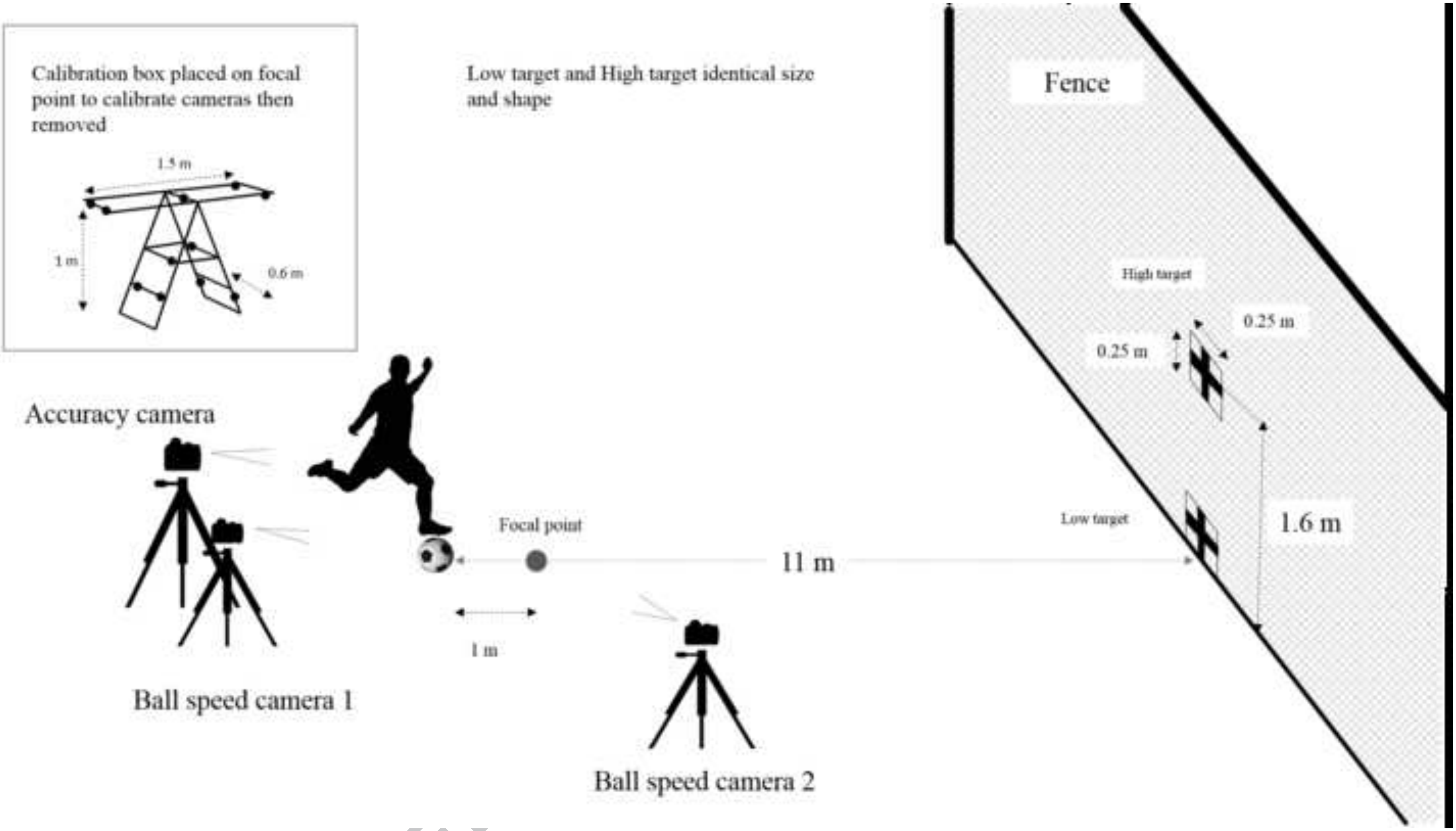
Table 1. Models of ball position along the horizontal plane were ranked according to their values of the Akaike information criterion (AIC). In the most likely model, the variance increased as a power of speed for each kicking technique and each target height. For each model, we also report the difference between its AIC and the AIC of the most likely model (ΔAIC). The Akaike weight (*w*) is the likelihood that a model describes the data better than other models.

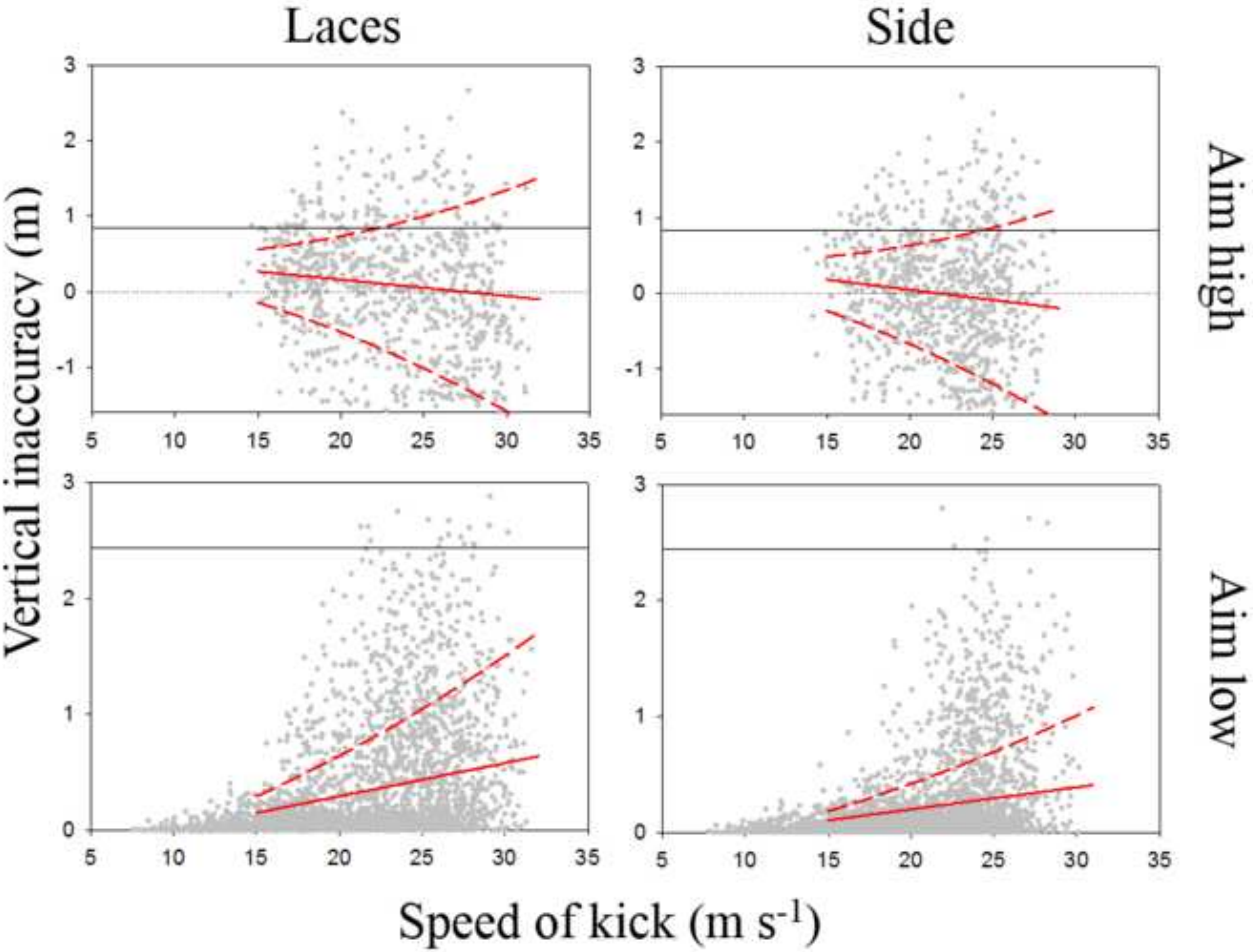
Table 2. Models of ball position along the vertical plane were ranked according to their values of the Akaike information criterion (AIC). In the most likely model, the variance increased as a power of speed for each kicking technique and each target height. For each model, we also report the difference between its AIC and the AIC of the most likely model (ΔAIC). The Akaike weight (*w*) is the likelihood that a model describes the data better than other models.

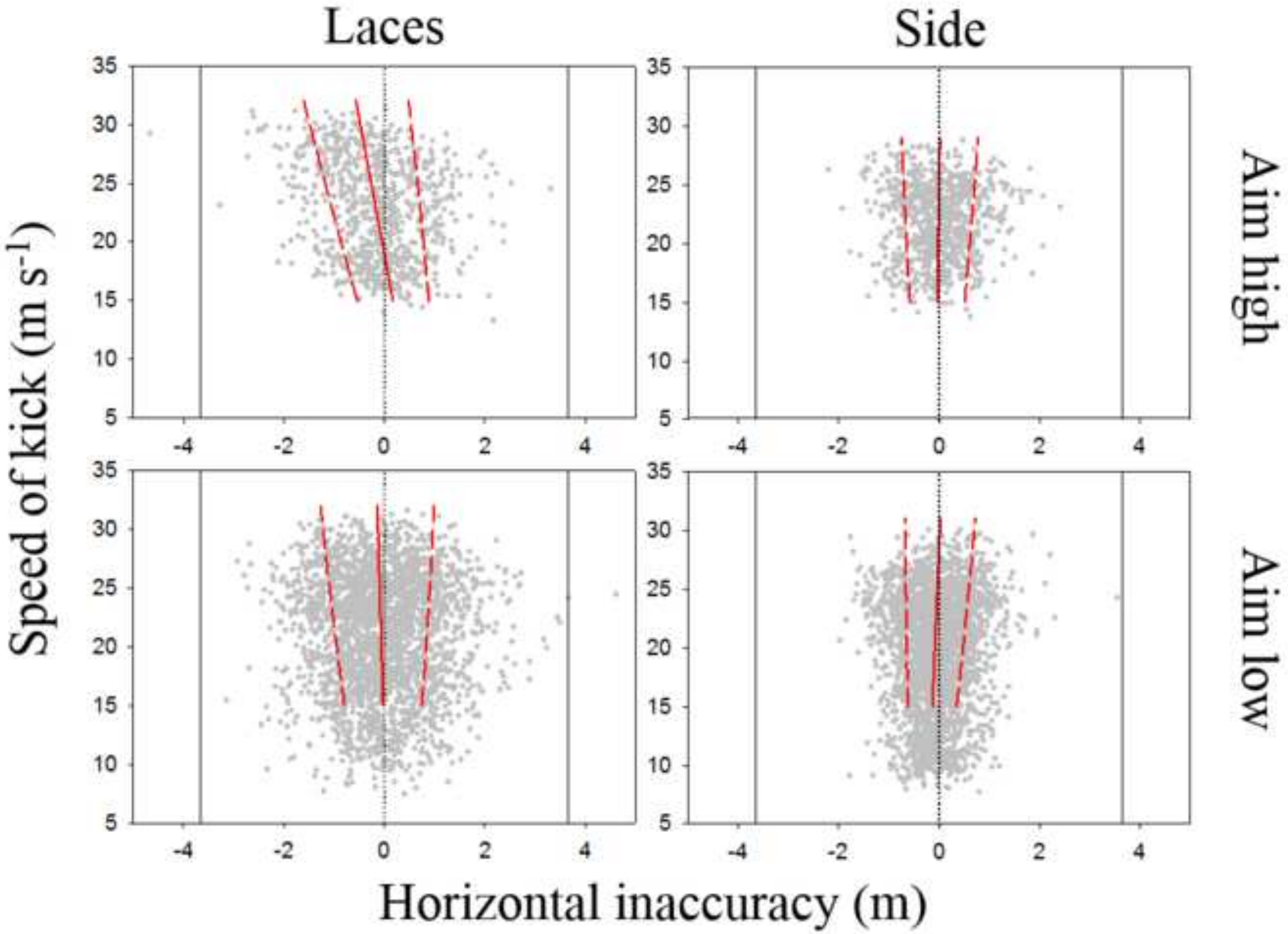
Table 3 . Parameters of the most likely model of ball position along the horizontal plane. The variance increased with speed for each kicking technique and each target height; this effect was best described by a power function: $\alpha \cdot \text{speed}^{(2\delta)}$, where δ = 0.5056909 and α depends on the combination of kicking technique and target height (laces, ground = 0.195691; side, ground = 0.123205; laces, high = 0.180627; side, high = 0.138678).

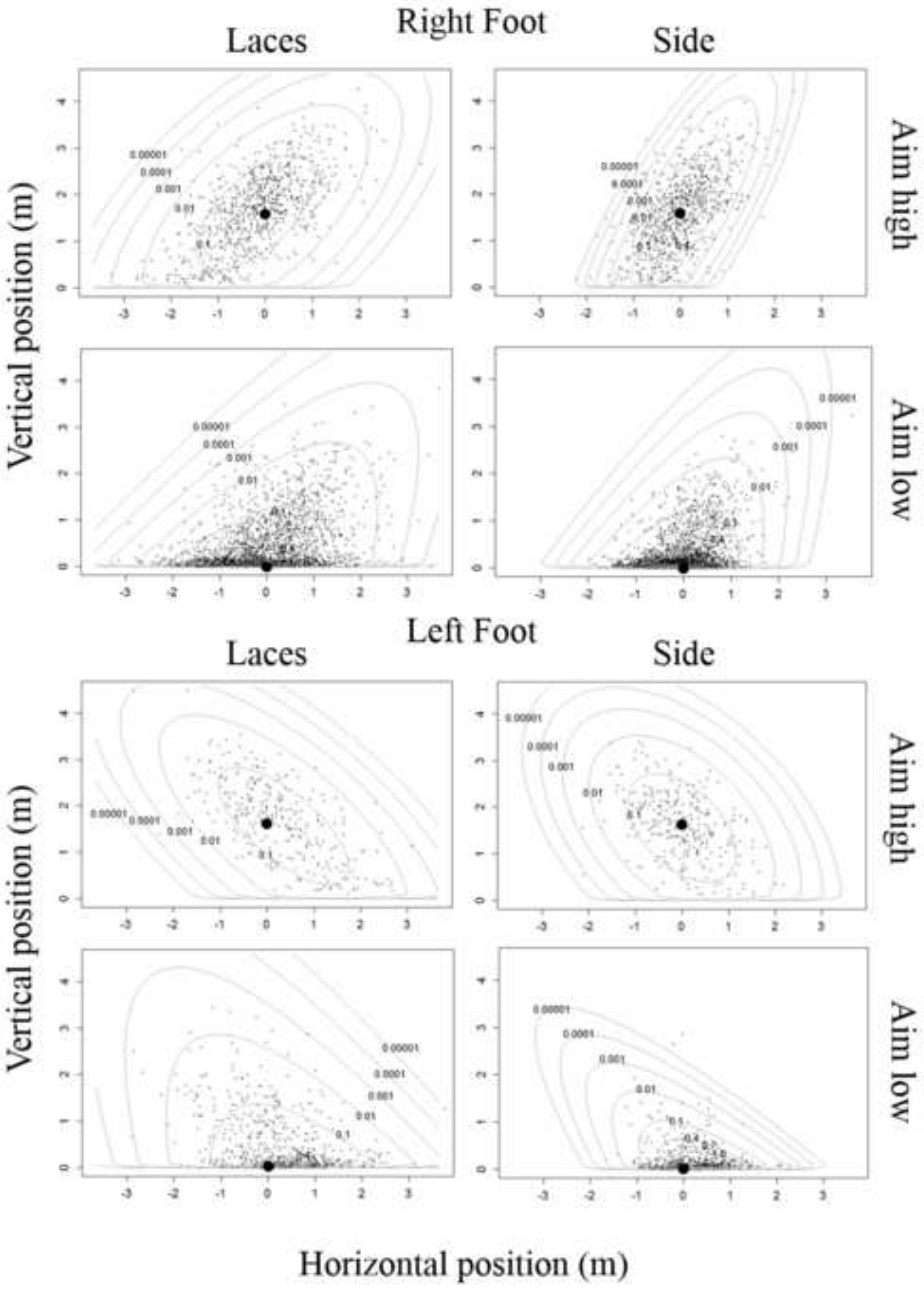
Table 4 . Parameters of the most likely model of ball position along the vertical plane. The variance increased with speed for each kicking technique and each target height; this effect was best described by a power function: $\alpha \cdot \text{speed}^{(2\delta)}$, where δ = 2.057649 and

α depends on the combination of kicking technique and target height (laces, ground = 0.000858; side, ground = 0.000594; laces, high = 0.001336; side, high = 0.001372).


Calibration box placed on focal point to calibrate cameras then removed
1.5 m
1 m
0.6 m
Low target and High target identical size and shape
Fence
High target
0.25 m
0.25 m
Accuracy camera
Focal point
11 m
Low target
1.6 m
1 m
Ball speed camera 1
Ball speed camera 2


Laces
Side
Aim high
Aim low
Vertical inaccuracy (m)
Speed of kick (m s-1)
3
2
1
0
-1
5
10
15
20
25
30
35


Laces
Side
Aim high
Aim low
Speed of kick (m s-1)
Horizontal inaccuracy (m)
35
30
25
20
15
10
5
-4
-2
0
2
4


Right Foot
Laces
Side
Aim high
Aim low
Left Foot
Laces
Side
Aim high
Aim low
Vertical position (m)
Vertical position (m)
Horizontal position (m)
0.00001
0.0001
0.001
0.01
0.1
-3
-2
-1
0
1
2
3
4

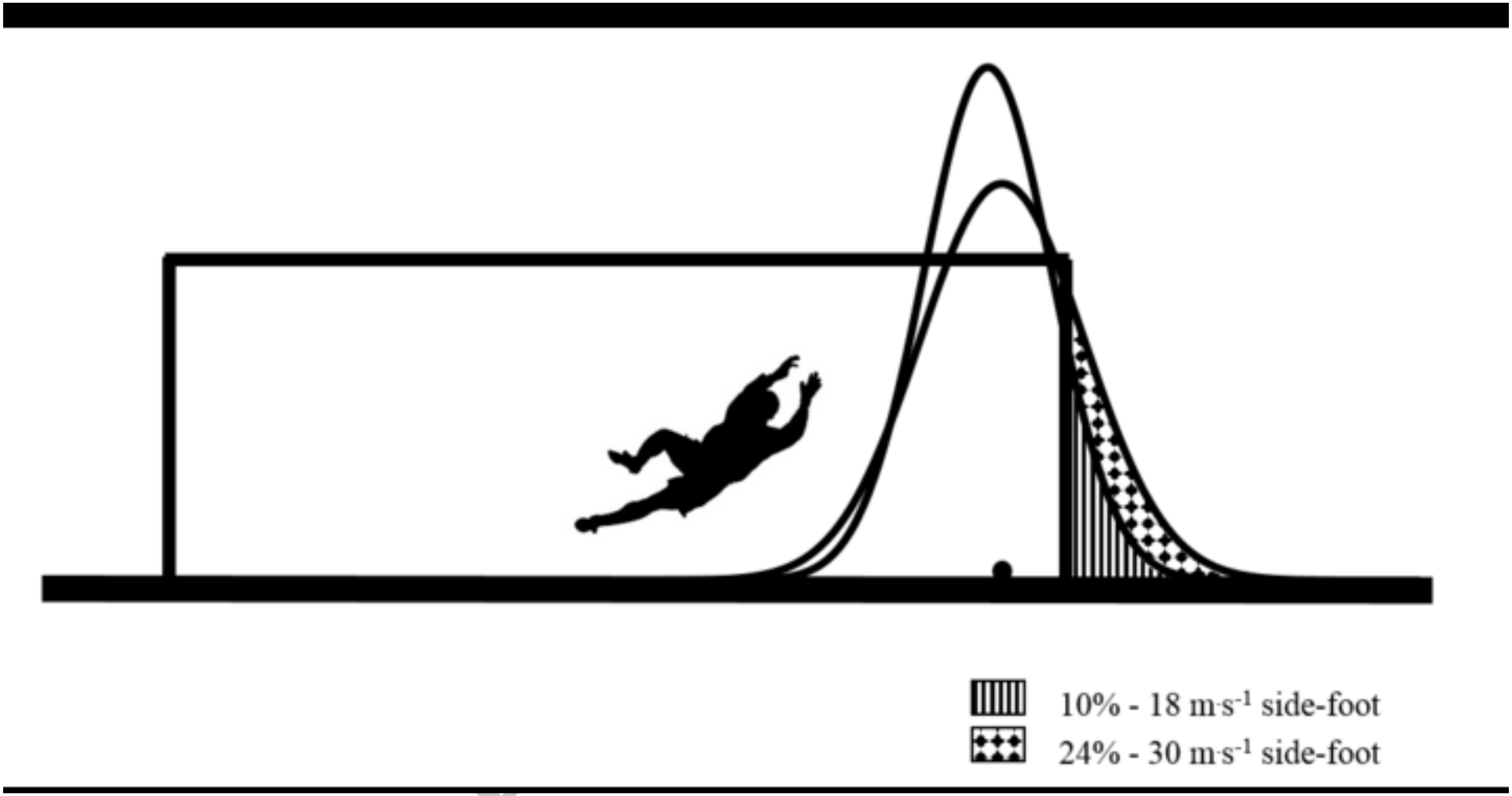

10% - 18 m·s^{-1} side-foot
24% - 30 m·s^{-1} side-foot

Table 1. Models of ball position along the horizontal plane were ranked according to their values of the Akaike information criterion (AIC). In the most likely model, the variance increased as a power of speed for each kicking technique and each target height. For each model, we also report the difference between its AIC and the AIC of the most likely model (ΔAIC). The Akaike weight (*w*) is the likelihood that a model describes the data better than other models.

Model	*Parameters*	*AIC*	*ΔAIC*	*w*
(technique * target) · $\text{speed}^{2\delta}$	22	16804.38	0.00	0.86
(technique * target) · $e^{\text{speed}*2\delta}$	22	16807.99	3.61	0.14
technique · $\text{speed}^{2\delta}$	20	16831.57	27.19	< 0.01
(technique + target) · $\text{speed}^{2\delta}$	21	16831.93	27.54	< 0.01
technique · $e^{\text{speed}*2\delta}$	20	16835.47	31.09	< 0.01
(technique + target) · $e^{\text{speed}*2\delta}$	21	16835.80	31.41	< 0.01
technique * target	21	16903.42	99.04	< 0.01
target · $e^{\text{speed}*2\delta}$	20	17395.39	591.01	< 0.01
target · $\text{speed}^{2\delta}$	20	17398.60	594.22	< 0.01

Table 2. Models of ball position along the vertical plane were ranked according to their values of the Akaike information criterion (AIC). In the most likely model, the variance increased as a power of speed for each kicking technique and each target height. For each model, we also report the difference between its AIC and the AIC of the most likely model (ΔAIC). The Akaike weight (*w*) is the likelihood that a model describes the data better than other models.

Model	*Parameters*	*AIC*	*ΔAIC*	*w*
(technique * target) · $\text{speed}^{2\delta}$	22	10734.85	0.00	> 0.99
(technique * target) · $e^{\text{speed}*2\delta}$	22	10825.87	91.02	< 0.01
(technique + target) · $\text{speed}^{2\delta}$	21	10847.77	112.92	< 0.01
(technique + target) · $e^{\text{speed}*2\delta}$	21	10937.28	202.43	< 0.01
target · $\text{speed}^{2\delta}$	20	11058.36	323.51	< 0.01
target · $e^{\text{speed}*2\delta}$	20	11138.71	403.85	< 0.01
technique * target	21	11984.71	1249.86	< 0.01
technique · $\text{speed}^{2\delta}$	20	12168.36	1433.51	< 0.01
technique · $e^{\text{speed}*2\delta}$	20	12228.14	1493.29	< 0.01

Table 3 . Parameters of the most likely model of ball position along the horizontal plane. The variance increased with speed for each kicking technique and each target height; this effect was best described by a power function: $\alpha \cdot \text{speed}^{(2\delta)}$, where $\delta = 0.5056909$ and α depends on the combination of kicking technique and target height (laces, ground = 0.195691; side, ground = 0.123205; laces, high = 0.180627; side, high = 0.138678).

Parameter	Estimate	SE	df	*t*	*P*
intercept	0.6249	0.2214	7360	2.8229	0.0048
speed	-0.0163	0.0100	7360	-1.6196	0.1054
right-footed	-0.5268	0.2493	19	-2.1134	0.0480
sidekick	-0.6606	0.2724	7360	-2.4255	0.0153
high target	-1.9684	0.3791	7360	-5.1922	< 0.0001
speed:right-footed	0.0095	0.0113	7360	0.8430	0.3993
speed:sidekick	0.0292	0.0126	7360	2.3135	0.0207
right-footed:sidekick	0.3036	0.3052	7360	0.9948	0.3198
speed:high target	0.0837	0.0168	7360	4.9948	< 0.0001
right-footed:high target	2.7070	0.4293	7360	6.3054	< 0.0001
sidekick:high target	1.2130	0.5045	7360	2.4044	0.0162
speed:right-footed:sidekick	-0.0125	0.0141	7360	-0.8876	0.3748
speed:right-footed:high target	-0.1200	0.0190	7360	-6.3121	< 0.0001
speed:sidekick:high target	-0.0632	0.0227	7360	-2.7794	0.0055
right-footed:sidekick:high target	-1.7615	0.5720	7360	-3.0793	0.0021
speed:right-footed:sidekick:high target	0.0933	0.0258	7360	3.6161	0.0003

Table 4 . Parameters of the most likely model of ball position along the vertical plane. The variance increased with speed for each kicking technique and each target height; this effect was best described by a power function: $\alpha \cdot \text{speed}^{(2\delta)}$, where $\delta = 2.057649$ and α depends on the combination of kicking technique and target height (laces, ground = 0.000858; side, ground = 0.000594; laces, high = 0.001336; side, high = 0.001372).

Parameter	Estimate	SE	df	*t*	*P*
intercept	-0.5892	0.1110	7360	-5.3097	< 0.0001
speed	0.0499	0.0053	7360	9.3971	< 0.0001
right-footed	-0.1461	0.1245	19	-1.1735	0.2551
sidekick	0.219335	0.1312	7360	1.6716	0.0946
high target	1.9039	0.285	7360	6.6738	< 0.0001
speed:right-footed	0.0029	0.0059	7360	0.4962	0.6198
speed:sidekick	-0.0231	0.0066	7360	-3.4776	0.0005
right-footed:sidekick	-0.1320	0.1468	7360	-0.8988	0.3688
speed:high target	-0.1036	0.0136	7360	-7.5925	< 0.0001
right-footed:high target	-0.4639	0.3219	7360	-1.4413	0.1495
sidekick:high target	-1.7837	0.4337	7360	-4.1130	< 0.0001
speed:right-footed:sidekick	0.0138	0.0074	7360	1.8542	0.0638
speed:right-footed:high target	0.0241	0.0155	7360	1.5545	0.1201
speed:sidekick:high target	0.086448	0.020879	7360	4.140342	< 0.0001
right-footed:sidekick:high target	1.633646	0.489659	7360	3.336294	0.0009
speed:right-footed:sidekick:high target	-0.07934	0.023706	7360	-3.34674	0.0008