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Identifying the best strategy for soccer penalty success: A predictive model for optimising behavioural and biomechanical trade-offs

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ABSTRACT

Success in a soccer penalty can be the difference between winning and losing matches. The outcome is determined by a complex interaction between the shooter and goalkeeper, whose performances are constrained by biomechanical trade-offs. To overcome these performance constraints, each player has a range of available strategies. Shooters can kick at different speeds, affecting accuracy, while goalkeepers can move at various times (leave-times), affecting the time available to move and the probability they move in the correct direction. Previous models of penalty success ignore such trade-offs and how they interact to influence the outcome. Here, we present a model that accounts for shooting inaccuracy to predict the probability of success for all shooting strategies, defined as any combination of: shot speed, position where the shooter aims, shooter footedness, and kicking technique (side-foot or instep). To estimate the probability of success each shooting strategy is matched against all possible goalkeeper leave-times, considering the probability each leave-time is chosen. We test the model against an average goalkeeper and a goalkeeper who tends to move later. Against the average goalkeeper, aiming on the ground toward the centre of the goal is optimal; however, against a late moving goalkeeper, aiming on the ground to the extremities of the goal is effective, with the optimal target in the horizontal dimension dependent on shot speed, kick technique, and footedness. Coaches could use this model to identify their best penalty takers and each players' optimal shooting strategy against either the average goalkeeper or a specific goalkeeper.

1. Introduction

A penalty shot in soccer is enthralling for spectators and can determine the outcome of matches and multi-million-dollar tournaments. Since 1986, 39% of knockout matches in the World Cup Finals involved a penalty kick or were decided by a penalty shoot-out. With the inclusion of the Video Assistant Referee system (VAR) for the first time during the 2018 World Cup Finals, 29 penalty shots were awarded across 63 games, the most ever in a World Cup Finals. During a penalty, both the shooter and goalkeeper must choose and execute a strategy they believe will be successful – but which strategy is best? Previous research has attempted to answer this question but has focussed on strategies that do not account for the complex interaction between shooter and goalkeeper (Azar & Bar-Eli, 2011; Bar-Eli et al., 2007; Botwell et al., 2009; Chiappori et al., 2002; Leela & Comissiong, 2009; Weigelt et al., 2012).

When taking a penalty shot, shooters attempt to kick the ball past the goalkeeper and into the goal. They must decide where to aim, how fast to kick the ball, and which kicking technique to use (side-foot or instep). These factors interact to determine where the shot is likely to go (Hunter, Angilletta Jr, et al., 2018), contributing to the probability of scoring a goal. For example, if kicking near maximal speeds and aiming close to a goal post, there is a significant probability the ball will miss the goal due to the inherent trade-off between speed and accuracy (Hunter, Angilletta Jr, et al., 2018). To account for this, shooters may choose to kick slower to increase precision, but this allows the goalkeeper more time to move across the goal to block the shot. Alternatively, shooters could shift their target further inside the goal post and kick at maximal speed. In this case, the goalkeeper does not need to move as far to block

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the shot, and decreased shooting accuracy could place the ball closer to the goalkeeper than intended or miss the goal completely. Shooters must balance the need for accuracy against the ball's flight time and choose an appropriate strategy given this trade-off. In principle, predictive models may be used for analysis of kicking decisions, but these models must formally capture the trade-off between speed and accuracy to determine the efficacy of any shooting strategy.

Existing models of soccer penalty success were developed by analysing penalties from professional games (Azar & Bar-Eli, 2011; Bar-Eli et al., 2007; Chiappori et al., 2002). They predict how often shooters/goalkeepers should shoot/dive to the left, right, or down the centre of the goal to maximise scoring/saving success (Azar & Bar-Eli, 2011; Bar-Eli et al., 2007; Chiappori et al., 2002). Shooting toward the top of the goal is considered an effective strategy with a high chance of success as these shots are very difficult for goalkeepers to defend (Bar-Eli & Azar, 2009). However, these approaches, which are limited to suggesting regions of the goal to kick toward, are overly simplistic. They ignore shot speed as an element of a shooter's strategy and assume the shot will be accurate, despite the inherent error associated with kicking a ball (Hunter, Angilletta Jr, et al., 2018). A recent study by Hunter and colleagues (Hunter, Angilletta, et al., 2018) filmed 1278 penalty shots and also recorded where shooters intended to kick the ball. Shots that landed in the top third of the goal were almost always a goal. However, of those shots landing in the top third, the vast majority were not aimed there, and those aimed in the top third of the goal were less likely to be goals than those aimed in the bottom third (see Supplementary Section 1 for further details). Clearly, shooting error must be included in predictive models of penalty shots. Another model (Leela & Comissiong, 2009) described an optimal trajectory angle for shooters and included an "error margin" to account for inaccurate kicking but failed to empirically describe how shooting error changes as a function of shot speed. To identify the optimal shooting strategy when taking a penalty shot, more comprehensive predictive models are required.

When facing a penalty shot, goalkeepers try to stop the ball from entering the goal. To achieve this, they must: move at an appropriate time that allows them to intercept the ball before it crosses the goal line; move in the correct direction and trajectory to intercept the ball; and prevent the ball from entering the goal using their body. Generally, goalkeepers start moving toward one side of the goal before the shooter's foot contacts the ball (Dicks, Davids, et al., 2010), using visual cues presented by the shooter's body to predict shot direction (Savelsbergh et al., 2005), or simply guessing. Predicting shot direction becomes more accurate as goalkeepers delay their movement to garner increasingly accurate information from the kicker (Hunter, Murphy, et al., 2018; Smeeton & Williams, 2012). However, waiting longer reduces the time available to move towards the ball to block the shot. Goalkeepers must consider this trade-off, moving at an appropriate time (leave-time) and direction to maximise their chance of success. Incorporating the influence leave-time has on the outcome of penalty shots and the variation observed both within and among individuals (Hunter, Angilletta, et al., 2018) has the potential to significantly improve the performance of predictive models over those that currently ignore them (Azar & Bar-Eli, 2011; Bar-Eli et al., 2007; Chiappori et al., 2002; Leela & Comissiong, 2009). Furthermore, if goalkeepers successfully reach the ball before it enters the goal, they must block it with their body. This becomes more difficult as ball speed increases, due, in part, to a trade-off between speed and accuracy (Fitts, 1954). For faster shots with less flight time, the goalkeeper's movement to intercept the ball must be faster compared to slower shots. This movement will be less accurate, with the ball more likely to be missed completely or only partially defended, deflecting off the goalkeeper into the goal (Hunter, Angilletta, et al., 2018). Additionally, faster shots are likely more difficult to defend because they require more force to alter their direction than slower shots. For example, a goalkeeper's outstretched fingers may deflect a slower shot enough to miss the goal, but a fast shot that hits the goalkeeper's fingers is more likely to continue a trajectory that enters the goal. In existing predictive models, the importance of this phenomenon has been overlooked.

Finally, penalty shots are interactive, with the effectiveness of the strategy of both the goalkeeper and the shooter dependent on the strategy employed by the other. Furthermore, one player's strategy may influence the strategy the other player chooses (Botwell et al., 2009; Weigelt et al., 2012). For example, when shooters kick near maximal speeds, goalkeepers tend to dive earlier compared to slower shots (Hunter, Angilletta, et al., 2018), a decision made before the shooter kicks the ball. This decreases the probability goalkeepers dive in the correct direction (Hunter, Murphy, et al., 2018; Smeeton & Williams, 2012) greatly impacting the outcome. No existing predictive model of penalty success accounts for this interaction between a shooter's strategy and goalkeeper's strategy.

Here, we present a predictive model that estimates the probability of scoring success when shooting a soccer penalty. This model considers the trade-off between speed and accuracy when kicking a ball, incorporates a distribution of when goalkeepers move and how this affects the probability they dive in the correct direction, and accounts for elements of each player's strategy that interact to affect the outcome of penalties. This model predicts the probability of scoring for all strategies available to shooters, identifying that with the greatest chance of success. Our proposed model can be used to provide strategic recommendations tailored to the biomechanical trade-offs of individual players.

2. Method: Model, parameters, and predictive approach

First, we present a brief overview of the model. Then, drawing from previous studies (Hunter, Angilletta, et al., 2018; Hunter, Angilletta Jr, et al., 2018; Hunter, Murphy, et al., 2018), we describe the shooter and goalkeeper parameters and how these were obtained. We outline how these parameters were used to calculate the probability of a goal being scored and present the model's predictions. This model can be adapted to describe an individual shooter's relationship between speed and accuracy matched against a goalkeeper to provide individual specific predictions.

2.1. Overview of predictive model

The predictive model was written in Matlab version 2017b (Mathworks, Inc, Massachusetts, United States). Simply put, it competes a single shooting strategy against all strategies the goalkeeper might use weighted by the probability of each goalkeeper strategy occurring; this way, the optimal shooter strategy will account for all possible goalkeeper defences without being overly sensitive to unlikely, but possible, defences. A shooter's strategy is defined as any combination of shot speed ($m.s^{-1}$), target location in the goal (t_x, t_y), kick technique (side-foot or instep), and footedness (right or left). A goalkeeper's strategy is defined as when they move relative to the shooter's foot contacting the ball (leave-time (s)). The model currently does not account for deceptive shooting strategies or the keeper-dependent strategy (Kuhn, 1988). However, it is possible to include the effect of these strategies, as outlined in the Supplementary section.

For a given shooting strategy, the model estimates (for all locations in the goal) the probability the ball will go to a specific location. The model is parameterized by data from shooting assays and can be tailored to a particular shooter or the average behaviour of a group of shooters. The model also estimates the probability the goalkeeper's body will be blocking the same location as the ball when the ball reaches the goal line. To achieve this, the model includes a probability distribution of all leave-times the goalkeeper can select, which helps to predict the possible locations of the goalkeeper when the ball reaches the goal line. The model also modulates the effectiveness of the goalkeeper by the probability that the goalkeeper moves in the correct direction toward the ball. The model then estimates the probability the goalkeeper successfully stops the ball, given the speed of the shot. All these probabilities are combined to estimate the probability the shot is saved at any location within the goal (or that it misses the goal completely), giving an overall estimate of the efficacy of that shooting strategy. Repeating this across all shooting strategies identifies the strategy with the greatest chance of success for a given goalkeeper leave-time distribution and shooter performance data.

2.2. Shooter parameters

With left- and right-footed amateur/semi-professional soccer players, Hunter and colleagues (Hunter, Angilletta Jr, et al., 2018) modelled the accuracy of penalty kicks across a range of speeds, also varying kick technique (side-foot or instep) and target height. Using their data, we developed a protocol to generate probability densities describing where a shot is likely to go dependent on the shooter's strategy (see Supplementary Section 2 for more details). In brief, whenever a ball is kicked, it can go in the air or along the ground. The probability either of these events occurs is likely dependent on factors such as kick technique, ball speed, and target height. Therefore, to predict where a shot is likely to go, the first step is predicting the probability the ball goes in the air or along the ground. Next, any kick will have horizontal and vertical error relative to the desired target. However, the bivariate distribution of error is likely different for shots that go in the air compared to those that go along the ground. As such, we differentially modelled kicking error for these two conditions. With a combination of existing statistical models from Hunter and colleagues (Hunter, Angilletta Jr, et al., 2018) and new models developed here, we can generate a probability density for any shooting strategy that describes where the ball is likely to go after first considering the probability the shot goes in the air or along the ground (see Supplementary Section 2 for more details). Examples of probability densities for different shooting strategies are presented in Fig. 1 – note the probability density "expands" when shot speed increases, with shots less likely to hit near the target (compare Panel A to Panel B). Shooting accuracy further decreases with an instep kick technique (i.e. using the top of the foot) (compare Panel B to Panel C). Last, Hunter and colleagues (Hunter, Angilletta Jr, et al., 2018) modelled the tendency for right-footed players to miss the target high and to the right or low and to the left,

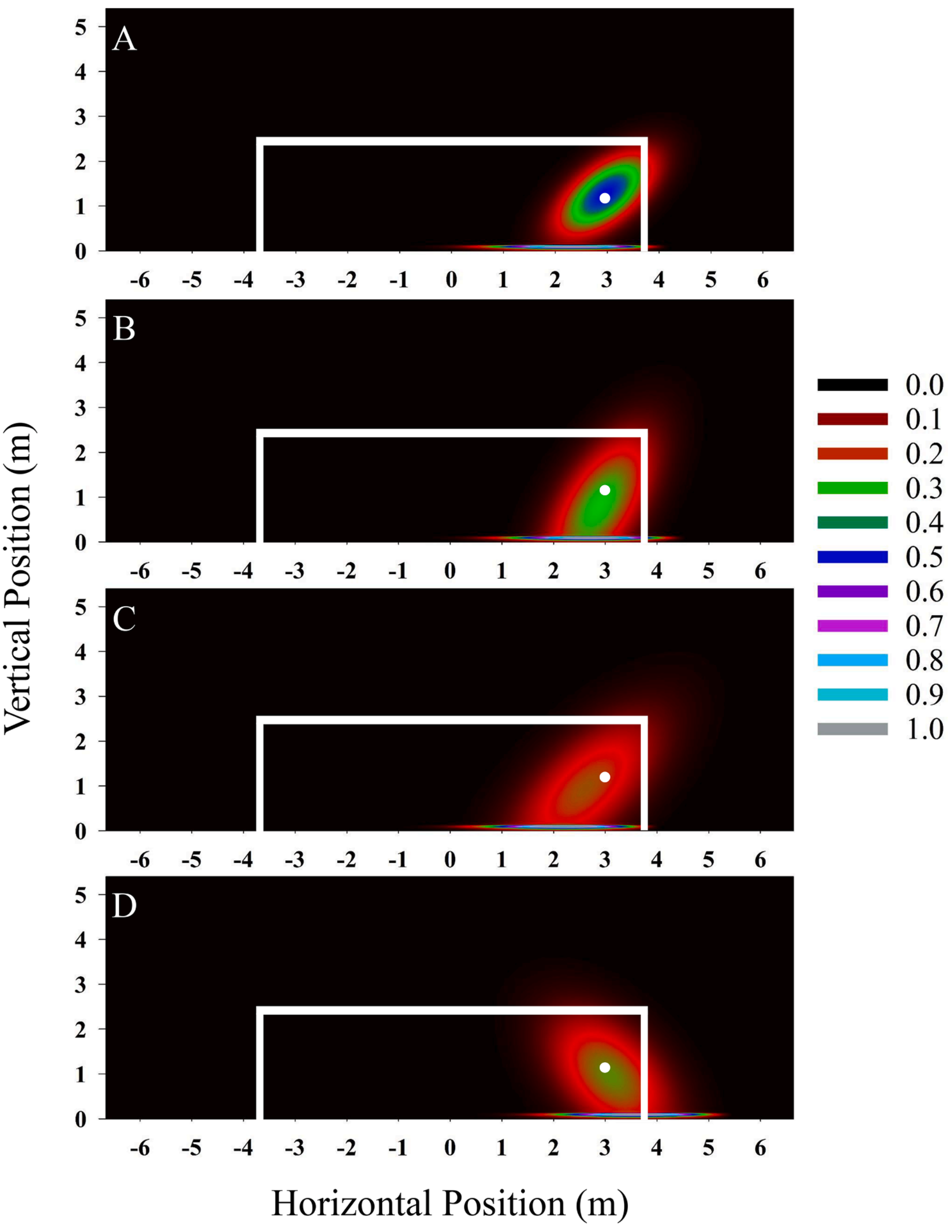

Fig. 1. Probability densities describing where shots are likely to go for specific shooting strategies (target {t_x, t_y}; ball speed; kick technique; footedness). In each plot the contour colours represent the probability density. In all plots the target (white dot) is held constant (x = 3, y = 1.2), and the solid white lines represent the dimensions of the goal seen from the shooter's perspective. **A)** ball speed = 18 m.s^{-1}, kick technique = side-foot, shooter = right footed. **B)** 24 m.s^{-1}, side-foot, right footed. **C)** 24 m.s^{-1}, instep, right footed. **D)** 24 m.s^{-1}, side-foot, left footed. These plots consider the probability the shot goes on the ground or in the air. That is, within each plot, integrating under the ground and air distributions sums to 1.

with the opposite true of left-footed players. We capture that effect here (compare Panel B to Panel D).

2.3. Goalkeeper parameters

To model the goalkeeper, we needed to describe four aspects of their behaviour, drawing in part from three previous studies (Dicks, Davids, et al., 2010; Hunter, Murphy, et al., 2018; Hunter, Angilletta, et al., 2018): when they move, how they move, if they move in the correct direction, and the probability they successfully block the ball when within reach. In brief, goalkeepers tend to start moving before the ball is kicked but there is variation both within and among goalkeepers in when they choose to move (leave-time) (Hunter, Angilletta, et al., 2018). Greatly affecting the outcome, leave-time influences the probability of correctly guessing shot direction with goalkeepers who move later showing better prediction (Hunter, Murphy, et al., 2018; Smeeton & Williams, 2012). If they move before the ball is kicked, goalkeepers tend to dive across the lower half of the goal toward either goal post. If they delay movement until seeing the ball's initial trajectory (we have termed this the "recognition point"), they can move toward the ball's actual trajectory to intercept. Here, we differentially modelled goalkeeper movement under these two general conditions. Last, shot speed affects goalkeeper behaviour, with faster shots eliciting earlier movement (Hunter, Angilletta, et al., 2018). Compared to slower shots, faster shots are also more difficult to block, increasing the probability of a goal (Hunter, Angilletta, et al., 2018). See Supplementary Section 3 for more details on the goalkeeper parameters.

With the parameters described above, we can generate goalkeeper probability densities describing the probability the goalkeeper will save a shot at any location in the goal, given the shot's speed and intended target (see Supplementary Section 3 for more details). These probability

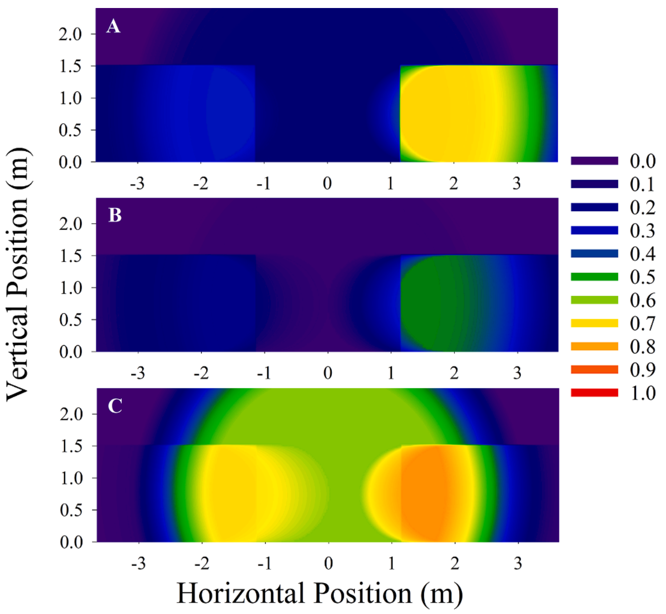

Fig. 2. Probability densities describing the probability the goalkeeper will save a shot at any location within the goal, given the shooter's target (left or right side of the goal) and ball speed (m.s^{-1}), and the goalkeeper's leave-time distribution (Mean, SD). These plots consider the probability the goalkeeper moves in the correct direction, and the probability the shot is saved dependent on ball speed. Each plot is the dimensions of a soccer goal (7.32 m × 2.44 m) seen from the shooter's perspective, and the contour colours describe the probability of a save dependant on where the ball enters the goal. For each plot, the shooter has aimed to the right and goalkeeper leave-time SD (0.14) was held constant. **A)** Average goalkeeper (Mean leave-time = -0.19 s), ball speed = 18 m.s^{-1}. **B)** Average goalkeeper (Mean leave-time = -0.19 s), ball speed = 24 m.s^{-1}. **C)** Late moving goalkeeper (Mean leave-time = 0.04 s), ball speed = 18 m.s^{-1}.

densities can be customised to individual goalkeepers, defined by the mean and variance of their leave-time distribution. Fig. 2 presents examples of goalkeeper probability densities generated for the average leave-time of all goalkeepers from Hunter and colleagues (Hunter, Angilletta, et al., 2018) (Mean leave-time = −0.19 s) and for the goalkeeper who tended to move latest (M = 0.04 s). The variance parameter (SD = 0.14), calculated across all goalkeepers from Hunter and colleagues (Hunter, Angilletta, et al., 2018), was held constant for both goalkeepers. It should be noted the goalkeepers used by Hunter and colleagues (Hunter, Angilletta, et al., 2018) were amateur/semi-professional players. Each plot in Fig. 2 represents the dimensions of a goal and for a given shooting strategy describes the probability the goalkeeper will successfully block the shot at any location within the goal. First, based on the shooting parameters, these plots consider the probability the goalkeeper dives in the correct direction. Note the asymmetry between the left and right sides of the goal – in all three plots the shot was directed to the shooter's right, and the goalkeeper was more likely than not to correctly predict this shot direction. Second, the plots consider ball speed of the shot. Comparing Panel A (shot speed = 18 m.s^{-1}) to Panel B (shot speed = 24 m.s^{-1}), note in Panel A the goalkeeper is more likely to block the shot across all locations and is more likely to block shots closer to the right-hand goal post. Given the slower shot speed in Panel A, the goalkeeper has more time to move further across the goal, and, if the ball is reached, is more likely to successfully block the shot. Last, these plots consider when the goalkeeper is likely to move. Panel C represents a late-moving goalkeeper while Panel A (and B) represent an average goalkeeper. Given a large portion of the late moving goalkeeper's leave-time distribution is after the recognition point, they are often modelled as moving directly toward any possible location the ball may enter the goal, as is evident when comparing Panel C to Panel A. For clarity, the term "average goalkeeper" used henceforth refers to a goalkeeper with a mean leave-time of −0.19 s (SD = 0.14) (Hunter, Angilletta, et al., 2018).

2.4. Calculating the probability of a goal

For a given shooting strategy (target location {t_x, t_y}, shot speed (m.s^{-1}), kicking technique (side-foot or instep), and footedness (right or left)), the predictive model generates a shooter probability density and a goalkeeper probability density. With these, the probability the shot goes to a specific location and the goalkeeper achieves a save at this location can be estimated. Repeating this across all locations in the goal and summing the resultant probabilities gives the probability the goalkeeper will save the shot, with the complementary probability the probability of a goal (See Supplementary Section 4).

For either a left- or right-footed player, the model identifies the specific combination of target (t_x, t_y), shot speed, and kick technique with the greatest chance of scoring success. However, to best present the model's predictions, we can simplify the shooter's strategies we compete against the goalkeeper. Holding constant shot speed, kick technique, and footedness, we can generate a probability density that estimates the probability of a goal depending on target location. We can also change the goalkeeper leave-time parameters to compete the shooter against a goalkeeper who tends to dive earlier or later than average.

We have competed the following three shooting sub-strategies (all right-foot) against the average goalkeeper from Hunter and colleagues (Hunter, Angilletta, et al., 2018) (Mean leave-time = −0.19 s, SD = 0.14) and a late moving goalkeeper (M = 0.04 s, SD = 0.14). From Hunter and colleagues (Hunter, Angilletta, et al., 2018), shooters most often kicked at submaximal speeds (mean ≈ 24 m.s^{-1}) with a side-foot technique, a strategy that prioritises accuracy (Strategy 1: shot speed = 24 m.s^{-1}, side-foot technique). When shooters choose a strategy that prioritises speed, they generally use an instep kicking technique and kick at maximal speeds (up to 32 m.s^{-1}) (Hunter, Angilletta, et al., 2018) (Strategy 2: shot speed = 32 m.s^{-1}, instep technique). Another strategy used by shooters is to kick at lower speeds and aim down the centre of the goal, with this sometimes termed the "Panenka," named after the professional soccer player who first used this strategy. The rationale for this strategy is the goalkeeper will often move before ball contact, diving to either side of the goal. Kicking at a slow speed ensures the goalkeeper has time to empty the space in the centre of the goal, allowing the ball to enter the goal undefended (Strategy 3: Shot speed = 18 $m.s^{-1}$, side-foot technique).

3. Results

Against an average goalkeeper and a goalkeeper who tends to move late, we competed three shooter strategies, varying only target location. The first strategy was a right-footed player shooting with a side-foot technique at 24 $m.s^{-1}$. Against the average goalkeeper (Hunter, Angilletta, et al., 2018), the optimal target was close to the ground toward the centre of goal (Fig. 3A). Given the average goalkeeper tends to dive before ball contact (mean leave-time = −0.19 s), the centre of the goal is often undefended by the time the ball reaches the goal. Aiming closer to the ground decreases the chance of missing above the goal. Against a goalkeeper who tends to wait longer before moving, the optimal targets were toward either side of the goal aiming approximately 1 m inside the goal post (Fig. 3B).

The second strategy was a right-footed player shooting with an instep technique at 32 $m.s^{-1}$. Against the average goalkeeper, the optimal target was central and close to the ground (Fig. 3C). Against a late moving goalkeeper, the optimal target was also central (Fig. 3D), but the late moving goalkeeper was more likely to save these shots than an earlier moving goalkeeper. Aiming toward either side of the goal also had a high chance of success against a late moving goalkeeper. However, given less precision when kicking at high speeds and with an instep kick technique, the optimal distance to aim inside the post (≈ 1.5 m) (Fig. 3D) was greater than when kicking with a side-foot technique at slower speeds (Fig. 3B). In both Panel C and Panel D, there is asymmetry when comparing shots directed close to either goal post (within 0.5 m). On the shooter's left, there is generally less than 50% chance of scoring, with this probability decreasing as target height increases. Conversely, on the shooter's right, the chance of scoring ranges between approximately 50% and 60% depending on target height. This asymmetry is caused by two factors. First, for a right-footed player kicking with an instep technique at high speeds, the central tendency of shots that go in the air is left of the target (Fig. 1C). Second, for all shots that go below the target, most tend to miss left (Fig. 1C). Together, this means most shots miss left of the target. When aiming close to the left-hand goal post, a relatively large proportion of shots will therefore miss the goal. When aiming close to the right-hand post, errors tend to miss left and stay within the goal, increasing the probability of scoring.

The third strategy was a right-footed player shooting with a side-foot technique at 18 $m.s^{-1}$. Against the average goalkeeper, the optimal target location was to aim centrally (Fig. 3E). However, compared to faster shot speeds aimed centrally, this strategy had a lower probability of success because slow shots are almost certainly saved if the goalkeeper reaches them whereas faster shots are less likely defended accurately. Against a late-moving goalkeeper, slow shots to the centre of the goal are relatively easy to block. The optimal strategy in this case is to shoot higher in the goal toward either goal post (Fig. 3F). With the ball's long flight time, even a late moving goalkeeper has enough time to move and block most parts of the goal. With a slower ball speed increasing accuracy, aiming higher in the goal increases the distance a goalkeeper must travel, providing the best chance of success.

4. Discussion

To optimise scoring success, existing research suggests shooting centrally (Bar-Eli et al., 2007; Chiappori et al., 2002), aiming high in the goal (Bar-Eli & Azar, 2009), or aiming toward the extremities of the goal (Leela & Comissiong, 2009). We show the efficacy of these strategies is dependent on an interaction between the shooter's strategy and the goalkeeper's strategy. Aiming centrally is effective against the average goalkeeper because they have moved to a side of the goal, leaving the middle undefended (Fig. 3A, E). Conversely, shooting toward the edges of the goal is effective against a late moving goalkeeper (Fig. 3B, F). When aiming toward either goal post, the optimal target in the horizontal dimension is dependent on shot speed, kick technique, and footedness. For example, to account for greater error when kicking at maximal speed, the optimal horizontal target is further inside the goal post (Fig. 3D) compared to when kicking at sub-maximal speeds (Fig. 3B). Generally, aiming near the ground is a better strategy than aiming high in the goal as this reduces the chance of missing above the goal. However, if the shooter chooses to kick the ball slowly, aiming higher in the goal can increase the chance of success (Fig. 3F).

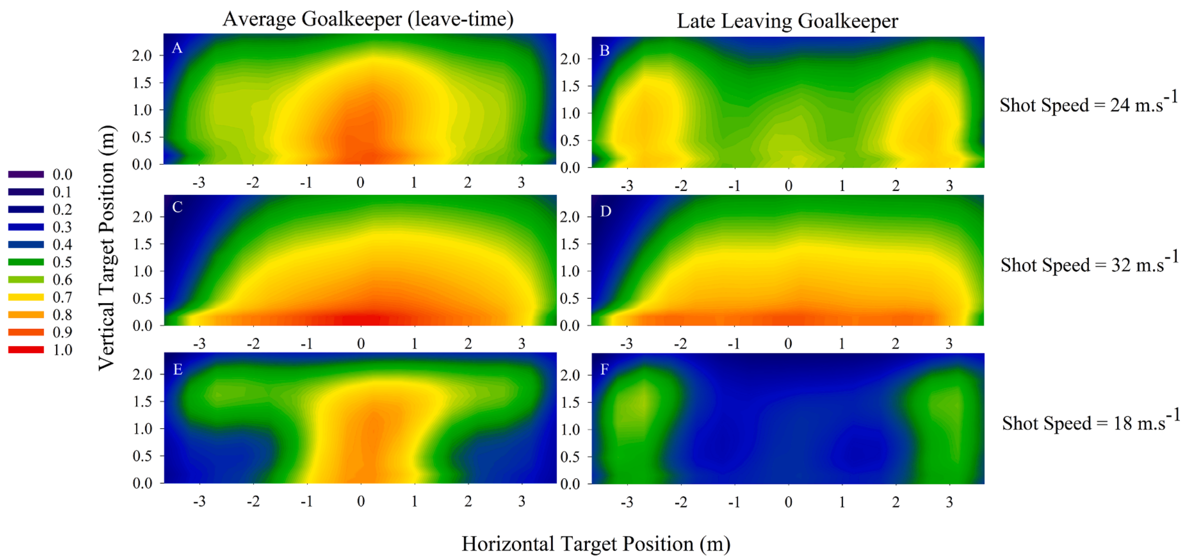

Fig. 3. Probability of scoring a goal dependent on target (t_x, t_y), shooter sub-strategy (shot speed, kick technique, footedness), and goalkeeper (average goalkeeper or late leaving). Each plot represents the dimensions of a goal seen from the shooter's perspective. Contour colours are the conditional probability describing the probability of a goal depending on the target. **A)** shot speed = 24 $m.s^{-1}$, technique = side-foot, footedness = right, goalkeeper leave-time = average; **B)** 24 $m.s^{-1}$, side-foot, right, late; **C)** 32 $m.s^{-1}$, instep, right, average; **D)** 32 $m.s^{-1}$, instep, right, late; **E)** 18 $m.s^{-1}$, side-foot, right, average; **F)** 18 $m.s^{-1}$, side-foot, right, late.

Faster shots have a greater chance of scoring a goal than slower shots and give the shooter a variety of effective strategies to choose from. In Fig. 3C and 3D, a broad range of target locations have a high chance of success when kicking at 32 m.s^{-1} against either a late-moving or average goalkeeper. This is largely due to these shots being difficult to save – if the goalkeeper reaches the shot, there is still only a 30% chance it will be successfully blocked (Supplementary equation 10). Conversely, shooting slowly is only effective against an average goalkeeper and only when aiming down the centre of the goal (Fig. 3E). Thus, shooting at fast speeds gives the greatest chance of success, particularly when the shooter has no prior knowledge of when the goalkeeper is likely to move.

We expect the model's predictions to change depending on the skill level of players. Here, the model was parameterised using data from amateur/semi-professional shooters and goalkeepers. However, we assume the best outfield players in the world to be highly accurate shooters at high speeds. Compared to amateurs, a professional player's optimal target would be closer to the goal post and have a greater chance of success as the shot is likely further from the goalkeeper. Goalkeepers are likely to vary in their ability to block shots within reach. From Hunter and colleagues (Hunter, Angilletta, et al., 2018), faster shots were less likely saved than slower shots if within reach. We expect this relationship to be less pronounced for professional goalkeepers, with them saving a higher proportion of fast shots. This effect could be easily captured by decreasing the slope of the equation modelling the relationship between shot speed and shot blocking (Supplementary equation 10). This would greatly alter the model's predictions for fast shots against better goalkeepers. Against professional goalkeepers, we would expect the optimal strategies to be those that place the ball beyond the goalkeepers reach rather than those that rely on goalkeeper error (See Supplementary Section 5 for more details).

In conclusion, we have presented a predictive model that estimates the probability of scoring a soccer penalty for any strategy a shooter may choose, identifying the strategy with the greatest chance of success. We surpass previous models by: including an error structure for shooters dependent on shot speed, kick technique, and footedness; quantifying variation in goalkeeper strategies by including a distribution of leave-time and how this affects shot prediction; and accounting for interactions between the shooter's strategy and goalkeeper's strategy – specifically, how shot speed affects goalkeeper leave-time and the probability the shot is saved if within the goalkeeper's reach.

Coaches could use our model to select the best penalty takers in their team and identify for each player their optimal shooting strategy. After first describing how a player's kicking accuracy is affected by shot speed, the model could compete them against the average goalkeeper to identify their best shooting strategy and the probability of its success. Comparing these probabilities across a team would identify the best penalty takers. The model could also be used to identify a shooter's best strategy against a specific goalkeeper. For example, existing footage of professional goalkeepers facing penalty shots is readily available on platforms such as YouTube. A coach could easily collect data on an opponent goalkeeper's leave-time and modify the model to identify the optimal shooting strategy for each of their penalty takers for that matchup. Such information could make the difference between winning and losing a penalty shootout in a major tournament.

CRediT authorship contribution statement

Andrew H. Hunter: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Theodore P. Pavlic:** Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization. **Michael J. Angilletta:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Robbie S. Wilson:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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